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Utility Applications of Smart Online Energy Systems:

A case for Investing in Online Power Electronics

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By

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Abbreviations - Nomenclature

Kahramaa- Qatar General Electricity & Water Corporation

QPTS- Qatar Power Transmission System

QPDS- Qatar Power Distribution System

QPS- Qatar Power System

CPBD-Corporate Planning and Business Development Department in Kahramaa

OPE- Online Power Electronics

FACTS- Flexible Alternating Current Transmission

HVDC- High Voltage Direct Current

SVC- Static VAr Compensator

STATCOM- Static Compensator

SC- Series Compensation

TCSC- Thyristor Control Series Capacitor

SSSC- Static Synchronous Series Compensator

UPFC- Unified Power Flow Controller

UPQC- Unified Power Quality Conditioner

MSC- Mechanically Switched Capacitor

TSC- Thyristor Switched Capacitor

TCR- Thyristor Controlled Reactor

FSC- Fixed Series Capacitor

PST- Phase Shifting Transformer

TCPST- Thyristor Controlled Phase Shifting Transformer

STS- Static Transfer Switch

VSC- Voltage Source Converter

CSC- Current Source Converter

LCC- Line Commutated Converter

MMC- Modular Multilevel Converter

IGBT- Insulated Gated Bipolar Transistor

GTO- Gate Turn-off Thyristor

GCT- Gate Commutated Thyristor

DVR- Dynamic Voltage Restorer

PWM- Pulse Width Modulation

PMU- Phasor Measurements Unit

PMU- Performance Monitoring Unit

SMT-Synchronized Measurement Technology

WAMPAC-Wide Area Monitoring, Protection and Control

WAM-Wide Area Monitoring

WAC-Wide Area Control

WAP-Wide Area Protection

PAR- Phase Angle Regulating transformers

PSS- Power System Stabilizer

Abbreviations – Nomenclature (continued)

ACCC- Aluminium Conductor Composite Core

ACCR- Aluminium conductor Composite Reinforced Conductor

TES- Thermal Energy Sources

RES- Renewable Energy Sources

ESS- Energy Storage System

OHL- Over-Head Line

BESS- Battery Energy Storage System

DSM- Demand Side Management

OOF- Out of Firm

ICT- Information, Communications Technology

GA- Genetic Algorithm

PSS®E -Power Systems Simulator Software

DG-Distribution Generations

PV-Photo Voltaic

GPS-Global Positioning System

Acknowledgements

Declaration

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Hatim Ibrahim Elsayed

April 2014

Abstract

The backbone of any power grid, the transmission and sub-transmission networks, should be flexible, robust, resilient and self-healing to cope with wide types of network adverse conditions and operations. Power electronic applications are making a major impact on the present and future state of power systems generation, transmission and distribution. These applications include FACTS (Flexible Alternating Current Transmission), HVDC (High Voltage Direct Current) in transmission and Custom Power devices in distribution. FACTS devices are some of the advanced assets that network planners can use to make the transmission grid become more flexible and robust. Many established research ideas to advance operations of these devices have been published in the open literature over the last ten years. The most recent publications in this field are reviewed in this thesis. A critical analysis of literature and existing conditions reveals a range of potentials that are ideal for development in Qatar's increasingly strained electricity network.

As a result of demand surge in Qatar in recent years and the forecast to grow in the same rate, the need for improvement in Qatar Power Transmission System (QPTS) is great and significant. Conventional planning and operational solutions such as conductor up-rating, and fixed series capacitors (FSC) are considered. However there are growing challenges on getting new rights of ways for new overhead lines and even corridors for new cables. Advanced FACTS devices are considered for dynamic control of power flows and voltages, such as TCSC (Thyristor Controlled Series Capacitor) and GUPFC (Generalized, Unified Power Flow Controller). The research in this thesis examines the potential for QPTS to improve and develop, with emphasis on increased output through integrated online energy systems, online FACTS and HVDC controllers based on synchrophasor measurements. The devices are modelled in Siemens PTI's PSS®E software, through steady-state mode case study to investigate power flow control and voltage support. Comparison between similar FACTS technologies, such as SVC and STATCOM, is also presented.

The improvement in power flow imbalance between transmission lines with different ratings and lengths is studied. The FACTS devices are tested for voltage support to enhance the network voltage profile and hence increase security and reliability to important industrial customers. Optimization techniques of the FACTS devices allocation and rating are generally discussed considering the voltage improvement and optimal power flow control. The results achieved showing the network improvement with using the FACTS are presented in the case studies. In a separate case study, applying medium voltage custom power devices to convert DC battery storage and photovoltaic energy into AC energy using a power conversion system is discussed. The dynamic mode of the STATCOM is modelled in QPTS in the succeeding case study using the same software and compared with the capacitor banks. This is followed by another case of HVDC analysis modelled with and without STATCOM present.

The thesis discussed the real time operation and control of power system physical parameters in QPTS using capacitors, FACTS and HVDC. The key contribution of this thesis is the application and resting of all sorts of FACTS and HVDC in QPTS. The system wide area, coordinated control of FACTS (Online Power Electronics-OPE) is a new concept. Another major contribution is being able to look at a system wide approach for a transmission smart grid application. The results of thesis are presented in international conferences in USA, Hong Kong, France, Portugal, and locally in the Arabian Gulf (Dubai, Oman and Qatar). The thesis's papers are listed in the 'References' section and in Appendix-F.

Chapter 1: Introduction and Commentary

1.1 The Thesis Structure

The preceding 'Abstract' is an executive summary of this research work, followed by some detailed description of the thesis's main objective, practical approach, original contributions, and future works in this Chapter 1: 'Introduction and Commentary'. More focus on the thesis research questions, aim, techniques and tools used are given in Chapter 2: 'Research Questions, Tools, Techniques, Methodology'. Chapter 3: 'Operational Constraints in QPTS' illustrates the most significant challenges facing QPTS starting with the rising power demand, power loops flow, and under-voltage conditions. This pressures the research to study in details the power electronic technology efficiency and effectiveness at maximizing power transmission accessibility. The enhancement of transmission capacity is developed in Chapter 4: 'Compensation from FACTS and Non-FACTS Devices'. The chapter uses mathematic equations to explain the physical parameters inherited within power systems that impede the efficient delivery of active power followed by the mathematical equations to improve the situation. The chapter then exhibits different FACTS and non-FACTS devices can be used to help with active and reactive power compensation. The research also considered related technologies in power electronics and non-power electronic based solutions.

Chapter 5: outlined the applications of smart energy systems and online power electronic (OPE) in QPS including FACTS, distributed generations, energy storage, renewable, etc. Chapter 6: 'Literature Review of Power Electronics and Online Energy Systems', reviews critical literature details regarding this situation and other concepts. The research plan was strategically created and implemented to collect and analyse unique data in this area. The analysis and studies followed proper modelling and comparison with the existing data of load flow available, are included in Chapter 7: 'Case Studies: Power Electronics Applications in QPTS'. In this research, QPTS steady-state load flow models have been created using Siemens PTI's Power System Simulator software (PSS®E) for the current year and the forecasted years until 2017.

Chapter 8: 'Potential Application of Smart Distributed Generation in QPS' is a pure applied research investigated the practical use of distributed generation in QPS using solar cells

and battery storage systems. The analysis showed how the smart DGs could assist the distribution network to cope with the overloading situations. The outcome of this thesis is augmented in Chapter 9: 'Discussions, Conclusions, and Recommendations'. The last part of the thesis encompassed the Appendices, commencing with Appendix-A: - 'PSS®E Software used for power system analysis in the study'. Appendix-B is the 'Research dissemination artefact and plan' discussing the option of HVDC and upcoming research in this area post to doctorate degree. This is followed by Appendix-C: 'Research theory in power electronics technologies', with refined selection of basic power electronics theory from books, lectures and papers. Appendix-D elaborates in the details of 'FACTS, and Custom Power devices design characteristics'. The 'Optimization of power losses' explained in Appendix-E is a pure original research effort of this thesis reviewing one of the existing theories in power losses optimisation. The list of the papers published during the course of this PhD work is included in Appendix-F: 'Authors' publications- doctoral research published papers'.

1.2 Rationale for the Research Work undertaken

The main objective of this thesis is to study the potential to improve the Qatar Power Transmission System (QPTS), using smart online energy systems, and the introduction of the new terminology 'Online Power Electronics' (OPE). The OPE utilisation included online FACTS (Flexible Alternating Current Transmission), HVDC (High Voltage Direct Current), ESS (Energy Storage Systems). What has been done thesis is an implementation of OPE in real networks (this is also a contribution). The research work started with modelling QPTS using Siemens PTI's PSS®E [88] and followed by identifying the planning and operational problems in the existing power network. The next research step is the testing and nesting of power electronics devices into QPTS and find how they solve the mentioned problems. The last step is the inspection of how the new technologies of GPS synchrophasors, online systems could impact the efficient operation of QPTS. The literature review has unveiled part of the survey for online energy systems applications in real power networks [6]. Since the online systems are emerging as a new research arena and utility applications are spreading around, the main result of this thesis concluded that the control of power flow and voltage on a real time basis using power electronics devices is an online application and hence the new term 'OPE' is nominated. This research work conducted was motivated by the insistent needs to find scientific solutions to some existing and anticipated operational and planning challenges in QPTS. The load demand of Qatar's transmission system is increasing rapidly due to the country's expansive infrastructural developments. This expansion will continue in the next 16 years especially with

the anticipated world cup football tournament in 2022 and Qatar National Vision 2030. The challenge of QPTS's load density increase triggered the need to control the flow of power to avoid loop flows that will become inevitable [1], [2], [3]. At the same time, the demand for power from remote and isolated locations far from the generating plants to feed the oil and gas companies' industrial loads poses significant challenges to the network. Conventional AC transmission systems alone cannot solve these challenges as they are constrained by cost and resources. FACTS devices and HVDC transmission would have to be incorporated in the network to help solve some of these challenges. The research also considered smart solutions from recent technologies in the arena of custom power devices and renewable incorporating photovoltaic (PV), battery storage, smart conductors. The contributions to knowledge from this thesis are explained in the next section.

1.3 The Original Contributions of this Thesis

The great impact of FACTS and HVDC in power systems real-time operation has inspired the research to call for the new nomenclature 'online power electronics-OPE'. The implementation of OPE in the real QPTS is an applied research contribution as described in section 1.2. The OPE concept is originated parallel to the anticipated utilisation of the real-time online FACTS controllers based on GPS time-stamped, measurements and an online knowledge base. The OPE concept is an integration of power electronics application into the ground breaking online energy systems. Emphasizing the potential for integrated online energy systems, there is demand for online power flow control, voltage control, monitoring, fault analysis, system estimation. This is one of the original contributions of this thesis together with the unique simultaneous analysis of FACTS and HVDC in QPTS. The application technique using the software is demonstrated by significant case studies on QPTS to achieve certain objectives coping with increased demand, voltage maintenance, and power flow balancing. The rating and location of GUPFC in QPTS were selected by simulating combinations of active and reactive power ratings on trial and error basis in the software. This FACTS optimal rating selection and allocation technique could not be found to have been conducted in the same practical approach in the past applied research. The applied research conducted within this thesis can help other researchers to build from it.

Since this PhD work is an applied research by definition all of them contribute to the science and have shown the importance of this PhD work. The original contributions on thesis can be summarised as below:-

1. Applied research on realistic, existing power network of Qatar (QPS) is the key contribution in this thesis.

2. Applying the concept of 'online power electronics'-OPE driven by online FACTS controllers set based on phasor measurements. The OPE proved feasible in solving planning and operational challenges in combination with conventional techniques.

3. Power electronics (FACTS and HVDC) modelling and analysis in a real utility transmission network (QPTS) is considered an applied research contribution.

4. There are no HVDC/GUPFC devices implemented in Qatar or in the Gulf States in general. This will be a new idea in the region and innovation that will contribute towards the advancement of knowledge.

5. Selection of the GUPFC among other FACTS devices as feasible for application in QPTS as a result of network modelling is an applied research contribution.

6. Custom solution to solve overload in distribution substations using distribution custom power electronic devices for energy conversion is an original applied research contribution.

The research results are published in the thesis's papers [1], [2], [3], [4], [5], [6], [7], [8].

1.4 Current or Planned Practice Use of the Doctoral Work

The research elements of this PhD piece of work have strong emphasis on practical application in an existing power transmission system. The results achieved from the extensive analysis carried out were significant with exposure to originality in terms of real applications in a utility. Several case studies were performed using the Siemens PTI's PSS®E software package for FACTS, HVDC modelling and analysis in the papers [1], [2], [3], [4]. This is in addition to analysis of renewable energy and battery storages, in the papers [5], [6], [7]. Online energy systems are covered in the research work in [6] and in the online network cyber security in [8]. Actually some of the proven technologies with direct impact on QPTS, such as reconductoring using the new conductors (ACCC and ACCR); have been sent for execution at site [1]. Implementation of the power electronic equipment recommended as part of the study reports is expected within the next five to seven years.

1.5 Contemporary Relevance and Implications for Future Research and Practice Development

This commentary introduces concepts, literature, case studies, and a research initiative designed to acquire original data in these areas. This section provides initial introduction to the research methodology, a detailed description of resources and research direction, and brief research hypotheses prior to presenting the results and data analysis. The following chapters contain the bulk of the entire presentation of research, the analysis of literature, relationship to the Qatar context, presentation and analysis of simulations using Siemens PTI's PSS®E [88], and initial conclusions. It is the overall goal of the research chapter to present original research while relating the results to developing practice and potential for development, providing a manuscript of the finding of literature review and research project. The dissemination artefact plan is further aiming at multiple stakeholders for the purpose of addressing the communication of the results in a way which facilitates the progressive development of practices in the field. According to the IEEE Power and Energy Society, the technologies of the FACTS and Custom Power concepts, have been moving ahead at an increasing pace, very significant near-to-long term benefits of the technologies are now recognized in the industry [1], [2], [3]. FACTS devices comprising SVC, STATCOM, UPFC and GUPFC; synchronized phasor measurements; and other technologies have been reviewed, applied, and assessed. The original research designed and carried out emphasizes the potential for online analysis to provide enhanced coordination of controls across a grid utilizing the FACTS devices such as, SVC, STATCOM, TCSC, UPFC, or GUPFC.

Case studies were also conducted using HVDC transmission to mitigate the same planning and operational problems, and the results were compared with FACTS impact on the same system. While online security and controls have been addressed in research such as that conducted, still there is a gap in literature regarding the direct emphasis of the potential for online analysis to improve coordination of advanced smart systems. Moreover, the area of emphasis for this research is Qatar, where the existing knowledge base for Qatar-specific operations is also below a desirable (and properly informative) level.

Examination of the background of recent research in Qatar, amid the assessment of power systems, has determined that there are both considerable challenges and considerable potential [2], [3]. Details of the research objective, methodology, techniques, tools used in this research, are further discussed in Chapter 2.

Chapter 2: Research Questions, Tools, Techniques, Methodology

2.1 Introduction

The content in this chapter falls mainly within the creation of new brainstorming questions, hypothesis, and objectives that led to developing smooth flow path of studies and analysis. The successful selection of research questions has resulted eventually to the new concept of 'Online Power Electronics'-OPE. The OPE is a bridge under construction between the ever evolving power electronics technology and the new emerging online energy systems [6]. While the research aim serves as the foundation for the research objectives, the research questions of the study provide a formal inquiry to be answered through the analysis and conclusions.

2.2 Research Aim and Objectives

The primary aim of this research is to examine the potential for a development plan to improve utilization of transmission resources in the Qatar power system. The main research objective is to present an increase of system performance using dynamic flow power controllers implemented within transmission systems in Qatar and will focus on balancing power flow and voltage improvement [2], [3]. This research effort was designed to assess the online analysis in Qatar smart power systems, with emphasis on coordinating FACTS such as SVC, TCSC, GUPFC, and UPFC. The study will assess challenges, and strategies to address them, using online power electronic and controls analysis. The research explores the potential application of new technologies in the Qatar power system which has thus far been scarcely used in the west and other developed countries in other corners of the world.

The detailed objectives for this research study entail i) assess the potential for online control systems to be integrated with existing systems of power coordination, ii) assess the potential for these systems to benefit from coordinated control of FACTS devices, iii) assess the installation of FACTS compensation that is controlled via synchrophasors, and iv) recommend techniques and strategies to overcome existing obstacles and reach the successful application of research objectives. The research will be followed by implementation on QPTS since the proposed solutions proved technically and economically feasible for implementation.

2.2.1 Research questions and hypothesis

As stated in the introductory Commentary Chapter, the research inquiries for this research effort are:

Primary Research Question: "What are the most immediate challenges and potential in the development of online technology integrated with QPS?"

Secondary Research Question: "How can existing equipment and software best facilitate the development of power system technology, and what are the most ideal directions for future developments or research initiatives?"

The research has established brief hypotheses for these research inquiries, while these hypotheses are further examined and compared in the concluding discussions and analyses of the findings. Addressing each inquiry namely, the researcher holds the following hypotheses:

Hypothesis 1: The most immediate challenges and potential for online systems and online power electronics integrated with power systems in Qatar lie within its ability to introduce advanced technology, and develop programs and methods beyond the accomplishments. The capacity to fund developmental projects aiming solely at innovation, implementation, or potential is also limited by the amount of monetary funding available for such projects, while the actions of academia can thereby largely benefit from this gap between desire and accomplishments. Opportunities for progressive development lie in the efforts of non-profit organisations, particularly those with interests in alternative energy, although some relationship or promise to dedicate or invest in alternative energy distribution may be required to receive sufficient attention and services from such organisations.

Hypothesis 2: Existing equipment and software can best facilitate the development of power system technology through an increasing emphasis on the potential for internet technology, for improved functions with power systems, and through continued attempts to simulate systems while seeking improved efficiency.

2.3 Research Methodology

The research methodology for this research initiative lies predominantly in the analysis of existing research, although further emphasis is to be placed on unique applications to existing Qatar systems, as well as the potential for system development through an analysis of PSS®E simulation results. Although existing information comprises the bulk of information used for the analysis and recommendations, the results are to be applied to Qatar systems for the progressive development of existing systems in a way which is ultimately an original research. The research methodology is thereby designed to generate unique solutions and recommendations from a combination of existing materials, implications from simulations, and unique applications.

2.3.1 Resources and research direction

As mentioned, the primary resources for this study are existing literature, as this serves as the foundation for the primary analysis. PSS®E simulation results are another resource, used in the analysed relationships between literature and existing Qatar systems, and further used as the foundation for proposed solutions and recommendations. The research direction begins with the presentation of the problem, presentation of the literature review and outline of the case study, and presentation of research for analysis, and then continues with an analysis of this data which emphasizes the acknowledgement of limitations and proposal of solutions. The research direction prioritizes the development of online systems, online power electronics and components of the power industry in the Qatar context. In parallel with the research aim, the research direction seeks to recommend actions which serve to optimize the improved efficiency and effectiveness of online systems and online power electronics.

2.3.2 Research and data analysis

The research and data analysis comprise the bulk of the research presented, while the literature is to be presented and related as described in the previous sections. The data analysis further relates PSS®E [88] results to literature, while the research and data analysis is thereby presented as a combination of conceptual relationships, comparative analyses, charts and tables showing existing capacity and potential for future developments, lists of limitations and opportunities, and recommendations for overcoming existing challenges. Multiple resources are used for this research initiative, including existing published literature, QPTS models

developed in power systems analysis software, and existing systems and technology. Published research serves as a foundation for the research background and direction. These resources are gathered and combined for an analysis relating to available information in a way which presents useful and unique relationships, potential improvements and developmental directions for technology, and recommendations. As this relates to the aim and objectives of the research, the data analysis entails their unique application and generation of original findings. Following the initial presentation of literature, research findings, and data analysis, a subsequent discussion, list of conclusions and recommendations, and dissemination plan will follow.

2.3.3 Dissemination artefact and plan

The findings involve recommendations relevant to the development of both power systems and online components. Further attempts to discern the potential for the controllers, to address demands, to be applied in new areas for new benefits in the future, or otherwise provide a research direction for similar analyses. The research provides comparative analysis with potential methods of optimization and design using a range of FACTS devices [3], [4]. Following the results and analysis presented in the following section, the dissemination artefact and plan provides a more dynamic and direct course of action for improving Qatar systems. This thereby summarizes the key findings of the results while applying them to an organized methodology for future research and development. This dissemination artefact and plan is designed as a formal call for action for progressive development and further research, and is presented in a way which is ideal for future publication, as it is the intention of this research to develop recommendations and facilitate awareness in a way which involves such an audience.

2.3.4 Validity, reliability, limitations, and ethics

Validity and reliability are not of as much concern to this research effort as is often present in primary research and clinical research trials, as a sample of individual participants are not questioned or tested. However, the study relies both on the reliability and validity of the literature analysed in the research and analysis, while this research and analysis is further dependent on the correct application and interpretation of the literature. Meanwhile, bias applies similarly, and while the researcher is not bias to any particular solution, the analysis and recommendations are presented objectively; the research itself was also conducted objectively. The validity and reliability of resources researched and applied were carefully examined for credibility; resources deemed unreliable, i.e. unaccredited websites or

publications from individuals without credentials were not applied to this analysis, for the sake of validity and reliability. On a similar note, the study is limited by a number of factors, and in addition to being bound by the original validity, reliability, and limitations of the literature interpreted and applied in the analysis. The study is limited by the quantity of resources, time, ability to access information regarding detailed Qatar-specific power system operations, and (by fault of the researcher) the clear ability to foresee the most optimal and precise solutions for the systems.

2.4 Analysis of Literature

The literature presented in the 'Literature Review' Chapter provides a foundation for a dissemination artefact and plan, while the resources used for this analysis met specific inclusion criteria to be used and applied for the subsequent analysis and presentation. A critical appraisal of the existing case and recommendations for development in Qatar facilitate a wider range of possible developments for online power electronics systems, power, and voltage controls in the area. The research generally examined the optimal developments for expanding transmission and power in QPS (rather than integrating and improving online controls).

Critically analysing the potential role of FACTS devices in the improvement of QPTS, relevant aspects of the online structure and demands become apparent [2], [4], [6]. This research pointed out that the development of online power electronics devices give rise to the voltage levels, enhanced transient stability, decreasing the amount of loops in power flows.

Online power electronic controls can address, integrating network operations with smart grid functions while improving efficiency and flexibility. The online analysis examining the capacity to enhance controls and improved transmission network would be of considerable benefit [6]. Next chapter provides a situational analysis of the current state of QPTS, models PSS®E, highlighting the challenges and the potential improvement using online power electronics, wide-area control and monitoring.

Chapter 3: Operational Constraints in QPTS

3.1 Introduction

This chapter is identifying QPTS problems from the available planning and operational data to establish a base for the analysis and solutions of these problems. The chapter also outlines the scientific creation of new steady state and dynamic models of QPTS for the years 2012, up to 2015-2017 using the PSS®E software. PSS®E is the main software tool used in this study and it belongs to Siemens Company, however it has become the utility standard used by worldwide utilities for power system analysis [88]. PSS®E is commercial software and absolutely fully verified for power system analysis for many years and used by consultants, contractors as well. The proper and verified modelling of QPTS has established the right direction for accurate analysis at later stages of the case studies. The research results are published in the thesis's papers [1], [2], [3], [5], [6], [7].

3.2 Overview of Qatar Power Transmission System (QPTS) Challenges

QPTS operates at the voltage levels of 400 & 220 kV, while the sub-transmission system operates at 132 & 66 kV voltage levels. The 400 kV network of QPTS is the primary backbone in supplying existing and new load centres. The majority of power generation facilities within this network are located in the northern, central and southern regions of the State.

QPTS has overhead lines (OHLs) in the rural areas while underground cables dominate in the developed land subdivisions. The industrial cities (Dukhan and Umm Bab) in the western-south part of Qatar have a growing demand as a result of expansion of oil, gas and cement industries. Figure 1 below presents an outline of QPTS network.
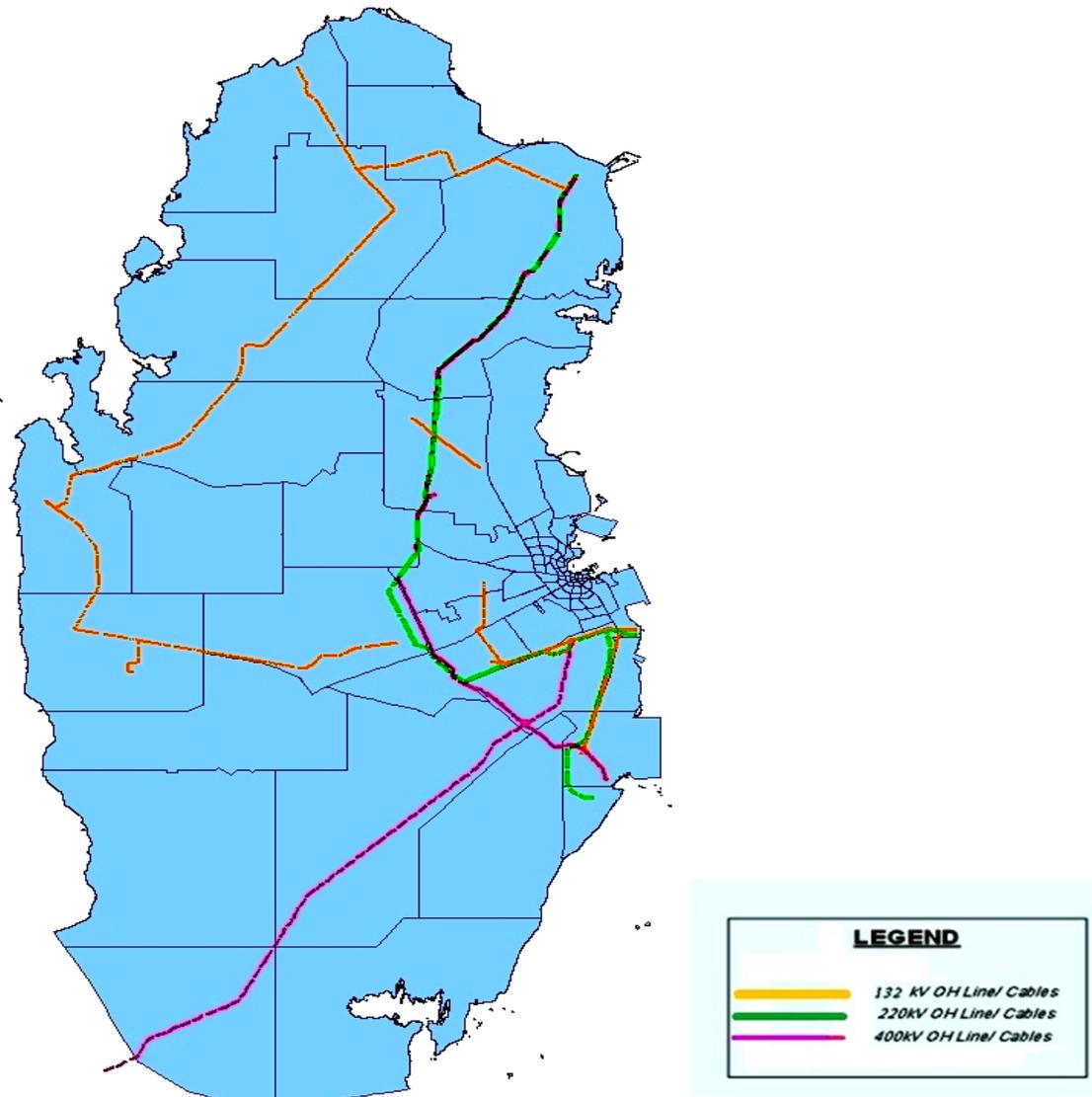
Figure 1: Qatar Power Transmission Network overview 400, 220 and 132 kV [9]

QPTS has seen unprecedented growth in capacity to cope with the rapid demand growth. The 5-years demand forecast (2012-2017), including the three scenarios (base, high and low), is shown in Figure 2. The overall power MW growth was 8.7% in the year 2012 while domestic MW growth amounted to 7.1%, and industrial growth was 6.1% [9]. The demand growth in the years 2006-2009 was a record high that varied between 12%-14% per annum, rendering it as one of the highest growth rates in the world at the time.
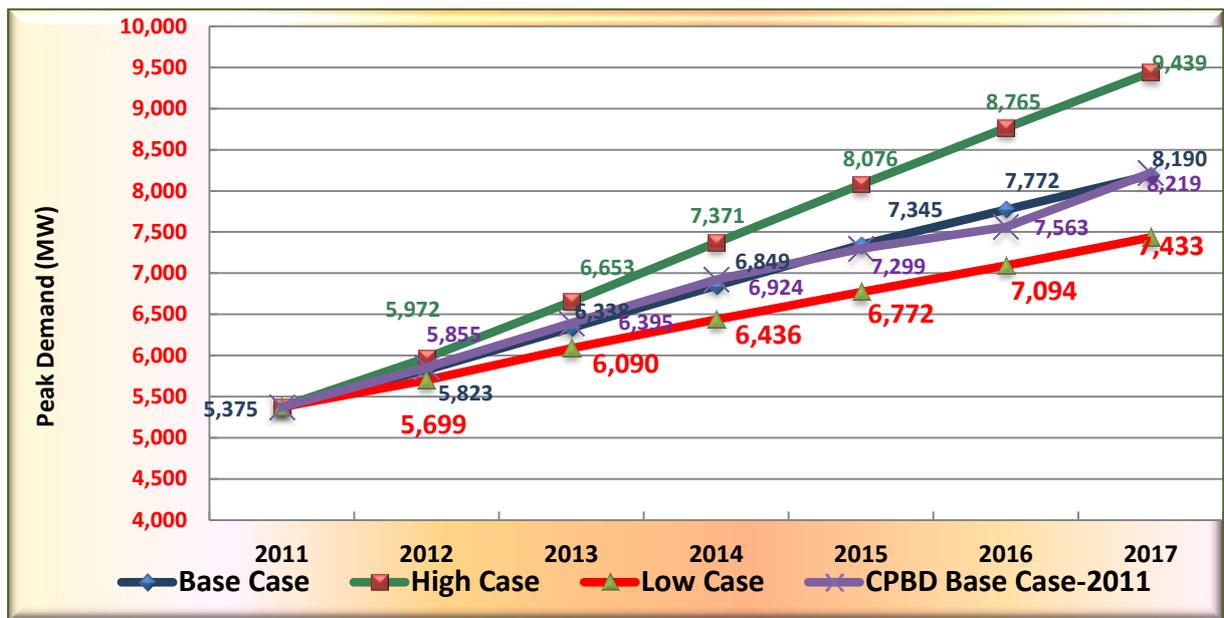
Figure 2: Demand forecast (MW) in Qatar for 2011-17 [9]

There are other challenges such as possible disturbances from external sources outside the QPTS, increasing fault current levels, and bottlenecks in the sub-transmission system. These challenges require more attention and investigation by network planners to foresee emerging solutions. The power electronics based compensation (FACTS devices) and other non-power electronics technologies such as the GE variable frequency transformers and the SEN transformers can play a useful role in addressing these challenges and improving QPTS operation while providing cost effective utilization of the existing transmission system. FACTS devices can achieve different objectives, and can be selected based on the requirements to improve QPTS operation and enhance smart grid implementation.

The information available from wide-area monitoring and controls coordination utilizing PMUs can be an effective solution to the challenges of QPTS. It will look at the integration of the voltage information provided by phasor measurement units to the online control of FACTS controllers and integration with energy management, state estimation and non-power electronics devices. The PMUs can supply real-time information necessary for FACTS and HVDC to perform their functions to control voltage and power flow in the network [1], [2], [3], [6].

3.3 QPTS Software Models

QPTS is modelled for two years 2015 and 2016 using the Siemens PTI's PSS®E software. The power flow cases include the bus loadings condition for the year 2015 based on the forecast carried by the electricity planning department of Kahramaa [9]. The power flow model for the existing network was tested and verified against the measured power flows and voltages data from the National Control Centre (NCC) for the past eight years. The accurate power flow model for the running year is used to develop the steady state models for the study.

Figure 3 is showing the 220/132 kV single line diagram (SLD) for QPTS for the year 2016 using the PSS®E software. The plot in the figure is a '2 in 1' plot, including both the, voltages and loadings with colour visualisation. The bars with the blue colour are the line loadings percentage (blue is the load percentage). The colours, from blue to red and in between are the voltage levels. The extremely red colours are the voltages above 1.05 pu or close to it and the extreme blue ones are the voltages that are at 0.95 pu or below. The colours in between, i.e. the yellow ones are the ones that are around 1.0 pu voltage.
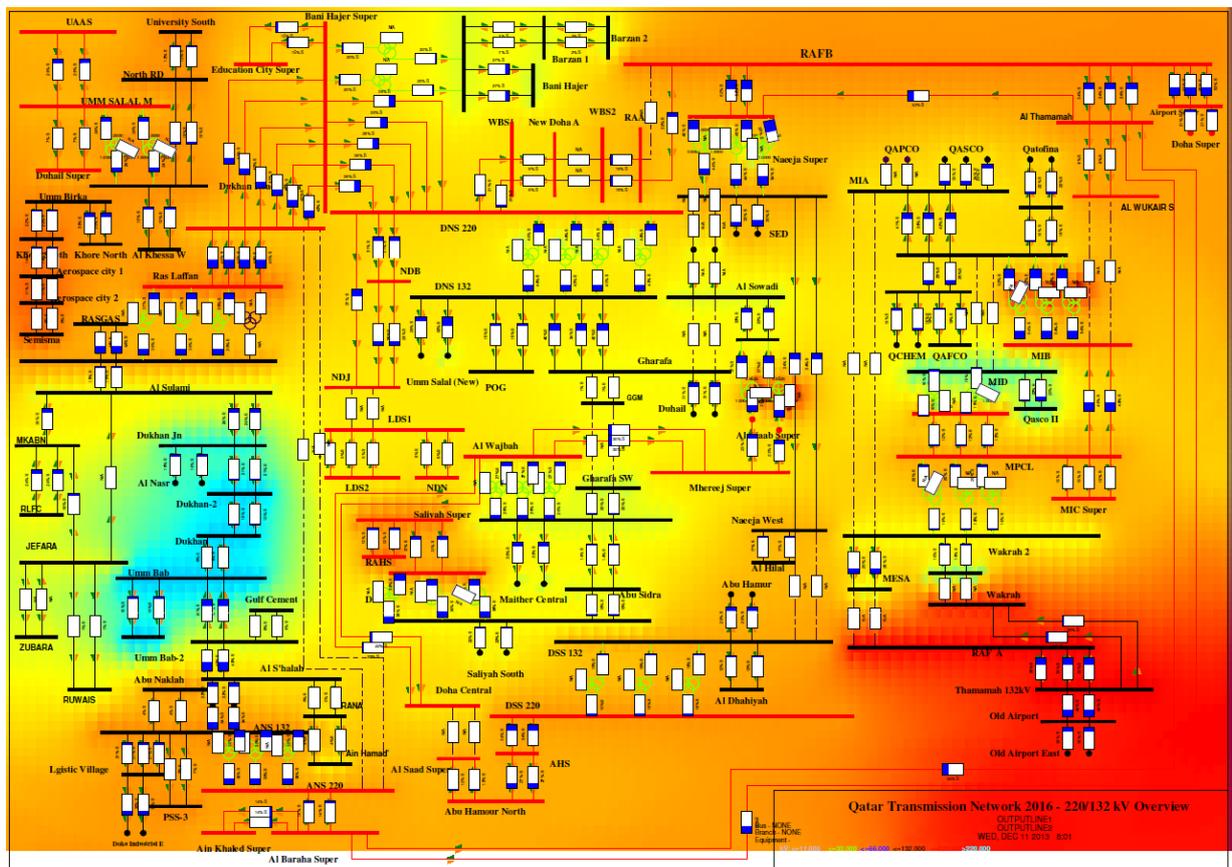
Figure 3: 220/132 kV QPTS SLD (PSS®E model 2016)

Figure 4 is showing the 400/220 kV network SLD of QPTS for the year 2016. The loading and voltage codes for this 400/220 kV network figure are similar to what have explained above for Figure 3.
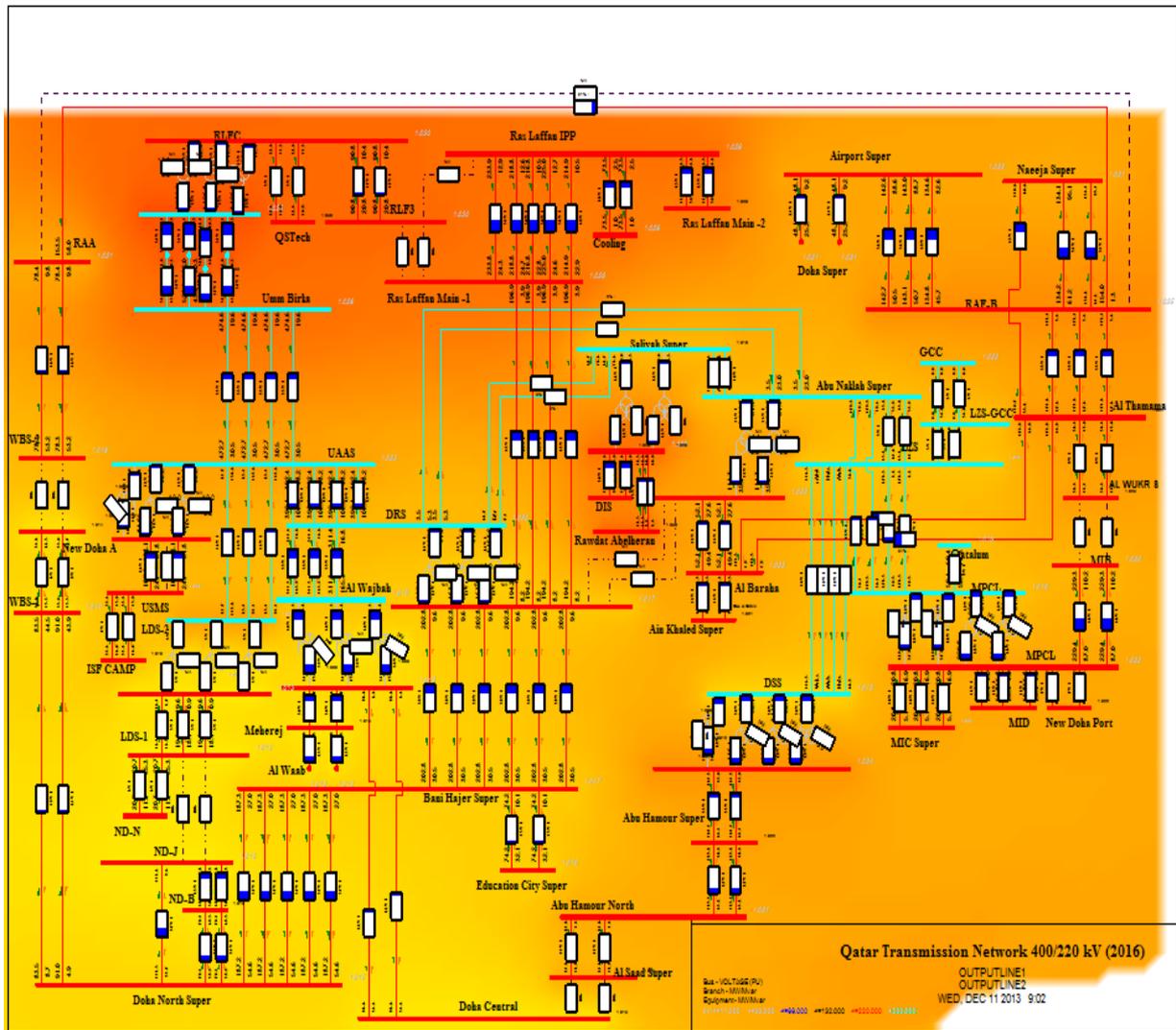
Figure 4: 400/220 kV QPTS SLD (PSS®E model 2016)

The western area (Dukhan- Umm Bab) is exhibiting low voltage levels (greenish blue colour), as well as power flow imbalance in one of the 132 kV ring feeding the region (Figure 3). Finding practical and advanced solutions, for this unhealthy operation state is the main focus of this thesis [1], [2], [3]. The next section explains more the problem in this area and analyse the case with more contingencies [2].

3.4 Overloading and Voltage problems in the 132 kV Western Ring

The western part of Qatar, including the Dukhan and Umm Bab areas, has big industrial load centres. The Dukhan and Umm Bab 132 kV networks are connected to the main grid through two 132 kV double circuit overhead transmission lines [1], [2], [3]. One of the OHLs is from the North of Qatar and the other OHL is from the South of the capital (Doha), and this network configuration creates the Western Ring. The 132 kV OHLs feeding this western part of Qatar have different ratings and lengths and are expected to pose problems, in the near future, in operating the ring system due to uneven power flows.

The system from the South is stronger and pushes more power onto the 132 kV OHL which unfortunately has the lower rating. In addition, the western system needs support because of the long OHLs and low voltage problems are also anticipated with the increase in industrial load in the area. Moreover, excess thermal limit loading on the older lines has become an issue in the connections between the central and western regions [1], [2], [3]. The 400 kV and 220 kV network have not yet been greatly extended to and across this region, due to scattered farm lands and houses, emerging authorities' rules, and difficulty in identifying corridors. There are plans to expand some industrial facilities, as the major industrial customers have established their 132 kV substations and internal 33 kV distribution network with the help of the power utility [2], [3].

Steady state and power flow analyses for 2015-2017 system load conditions have confirmed additional unwanted power flow loops and low voltage problems in the western region of Qatar, which are expected to increase in the year 2015 and beyond [1]. The reason for this is that the 132 kV network from the South (the old OHL from Al S'halah to Umm Bab) is closer to the load centres, thereby delivering most of the power. However, its thermal rating (133 MVA) is about half the thermal rating (260 MVA) of the 132 kV lines coming from the North (the double OHL from Ras Laffan– Al Sulami - Dukhan Junction) [1].

Figure 5 is showing the Western Ring normal power flow case for the model of 2015, before the load increase and without any re-enforcements [2]. The figure is indicating anticipated violation of voltages and power flows in system intact conditions for system load conditions.
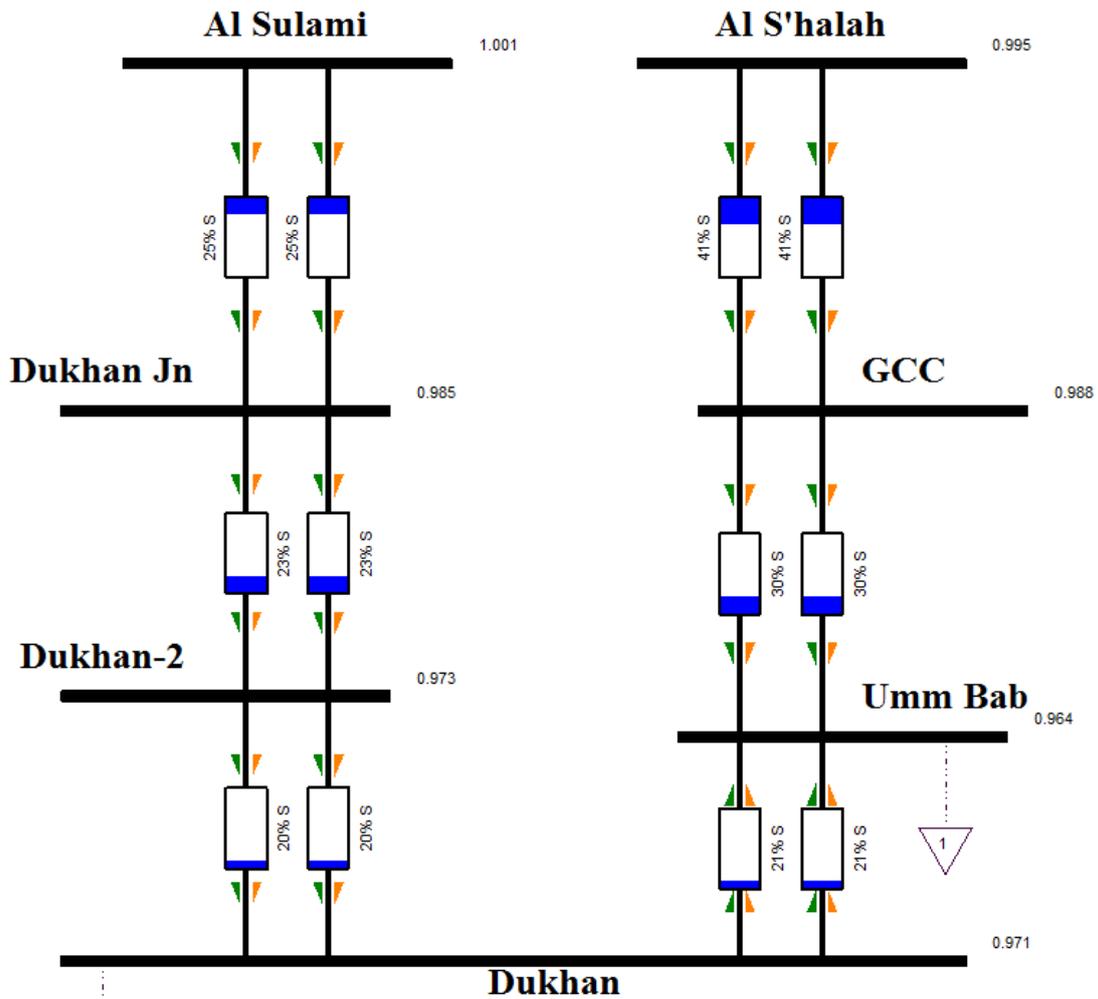
Figure 5: **Normal power flow case without capacitors, STATCOM or HVDC (PSS®E QPTS -2015 model)**
(generated using the Siemens PTI's PSS®E software)

When the load increased in the year 2016 (normal power flow case), voltage values are depressed at some busbars and the power flows started to show imbalance at certain lines (Figure 6) [2].
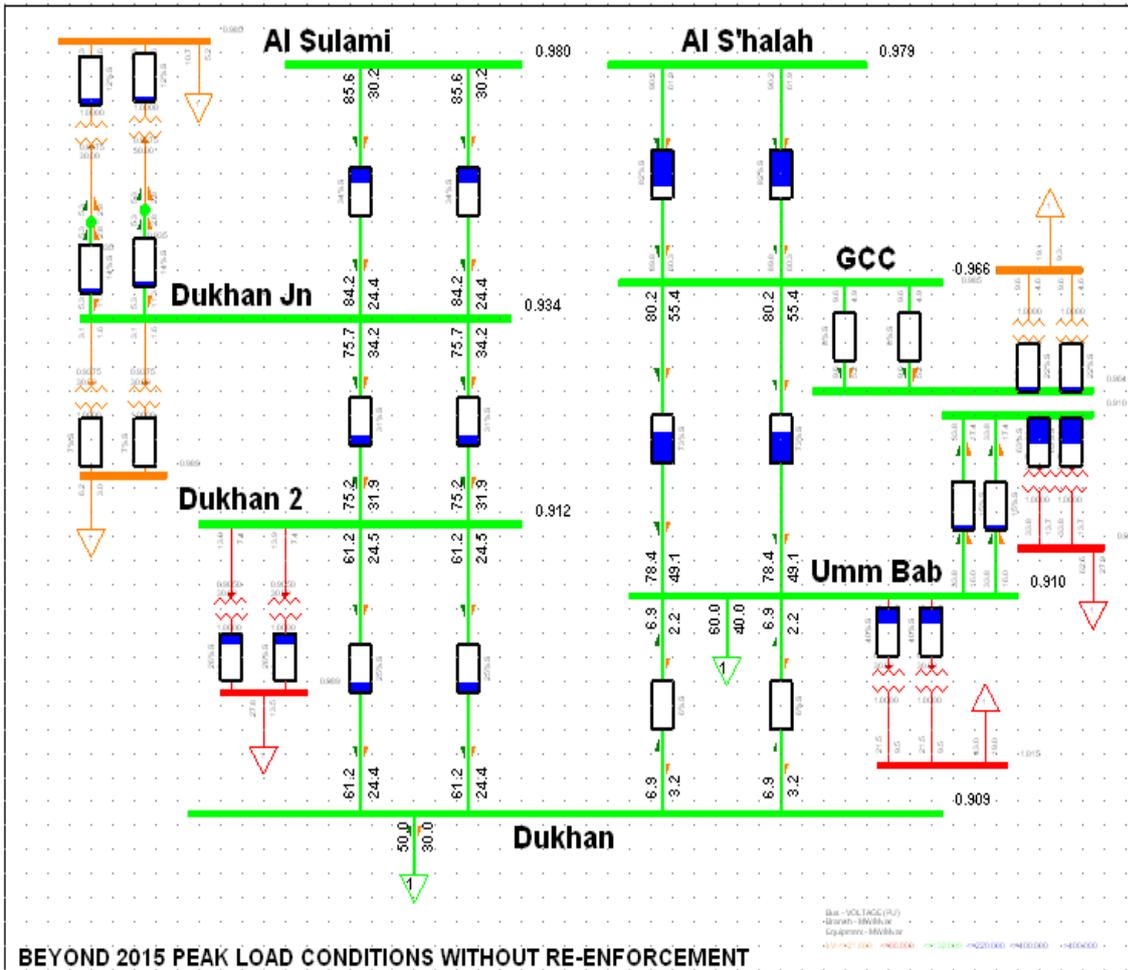
Figure 6: Normal case without capacitors, STATCOM or HVDC (PSS®E QPTS beyond 2015 model)

As shown in Figure 6, the blue colour indicates each circuit of Al S'halah-GCC 132 kV OHL is loaded at more than 50% of its thermal rating in normal conditions (about 80% loading on the lines from Al S'halah) [1], [2], [3]. The loss of any one of the circuits will result to a thermal overload of the other circuit. In addition, there are also low voltage problems in the area [10].

3.5 Concluding Remarks

The utility has continued to function with conventional systems, despite the doubling of demand in the past decade and anticipated doubling in less than another decade [2], [3], [4], [9]. A recent earth fault occurred at one of the transmission transformer has resulted into a transient voltage collapse in part of the distribution network. The widespread of the power supply disturbance (about 600 MW) in the distribution network, showed the need for smart grid to help mitigate the outage of the feeders. Indeed, during the summer months the higher

use of air-conditioning devices increases the loading of several distribution substations beyond their firm N-1 capabilities. To meet the summer peak demand in transmission and distribution systems while guaranteeing the N-1 reliability criteria, new smart planning methods have to be evolved. It is essential to improve the system voltage profiles, transfer capacities, power factors and system losses. The scenarios studied in this research are based on models of different modern devices that are able to mitigate the mentioned factors to result in more power flows and voltage improvement. This is one of the planning strategies to cope with the challenge of high power demand in Qatar and raise the smart online power electronics initiative [2], [6].

Chapter 4 addresses the theoretical power system transmission line models and the potential devices (power electronic or non-power electronic) that can be used for power compensation, series, parallel or both. These theoretical models form the basis for practical compensation models used in the subsequent analysis.

Chapter 4: Compensation from FACTS and Non-FACTS Devices

4.1 Introduction

This chapter comprises an original piece of research, reflecting the same level of quality and originality, but less extensive and usually with an applied focus. The research provides the relationship to developing practice in the area of online energy compensation systems, but does not include a great deal of theoretical or philosophical arguments. The chapter starts with explaining the main problems that hindering the efficient delivery of active power (P) in transmission lines, and how power electronics and non-power electronics devices can play a role in mitigating the situation [1], [2]. Then it explains the impact of different series and shunt compensations (or both) in QPTS. The mathematical equations, representing compensated and uncompensated power systems, are formulated in this thesis as part of the power electronics base post-graduate course taken [16].

4.2 Physical Constraints in a Typical Transmission Power System

Examining the scientific theory and mathematical modelling behind power system implementation and development, the power transfer equation is a known proportional relationship that is a key theoretical aspect in optimizing systems. Inspecting the basic transmission model in Figure 7, the well-known real power delivery equation (with no compensation) is [2], [3]:

$$P_{1,2uncomp}(\delta) = \{(\mid V_1 \mid * \mid V_2 \mid)/X_{12}\}.Sin(\delta_{12}) \qquad (1)$$
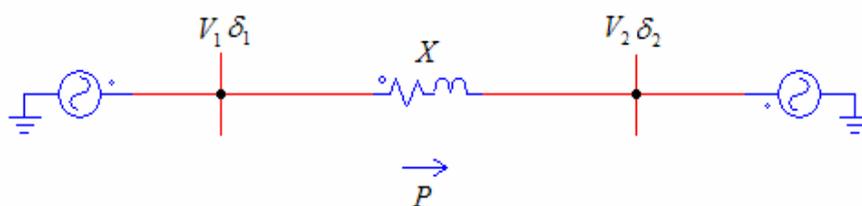
Figure 7: Typical power transmission line model

The reactance and phase angle are known to have a substantial impact on the overall power flow of the system. Other factors limiting the power transfer are the sending and receiving voltages. Varying these factors will impact the power delivery on transmission lines. Updating the phase angles and the line reactance will be influential in delivering more active power, while the voltage variation affects more the system reactive power map. Therefore a 'lagging' power factor is known to restrict transfer of active power, thereby inhibiting the optimization of a power system [3], [4]. Series compensation and shunt compensations have ability to provide solutions to power systems planning and operational problems. In this chapter, models for different devices have been discussed comprising both FACTS and non-FACTS devices.

4.3 Conventional Compensation

4.3.1 Phase shifting transformer (PST) compensation

Certain technologies, such as PSTs, have had the potential to improve transmission and distribution for the past 80 years, but they are not always useful in modern systems. The PST can be equivalent to a voltage source (VS) with phase shift angle delta α. The power transfer equation with PST becomes:

$$P_{1,2PST}(\delta) = \left[\mid V_1 \mid * \mid V_2 \mid /(X_{12} + X_{leak})\right] Sin(\delta_{12} \pm \alpha) \qquad (2)$$

The PST serves to regulate the nature of phase angles and flow, using a shunt transformer which processes power from the main line; the power is then processed through a secondary winding, and ultimately processed back to the main line with a series transformer [3], [4], [16]. In reality, the phase shift angle difference (δ) will be lower than 20º to 30º as the PST's angle can be less than 45º. The application of a phase shifter may or may not increase power transfer. The maximum power transfer may actually go down due to increase in line reactance due to the series transformer. However, the power transfer at smaller line angles will go up significantly with PST compared to the uncompensated case, which is where the method really helps. The transformer leakage reactance (X_{leak}) effectively makes the line looks longer. There will be a substantial increase in the transient stability margin which the PST can provide. The capability to maintain the maximum effective transmission angle during the first swing can be utilized to increase the transient stability limit. It can then improve oscillatory stability, if the compensator can change the angle quickly [16]. Usually best if needed to reverse power

flow from prevailing system conditions or to create an angle difference to allow power flow. The PST has mechanical switches for voltage reverse plus mechanical taps for voltage adjustment, but it is more costly than series compensation. Thyristors can be put and change the pace continuously on the cycle by cycle basis. This can be used to damp power swing in the power system and can increase the stability margin.

4.3.2 SEN transformer (ST)

Another device for independent control of bidirectional active and reactive power flow in transmission lines is the "SEN" transformer (ST). The ST design has tap changers that are used in on-load tap changers (OLTC) and a phase angle regulator. The ST can also control the voltage at a point of installation in the transmission line. The new ST can be an efficient device in controlling the active and reactive power flows selectively in utility transmission networks [39]. The ST operation is compared with the operation of UPFC and proved to be a reliable technology and cost-effective when compared with the VSC technology [39]. The drawback of ST is always lying in the slow operation of tap changers compared to the fast VSC technology and the inherited operational risks in using ST [16]. The maintenance of mechanical parts is another major techno-economic challenge.

4.4 Series Compensation

4.4.1 Concept of series compensation

Series Compensator- SC with VSC can also be used to inject voltage to compensate for magnitude change and phase due to a fault in one phase or compensate for magnitude change in three phases. SC with stored energy supply is named as dynamic voltage restorer- DVR and they can respond to voltage dips in less than a cycle or faster. Also SC can be used ideally to limit the fault currents in transmission lines by using a power converter that looks like a large inductor when the fault occurs [21], [16]. The chief drawback for SC is the potential sub-synchronous resonance. Other drawback is the impact on system protection due to protection bypass for out of system faults which leave compensation out of system during recovery from disturbance when is needed most. Series capacitor compensation suits longer overhead lines, but it is not practical for use in short overhead lines [21], [16].

4.4.2 Fixed Series Capacitor (FSC) compensation

Fixed series capacitor (FSC) compensation can be used to deliver more power. The real power transfer equation with series fixed capacitor compensation is [2], [4]:

$$P_{1,2Ser}(\delta) = \left[\left| V_1 \right| * \left| V_2 \right| / (X_{12} - X_{C-Comp})\right] Sin(\delta_{12}) \qquad (3)$$

The potential increase in power transfer due to cancellation of part of line reactance looks very high, however in most cases the actual power angle across the line will still be below 45º. The steady state power flow will not be as big, but it will be bigger than that for midpoint compensation (discussed later). The FSC installation has to be studied for the possibility of sub-synchronous resonance- SSR especially with steam turbines characterized with multi frequencies below 50/60 Hz. Therefore when designing a series capacitor in a system, it can be put with hydro generation and avoid steam turbines as they may have multiple resonant frequencies below 50/60 Hz. However exciting resonance frequencies above the nominal frequency will help damping oscillations on the transmission lines above 50/60 Hz [2], [3], [4], [16].

FSC is suitable more for longer and loaded overhead lines, while its use in shorter lines shall be avoided [2], [3], [4]. While capacitor compensation allows the user to deliver additional power, this takes place as the voltage must rise to a level below the over-voltage range [2], [3], [4]. System protection can be affected by protection bypass, while this leaves series compensation out of system during recovery from disturbance when is needed most. The approach generally has a considerable impact on both transient and voltage stability (assumed capacitor is not bypassed) as the margin of transient stability can be further enhanced. The approach can be used to inject voltage compensation for magnitude and phase resulting from a fault in one phase, and can also compensate for shifts in magnitude across three phases [2], [3], [4]. Moreover, the approach can be applied to the restrictions of fault currents through the use of power convertor, although the fault will nonetheless remain a challenge to the overall transmission [3], [4], [20].

4.4.3 Thyristor Controlled Series Capacitor (TCSC)

Another potentially beneficial approach to implementing FACTS devices is the application of thyristor controlled series capacitors– TCSC. TCSC has a reactor installed in series with a thyristor, connected in parallel with a fixed series capacitor. Basic series compensation is improved through the use of TCSC, as thyristor control can serve to improve transmission replacing the less reliable mechanical switches [2], [16]. TCSC basic configuration is shown in Figure 8.
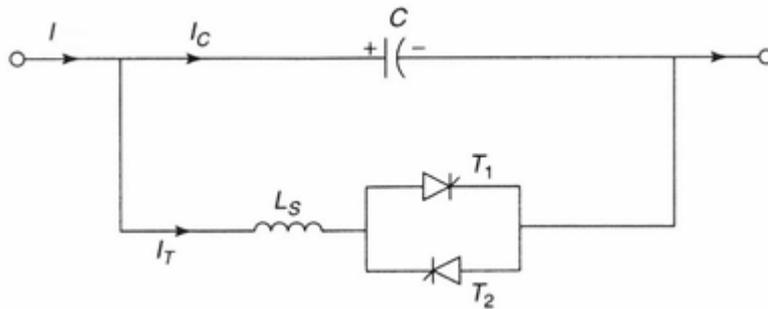
Figure 8: TCSC module

TCSC is connected in series with a transmission line with no coupling between phases and requiring no harmonic filters and can be applied to dampen power oscillations [16].

4.4.4 Static Series Synchronous Compensator (SSSC)

Yet another approach to compensation is achieved through the static series synchronous compensator (SSSC). This approach is actually one of the more fundamental approaches to FACTS devices implementation, while its design and benefits are similar to the compensation processes outlined in the previous discussion. Essentially, the SSSC is a generator which functions without an outside energy source as a compensator, and the technique can involve energy absorption equipment, rated energy storage, or other compensation of real power in a manner which affects the dynamic performance in the transmission structure [4]. Providing similar compensation benefits through this approach, the approach may or may not be superior to other methods, while the SSSC can only inject inductive or capacitive voltage. However, the technology can be combined with additional equipment, such as a superconducting magnet storage or a battery storage device, to inject series voltage [4], [16].

4.5 Shunt Compensation

A common solution is to have shunt capacitors at many locations, especially at the end of the lines, instead of just one in the middle. This solution shall be studied with more care in QPTS as the use of shunt capacitor banks has impact in system operation in relation to transients, resonance and faults. There is a case study in this thesis comparing the operation of shunt capacitors with STATCOM in steady-state and dynamic modes.

Reactive shunt compensator at midpoint of a transmission line can increase the maximum transmissible power. Shunt connected FACTS devices can also be used at sensitive nodes in the transmission networks to improve voltage stability or to compensate for rapid fluctuation on some industrial loads such as arc furnaces. There will be a substantial increase in the transient stability margin with ideal midpoint compensation [2], [4]. If we add shunt compensation at midpoint of the line, the power transfer equation will become [4], [16]:

$$P_{1,2uncomp}(\delta) = \{(|\ V_1\ | * |\ V_2\ |) / X_{12} / 2\}.Sin(\delta_{12}/2\ ) \qquad (4)$$

Or simply from sending end to midline:-

$$P_{1,m\_comp}(\delta) = 2\{(|\ V_1\ | * |\ V_m\ |) / X_{12}\}.Sin(\delta_{1m}) \qquad (5)$$

Where the variables can be further altered to reflect the resultant changes on the power transfer from midline to the receiving end bus is [2], [3]:-

$$P_{m,2\_comp}(\delta) = 2\{(|\ V_m\ | * |\ V_2\ |) / X_{12}\}.Sin(\delta_{m2}) \qquad (6)$$

The potential to increase the overall power transfer is higher than the potential for the phase shifting transformer implementation, however this implementation can result in a less than desirable steady state flow of power amid a less than desirable power angle (less than 45º). The ratio of deceleration to equal area rises significantly for a proportionally significant rise in transient stability margin. This method of shunt compensation can offer ideal voltage support; and can further raise the capacity for transmission across the 'post fault' system for a rise in transient stability [21], [22].

The increase in power transfer appears high but converter rating makes this option a less practical solution due to large magnitudes of reactive power need to be supplied by the shunt compensator. As a result, this approach is possibly less cost effective overall, especially if fast dynamic response of the compensation is required. A common solution is to have shunt capacitors at many locations instead of just one location. Real applications of shunt FACTS compensation devices are explained hereafter.

4.5.1 Static VAr Compensator- SVC

SVC typically comprises of a TCR and a fixed capacitor or TSC. SVC has Q compensation varies with V^2, with voltage/current characteristics as shown in Figure 9. This Q-V relation reduces the SVC's stability as it makes the reactive power drops quickly when voltage decreases. It produces or draws no real power except drawing relatively low losses in the vicinity of zero VAr output. On the average, the TCR- TSC low losses at zero will increase in steps with increasing VAr capacitor output [16], [21]. The ratings of the capacitor and the reactor depend on the required reactive power range. Harmonic filters are installed in parallel to SVC to shunt the current harmonics to ground. Often the TCRs are implemented in a 12-pulse configuration in order to lower the total harmonic distortion of harmonics generated in response to the changes in the thyristor's angle of firing delay [4], [16], [21], [40].
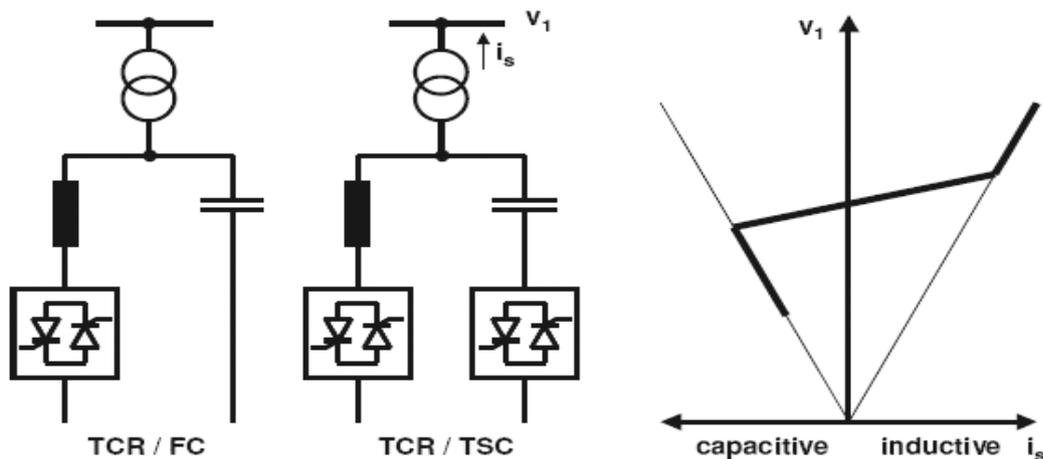
Figure 9: SVC building blocks and voltage/current characteristic [4], [13], [40]

SVCs are used to improve transmission and distribution performance by resolving dynamic voltage problems and to improve conventional power systems while addressing elements of their limitations amid rising demand [3], [23]. The accuracy, availability and fast response enable SVC's to provide high performance steady state and transient voltage control compared with classical shunt compensation. A rapidly operating SVC with appropriate control loops can provide rapidly varying reactive power required to damp dynamic voltage oscillations under various system conditions and thereby improve the power system transmission stability [16], [21]. SVC's are also used to dampen power swings, improve transient stability, and reduce system losses by optimized reactive power control. SVC is good for load balancing since it is possible to control the three compensating admittances individually by adjusting the delay angle of the TCRs for each phase so as to make the three compensating currents identical [2], [4], [21]. The coordinated control of a combination of these branches varies the reactive power.

4.5.2 Static Compensator - STATCOM

Static compensator – STATCOM, is a high speed shunt FACTS device employing voltage source convertor-VSC technology behind a reactor or transformer [16], [21]. The STATCOM technology uses controlled variation of this AC source to generate or sink the VAr (Q) demanded within power systems [2], [3], [21]. STATCOM has a linear Q-V relation compared to Q compensation varies with V^2 for SVC. Therefore STATCOM is better than SVC with regard to stability and its speed of response is faster. It has a lower harmonic emission and therefore needs little harmonics filtering. STATCOM can be utilized by the utilities to improve the voltage stability, load balancing and the power factor. STATCOM technology is approximately has a 40% smaller substation footprint than the static VAr compensator (SVC) technology but it costs 70-80% more [16], [21]. STATCOM topology and the terminal voltage, current compensation characteristics are shown in Figure 10.
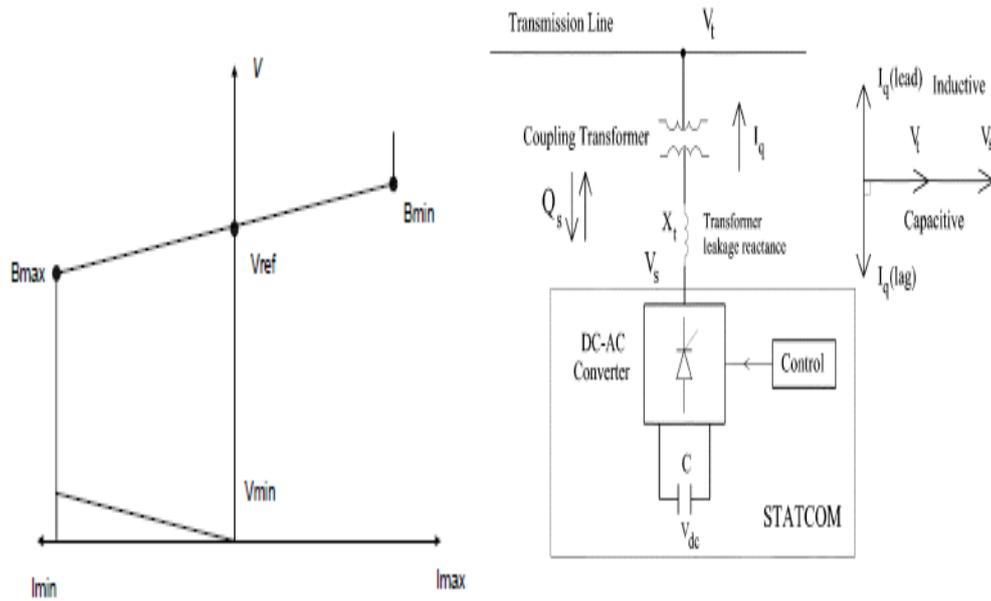
Figure 10: STATCOM structure and voltage/current characteristic [4], [40], [13]

There are little STATCOM applications in industry side, although the fast response in weak power systems facilitates a highly effective mitigating flicker compared to the SVC approach [4], [92]. Meanwhile, the shunt compensation can be ideal in the event, the system demands a dynamic control for the reactive power and maintenance of voltage stability [2], [4], [21], [16].

4.6 Series and Shunt Compensation FACTS Devices

4.6.1 Interline Power Flow Controller (IPFC)

Another potentially ideal FACTS compensation solution for improving transmission systems amid the rising demands can be derived from the Interphase Power Flow Controllers (IPFC). The IPFC is among many possible configurations of the multi-converter FACTS device, convertible static compensator (CSC). The IPFC is series equipment, which serves to control both reactive and active power across their phases (Figure 11) and consists of two series VSCs whose DC capacitors are coupled in a common dc link. This allows active power to circulate between the VSCs and thus between the series voltage injections in the lines.

CSC was recently installed by the New York Power Authority (NYPA), including IPFC as a pilot project to increase power transfer capability and maximize the use of the existing transmission network [16].
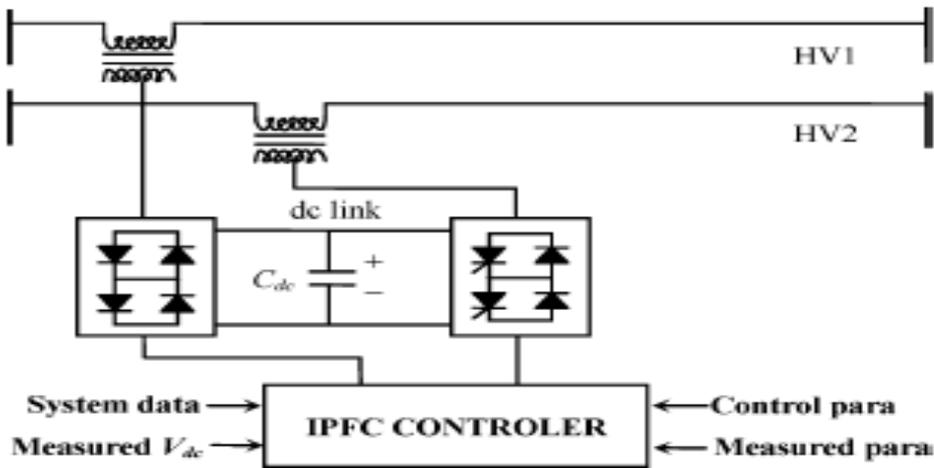
Figure 11: Interline Power Flow Controller -IPFC model [4], [13], [40]

Because of this flexibility, it can also be referred to as a Generalized Unified Power Flow Controller (GUPFC), but without shunt converter. The target is to control power flows of multiple lines leaving a substation or a sub-network rather than control the power flow of a single line by UPFC for instance. With this configuration two lines can be controlled simultaneously to optimize the network utilization. The equipment itself contains capacitive and inductive branches, while it does not contain the additional storage equipment characteristic of the STATCOM and SSSC approaches described above [4], [20].

4.6.2 Unified Power Flow Controller (UPFC)

A variation of phase shift transformer is the Unified Power Flow Controller (UPFC) which is a successful application of the evolutionary voltage source converter (VSC) technology for shunt and series compensations. UPFC is the most comprehensive FACTS device that is capable of providing active and reactive control, as well as adaptive voltage magnitude control and phase angle regulation [21]. The UPFC consists of shunt and series transformers, which are connected via two voltage source converters with a common DC-capacitor (Figure 12). The shunt VSC is similar to STATCOM and the series VSC for series compensation is similar to SSSC. The DC-circuit allows active power to circulate between shunt and series transformers to control the phase shift of the series voltage [16], [21].
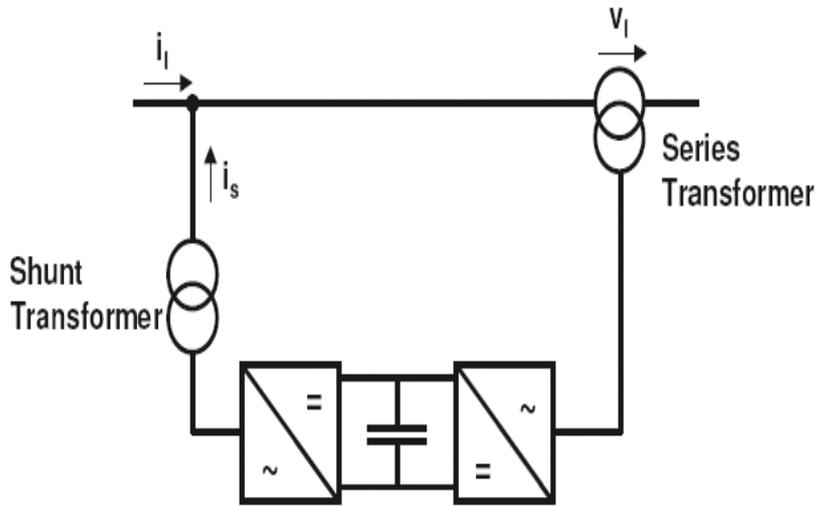
Figure 12: Unified Power Flow Controller (UPFC) [4], [40], [13]

Actually the UPFC can apply a series voltage with a continuously variable magnitude and effective phase angle instead of a voltage with a fixed phase angle [16], [21]. It has two degrees of freedom that can meet multiple control objectives by adding the series injected voltage with appropriate amplitude and phase angle to the sending end terminal voltage. A UPFC can inject zero power or produce no voltage or produce voltage 90° offset from the current, like SSSC. The UPFC can act as a capacitor and put power into the system or as an inductor and pull power off the system. When the power is non-zero the shunt converter has to be putting this much power back into the system and is circulated through the dc bus [16], [21]. Change in the injected voltage can increase or decrease the real power transfer and changing the angle of the injected voltage will also affect the real power flow. Voltage change coupled with angle change may reverse the direction of the real power flow. The injected voltage can be at any angle with respect to the line current and the UPFC can be used to control power flow through an electrical transmission line connecting various generators and loads at sending and receiving ends [16], [21]. In most cases it is normally required to maintain a constant level of real power flow with the angles variation. The UPFC can also maintain a constant flow through the line no matter what phase angle difference between the two ends of the line. When a constant current is maintained with voltages magnitudes, it is basically just implies that the angle difference between the two ends will vary, but the magnitudes won't vary [16], [21]. UPFC can also be used to control the current flow over a branch interconnecting two systems that are normally out of synchronism. It will also probably need very high current ratings on the shunt converter to support the circulating power for the 180° condition. So it will either need a very high rating, or it will need to be tripped, however UPFC is not recommended for such application, unless the systems are kept close to synchronization. Otherwise the angle

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across the line could get larger than the UPFC could compensate, requiring the line to be tripped [16], [21].

The series converter needs to be protected with a thyristor bridge to provide fast bypass in the case of nearby transmission faults. For faults slightly farther away it is possible to change the series injection to look like a large inductance, which could serve to lower the fault currents. At present, UPFCs are not designed for this type of operation, but it is possible with sufficient current ratings in the devices. Due to the high cost for the two voltage source converters and the protection, UPFC device is getting quite expensive, which limits the practical applications where the voltage and power flow control is required simultaneously [4], [16], [21].

4.6.3 Generalized Unified Power Flow Controller (GUPFC)

The Generalized Unified Power Flow Controller (GUPFC), a variant from UPFC and IPFC (Interline Power Flow Controller), can have one shunt converter in addition to the two series converters (VSC) whose DC capacitors are coupled in a common dc link (Figure 13).
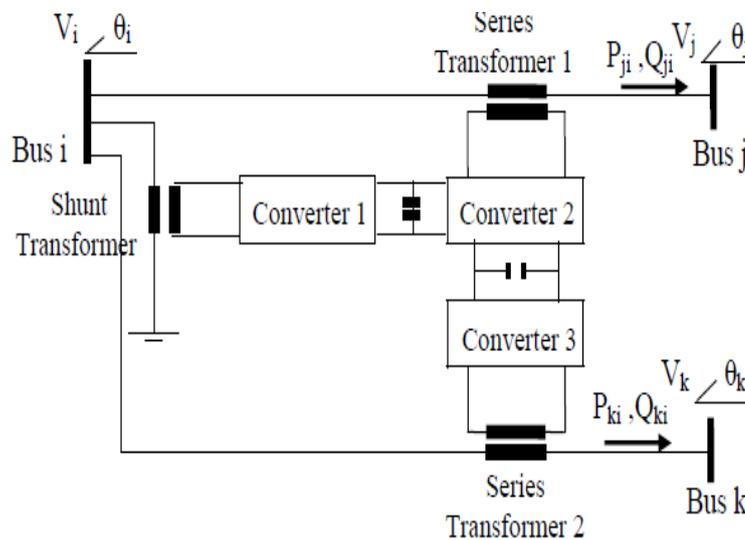
Figure 13: Generalized Unified Power Flow Controller GUPFC [4], [13], [40]

The merit of GUPFC (and also IPFC) is that it can control power flows of multiple lines leaving a substation rather than controlling the power flow of a single line [3], [4]. Two circuits on an overhead line would require two UPFCs or one GUPFC for controlling the flow to maintain N-1 criteria. The GUPFC has two operation modes one as a capacitor to inject

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power into the system and another as an inductor to absorb surplus power off the system, circulated through the dc bus [2], [16], [33]. GUPFC control can be set to maintain a constant active power flow with the angles variation, or maintain a constant flow through the line regardless of the phase angle difference between the two ends of the line. Constant current could be maintained with voltages magnitudes, while the angle difference varies between the two ends, but the magnitudes remain the same [2].

4.7 Concluding Remarks

This chapter has explained different mathematical power compensation equations and means of equipment compensations used in existing power systems. The chapter also presented a general description about various realistic FACTS devices used around by utilities.

Next chapter provides a situational analysis of online power electronics, and online systems, examining the case of QPTS as essential part to provide a foundation in this research effort.

Chapter 5: Smart Online Energy Systems and Power Electronics

5.1 Introduction

This chapter is an executive assessment to examine the applications of certain smart energy systems and OPE in QPS including both QPTS and QPDS [5], [6]. The technologies include FACTS, DGs, EES and renewable. The emerging online system has triggered the core of this thesis research to the new convention of online power electronics (OPE). The OPE is the state of FACTS and HVDC devices when they interact with QPTS (or other power network) in real time, or online operation and control of the network. As a follow up to the search work in this thesis, the concept of OPE shall be adopted further and relevant standard shall be established. The thesis is trying to bridge the OPE into the global online systems and to achieve the required knowledge. For this an exhaustive research survey was conducted on the emerging papers in the field.

Chapter 1 illustrated steps of OPE implementation in QPS networks starting with equipments modelling QPTS. The process continues with identifying QPS problems and the utilisation of power electronics devices into QPTS to solve them. The test of new GPS synchrophasors, online systems showed impact on the operation efficiency of QPTS. The implementation of OPE is in the real time control of power flow and voltage benefiting from emerging online energy systems applications.

5.2 Implementation of Smart Power Electronics initiative in QPTS and QPDS

Kahramaa faced the challenging task of planning, designing and managing an electrical power grid which is in continuous expansion, while applying the latest and most innovative smart grid solutions. One of the prime functions of power electronics devices in power transmission and distribution systems is to facilitate the delivery of active power either in form of AC or DC while maintaining the quality of supply. The operation of FACTS and HVDC controllers on real-time monitoring and control is still a challenge for many utilities. Many online control and measurement techniques can benefit from the performance of power electronics in many aspects. This chapter will identify the relevant literature in the field of

power systems in utilities with problems similar to those facing QPTS and QPDS. The discussion will explore arguments discussed in the published papers, while subjecting them to critique compared to the QPTS case studies. This review of power electronics literature is highlighting the experience of other utilities and is showing the latest advances in the field as well [4], [16].

For the last few decades, the need for a larger integration of renewable energy sources into the electrical grids, the ambition of offering a high quality electric service to increasingly sensitive loads, the evolution towards deregulated electric markets, the unbundling of electrical utilities, the necessity of reducing power consumption and the will of building a cost-effective business model, have led to a new grid paradigm of electricity networks, known in the public media as smart grids. There are solutions to these physical constraints in power transmission systems, through the use of power electronics including SVC, STATCOM, TCSC, HVDC, static transfer switches, and other power converters [1], [4], as described in the Case Studies Chapter. The research included review of potential use of distributed generation (renewable) in QPDS. The following sections cover the critical review of literature and comparing them with case studies conducted. This developed research into smart grid technologies is offering guidance and support to Kahramaa for establishing a smart grids roadmap that will be in line with the Qatar National Vision 2030 and the National Development Strategy 2011-2016.

5.3 Potential of using Online Power Electronics devices in QPTS

The Consultancy for "Qatar Transmission System Short/Medium Term Planning Support" [18] reported on the requirements of providing the shunt reactors to sustain voltage at required limits. The report claimed that change in the load cycles from day to day were not substantial, while mechanical switching can be implemented to improve the efficiency of control. The Consultant's report has concluded that the use of FACTS or HVDC devices QTPS is not needed. The report explained that reason for not recommending FACTS devices, as fast dynamic control is not necessary in QPTS [18]. The case studies discussed in this thesis have proven the reverse, that implementation of FACTS devices can be beneficial in QPTS. The results achieved showed evidence of better system performance when using GUPFC, STATCOM, TCSC and SVC. Although the benefit, the cost for power electronics devices is still high and in some cases, it is not justifiable [1], [2], [3].

The applications conducted in [2], [3], [4] examined the potential for power flow controllers to enhance the power transmission operation of QPTS. In this analysis, greater emphasis was placed on the nature of GUPFC and UPFC compared to other FACTS devices such as SVC, STATCOM. The basic findings of the study are of potential solutions specifically, the history of power flow controllers, voltage support relevant physical theory and mathematical modelling, relationships to telecommunications. The potential effectiveness and applications of FACTS in modern power electronics were reviewed and analysed in [1], [2], [4]. FACTS devices have enhanced transient stability, improved load balance, decreased undesired loops in power flow, and exhibited the potential to address undesirably high fault current levels within the network [4].

The power electronic technology has been identified recently as one of key technologies needed for the successful implementation of the emerging smart grid and the creation of micro grids. The smart systems include other important areas in research as online analysis (for the sake of enhancing controls), wide-area control and monitoring (using phasor measurement units), and improved distributed generation and storage device operation [2], [4].

5.4 Potential Smart Grid and Micro Grid Evolution in QTPS and QPDS

Since the construction of the first electric power grids, by the end of the 19th century, electric power demand worldwide is progressively growing up, as illustrated in Figure 14 [19].
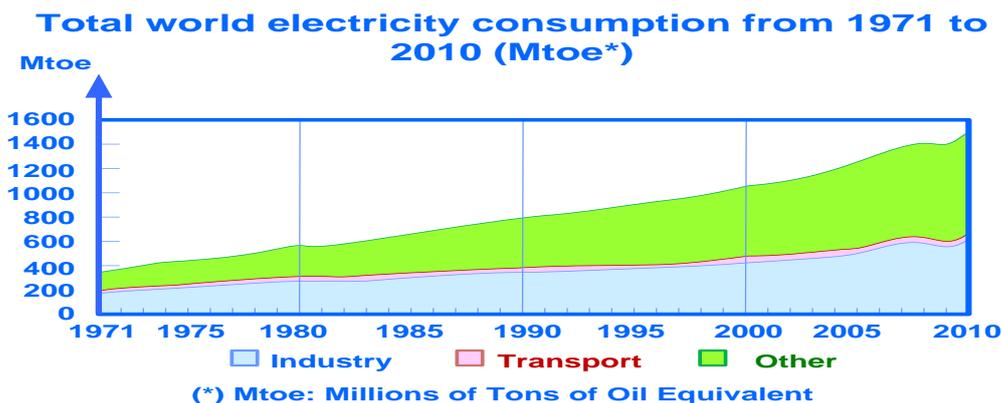
Figure 14: Electric power consumption worldwide, 1971-2010 [19]

This trend can also be observed in Qatar, due to a rapid economic and urban development of the country. Fully inscribed in the domain of smart grids, the purpose of the research carried in [5] is to perform a comprehensive analysis of the potential solutions to one of the challenges that Kahramaa is confronting. The research has created a five-year plan for

either upgrading the existing substations or either for diverting some loads to newly committed and commissioned substations. However, the long lead time needed for these projects (3-3.5 years), together with the need of disconnecting the substations during civil works and commissioning, have motivated this research to investigate alternative smart grid technologies to shave and to balance peak loads at substations during N-1 contingencies [5].

The resolution made by the case study for exploring the potential of smart grid solutions is well founded, since the capabilities of smart grid solutions are far beyond load shaving. Thanks to their great flexibility they can offer a broad portfolio of functions such as ancillary services (for instance frequency and voltage stability or black-start capability) or islanding. The integration of smart grid technologies in distribution grids is currently a subject of strong interest among the distribution operators (DSOs) in the world. In Europe, for example, a group of six major DSOs (see Figure 15) have decided to gather their expertise and propose a common project (known as Grid4EU) for smart grid development in Europe. To carry out this mission Grid4EU will conduct six demonstrators that will address the following topics:

- Innovative Power Management at MV level.

- Innovative Power Management at LV level.

- DER integration.

- Energy Storage Systems.

- Demand Side Management (DSM).

- Micro grids (intentional islanding).

Figure 15: DSOs participating in Grid4EU smart grid project [20]

Considering that distribution grids will need to adapt and accommodate to new "unknown" challenges, the comparison between different solutions shall not only be based in their capital cost, but also in other important criteria such as flexibility, greenhouse gas emissions, footprint, maturity and complexity. The accompanying improvements in QPTS demand effective online systems continually expanding in order to keep up with demands and with 'smart' grids and flexibility for a diverse range of power sources.

It must also be observed that traditional AC electrical equipment (i.e. transformers, busbars, overhead lines, cables and protective circuits) have a well-known technology that has been deployed during decades and thus, their low prices are a consequence of an economy of scale. Conversely, smart grid technologies have just passed from a development stage to pilot/demonstrator projects and their prices reflect the research and development efforts put on these promising devices. To an extent, there are limits to how low the cost will get for some of the technologies [16]. In order to make a definite choice between different solutions, Kahramaa shall attribute an importance (weight) to each of these criteria. The case study for battery storage and PVs presented in Chapter 8, analyses different DG options.

5.5 Online FACTS Monitoring and Control via Synchrophasors

WAMPAC systems are being installed by utilities in USA, Canada, Japan, Europe, Asia and Africa and improved operation efficiency of complex generation and transmission system. WAMPAC can assist the system operators in managing the real-time variances in the grid, using time-synchronized measurements, and prevent cascading outages, enable islanding. The steady state and dynamic control of QPTS have been recommended to be improved through coordinating the operation of the power system control loops. The range of control variables involved will effectively impact one another, leading to a demand for highly effective coordination. Without this level of coordination, the impact may be great enough to alter the intended harmonization of the FACTS components while generating detrimental interference [2], [3], [15], [23]. In online monitoring and control systems the output of the FACTS, could be maintained across the maximum and minimum series reactive powers, active powers, and shunt reactive power. The design recommendations presented in [23] can be applied to the design of the GUPFC controllers for transmitting the power through the Dukhan area discussed in the case study. They can be further used to assist the controller in facilitating coordination and steady state power control. The approach outlined is recommended for development,

design, and implementation of the GUPFC controller [23]. This involved using the Clark Transformation p-q theory, as well as the theory of instantaneous aggregate voltage, for controller optimization. The Clarke transformation is a special case of the Park's transformation (d-q transform). The Park's transformation is often used to go to a rotating reference frame synchronized to the system frequency, where the Clarke transform uses the Park's transformation to go to the stationary reference frame [23].

5.6 Compatibility of QPTS Online SCADA and EMS Systems with PMUs

Further recommendation is the use of signals for voltage control in remote ends, stating that the acquisition of angle and voltage signals could be achieved through remote systems or phasor measurement units (PMUs) [3]. The GUPFC controller could be integrated with telecommunication equipments, although further information would be required (from the energy management system - EMS) to develop an effective course of action for broadcasting the desired information [3], [23]. The integration and optimization of online systems is the compatibility of QPTS telecommunications with GUPFC controllers and using synchrophasors in a timely synchronized measured data. Telecommunication developments generally have potential for online applications, and with overhauling QPTS control and communication systems, it can integrate effective online systems. The standard way of applying transducers and remote terminals units (RTUs) to generate voltages or angles data naturally demands a revisit for modernisation [3]. More modern approaches may be ideal in the implementation of PMUs to transfer information to the GUPFC through the C37.118 protocol for phasor data [4]. The transformation of protocols for controllers in Qatar could be avoided by allowing the use of IEEE C37.118 protocol, and equipment which is not compatible with this could still be integrated by translating to DNP3 protocol. The EMS system used to relay data must be properly configured. The designer must use or structure a software program for the synchrophasors, to optimize communication with other devices and online controls [2].

The fundamental assessment of the telecommunication design showed that the voltages across Dukhan and Umm Bab can be measured and transferred to a power flow controller through optical fibres in overhead lines already installed within the transmission systems [2]. The telecommunications are stated to be compatible with both recommended types of static compensation and power controllers (SVC, STATCOM, TCSC, UPFC and GUPFC) through the outlined protocols. The network servers have been running on Microsoft Windows operating systems, and no issue has been discussed with this or is anticipated in the future. This

operating system is assumedly ideal for implementations of online controls. A range of other telecommunication components in place in Qatar's power systems, listing the SCADA system in the control centre (including its Decent dual ring FDDI), the connection between the FDDI and VMS TFE servers, data transfers between the control centre and stations using plesiochronous and synchronous digital hierarchies (PDH and SDH), the use of IEC60870 protocol for gateways and RTUs connections.

The case analysis consideration of wide area controls also has significant implications for Qatar's online systems, while it is recommended to integrate the PMUs, synchrophasors and wide area controls to address recent challenges in the Gulf and Qatar [3]. Moreover, these elements can be tested with GUPFC, as current relations and phase voltages can be measured by PMUs. These measurements further provide data which can be used to deduce states of dynamic performance, undesired power flow, and stability [3]. The PMUs data can be combined for use in other equipment in addition to the GUPFC as well, such as the SCADA system in use, state estimators, energy management, and more. Many aspects of these developments can be integrated with online controls and processes for maximized monitoring, estimation, and management processes [3].

5.7 Emerging Online Systems and Standards

The research of publications revealed the increased potential embedded within the online analysis applications [6]. There is an evidence of potential applications that can see the light for real implementation and can benefit power grids. The applications include online controls, state estimations, simulations, fault detection, power system stability enhancement, and online integrated IT and control systems, etc. [6]. New standards emerging on online systems, such as [66] and [67], are more related to the data exchange and the communication than to the applications. One of the other known data exchange standard is IEC, 68150 [68] pertains to communication automation for substations. The IEEE C37.118-2005 is the standard approach to systems, while it is capable of locating measurement processes, formatting messages, updating rates, signal processing, and PMUs are recommended to use this approach [3]. IEEE C37.118-2005 governs application of synchrophasors for power systems [69], while fault location on AC transmission and distribution lines is covered under the IEEE C37.114-2004 Guide [70]. The Wide Area Monitoring Protection and Control (WAMPAC) systems have two standards, the IEC 61850 (power systems communication) and the IEEE 1588 (precision time protocol). Next section highlights the need for wide area coordination of control and operation

in QPTS. In power electronic applications, the DNP3 protocol is inherently compatible through FACTS. QPTS uses Microsoft Windows' Network Management System, IEC60870-5-101 protocol for connections between gateways and RTUs, and the TCP/IP network in a range of transmissions (microwave radio, pilot cables, and fibre optics) [3].

5.8 Concluding Remarks

The chapter gave an executive summary of the readiness of QPS and its potential to accept the OPE and smart power applications. The future research is expected to progress the nomenclature of OPE further and develop new standards to govern its regulations similar to other news standards in online energy systems. Chapter 6 presents details of the literature review of power electronics and online energy systems applications within utilities. The chapter addresses the literature reviewed with appropriate references of present state of knowledge which has been built upon in the research procedure and main proposition of the thesis. An analysis of current literature in the next chapter also shows that the priority should remain on improving online power electronic and wide-area control and monitoring as possible.

Chapter 6: Literature Review of Power Electronics and Online Energy Systems

6.1 Introduction

This chapter is presenting the individual efforts exerted to review various literatures connected with power electronics especially with regard to real application in power utilities operating around the globe. The literature collection is extremely useful as it comprises real applications within utilities rather just theoretical models or assumptions on non-real power networks. The critique to the discussed literature is another genuine contribution thrilled by an engineering professional experience on real systems. This has led this research to develop a new concept known as Online Power Electronics (OPE). The emerging online system has triggered the core of this thesis research to develop the OPE. Also part of the research knowledge discussed in this chapter is acquired from a postgraduate course of power electronics applications in utilities, taken with a US university [16]. The main results of the research in this chapter are published in the thesis's papers [5], [6]. The next section of this research surveyed carefully and thoroughly, the literature of online energy systems and their potential use in QPTS. The information summary gained from publications, was incorporated in the online energy system survey paper [6] that published in the 2012, US, IEEE, PES conference. Other PMUs research is discussed in the thesis's papers [1], [2], [3], [4].

6.2 Literature Review of Utilities Applications in Power Electronics

6.2.1 SVC voltage control via synchrophasor in Southern California Edison's system

Paper [15] analysed applying synchronized phasor measurements to develop an effective plan for a system that could maintain voltage at remote buses utilizing SVC while avoiding overvoltage at the local bus where the compensator is connected. These researchers pointed out that previous utilization of synchronized phasor measurements had only been applied to the monitoring or after the assessment of system operations, despite the evidence that the potential applications for on line control had a far wider range. Potential applications include wide area control, remedial action schemes, and special protection schemes in the near future, with potential in still further areas in the more distant future. Citing the Southern

California Edison's (SCE) efforts to develop an effective use of synchrophasors in power systems, they claimed that their research and subsequent implementation of an SVC have satisfied the objectives of the SCE project, emphasizing the minimization of potential for over-voltage conditions [15]. Since the SCE project was the first closed-loop control application of synchrophasor measurements, the authors studied options for integration of the voltage information provided by a phasor measurement unit with an SVC controller. To achieve this, the experiment utilized SCADA protocol, and also attempted to provide readers with recommendations for integration with other systems of energy management and state estimation [15].

Following their review and description of their experiment, the researchers provided 'lessons learned' in addition to their detailed recommendations and conclusions. They stated that "several issues" would have helped ease the commissioning of the SVC control of voltage at a remote bus. The first is that all equipment should have been tested off-line prior to deployment in the field. They were not able to do this because of the project schedule. They were able to overcome this restriction with a lot of support by personnel at remote locations to identify and resolve any issues. The second issue was that "the communication channel should be implemented using a high-speed digital communication channel", however this is not a concern now if more recent standards are adhered to [16]. The developed controller for FACTS compensation controlled via synchrophasors with time synchronized data from a wide area measurement system (WAMS). The controller can also be utilized in other monitoring applications and can also be used in future smart Qatar power grid. When coupled with the information available from wide-area monitoring utilizing Phasor Technology, an SVC can be a very cost effective solution to maintain voltage stability of the high-voltage transmission network [15].

6.2.2 Various FACTS utilisation in Utilities

Similar to shunt capacitors combined with shunt reactors, the Static VAr Compensator (SVC) is the oldest FACTS device. SVCs have been widely used by utilities for shunt compensation for over 40 years. The first commercial SVC was installed to compensate for fluctuation in an electric arc furnace [4], [22]. On transmission level the first SVC (940 MVAr) was used in 1978/79 at the Shannon substation of the Minnesota Power System [22]. Since then the SVC is widely used as the most popular FACTS device, and is still selected in most new installations.

As for UPFC installation in the world, till recently only, two UPFCs were used around the world one in USA and one in South Korea. According to the [23], UPFCs have been used to control power flow and oscillation damping between a 345 kV and two 138 kV transmission systems [2], [3], [23]. The study showed the UPFC has the ability to increase power flow of the 138 kV lines by 103% and dampen oscillation between 138 kV and 345 kV systems [23]. KEPRI (Korean Electric Power Research Institute) the research centre for KEPCO (Korean Electric Power Corporation) studied a contingency case where a trip of the double circuit 345 kV overhead lines would lead to an overloading of the parallel 154 kV lines feeding the same area demand leading to under voltage situation [15]. KEPCO had a request for a new right of way to build a new 345 kV overhead line rejected, while the demand in the destination area continued to grow. The studies suggested the installation of UPFC with rating +/- 40 MVA (for each the series and shunt converters) for both the series and shunt converters, at the 154 kV substation to be supported by 100 MVAr additional compensation [15]. The utility had found a solution in this UPFC proposal, and studied the installation of +/- 40 MVA, at the 154 kV level, for controlling the voltage and power flow [15].

The paper presented a study that investigated the steady state operational strategies of UPFC in the Jeollanam-Do system in Korea. The study checked the operating points for the UPFC in normal and contingency conditions and concluded that, the UPFC improved the voltage performance of the study area. However additional shunt compensation of rating of 100 MVAr was needed to completely improve the low voltages during contingencies and ultimately 100 MVA installed in South Korea [15].

There is another GUPFC installed on the NYPA system and some papers called it a GUPFC and others called it a CSC (convertible series compensator). GUPFC was operational since 2003, however they were about to start one of the commissioning test days when the August 2003 blackout hit [16].

6.2.3 Modelling and control coordination of power systems with FACTS devices in steady state operating mode

In the thesis [22], modelling and control coordination of power systems with FACTS devices in steady state mode is studied. The application of WAC in protection and control has been recently initiated. The recent applications of phasor measurement units (PMUs), with advanced communication network to control local and remote voltages as in [15] have enhanced the network performance. Online application in relation to secondary voltage control

has been discussed. The control procedure is applicable to any load variation or changes in power system configuration, contingencies, interactions with generators, SVC, STATCOM etc. [22]. Optimal control with inherited power system nonlinearity is not suitable for online applications. In wide area coordination, the controllers receive signals from PMUs vide wide area network, power system database, power system configuration (breakers, isolators etc.) and try coordinate the set objectives for SVCs, UPFCs etc. As an option, it is practical to incorporate the wide area controller in the energy management system (EMS) to provide supporting functions necessary for control coordination. The authors confirmed that the information available from PMUs on voltage phasors allows a linear model to be formed and used in developing control strategy. This is considered as an online application for one aspect of global power system security which is voltage value. The other power system security that is gaining international recognition because of increasing marketing is the power flows in transmission networks [22].

The research in this thesis dealt with steady state operation of FACTS devices from another dimension and different angle. It looked at the real modelling of STATCOM, TCSC, GUPFC and SVC in an existing transmission with its inherited system characteristics including non-linearity and different load models. The FACTS allocation technique was too much in trial and error approach, though this; it is so practical and provided useful results.

6.2.4 Preventing voltage collapse by large SVCs at power system faults

Another practical review of usefulness of using FACTS in real networks, explained how the Saudi transmission system has improved in performance by using SVC to reduce the risk of voltage collapse during fault conditions [24]. The western region transmission system operates at 380 kV and 110 kV, and has including many transmission level reactors and capacitors and reactors at the distribution level. Although all they have these voltage devices, in addition to the transformers' tap changers, their transmission system still shows signs of weaknesses with regard to reactive power control [24]. The system suffered from control of voltage between peak load and light load and unhealthy voltage recovery at medium load condition and voltage collapse at peak [24]. The utility has conducted reactive power planning study that advised several mitigations to be considered including fast fault clearance, dynamic reactive power support during the faults and after fault clearing, and steady state reactive power support to control daily voltage fluctuation [24].

The study results recommended installing 3000 MVAr, (5 SVCs with rating of +600/-60 MVAr) at different 110 kV buses to resolve the motor stalling problem and daily load-voltage control. Three SVCs were installed at different locations in the year 2008; the other two SVCs were installed later to this date [24]. The paper [24] concluded that using SVCs was an efficient solution in supporting the positive sequence voltage during faults. The SVC can also combat the phenomena of stalling motors for those induction motors used in air-conditioning systems. The paper recommended that the SVC shall have a high capacity during faults; while fast response SVCs can have smaller ratings. The authors claimed that a few seconds operation during fault is sufficient. The paper recommended that the SVC shall block TSCs immediately after the fault clearance in order not to produce temporary over-voltages when the loads are dropped [24]. The paper reported that the SVCs responded very fast to actual three faults cases (phase to earth faults) that occurred in 2008. The SVC delivered full capacitive power at the bus location in one and a half cycle (25 msec. in the 60 Hz Saudi system). The system voltage has been maintained constant during the fault or even increased slightly, while the voltage of other two healthy phases didn't drop much [24]. It was reported further that the SVC has reduced its output to 500 MVAr for about 4 cycles (66.67 msec.). The SVC delivered 200 MVAr in the next 5 cycles (83.33 msec.) and stayed at this output for 30 seconds, while the faulted phase didn't fully recover to its pre-fault level during this period [24].

The critical review to this paper starts from the last contradicting statement that the faulted phase has not recovered fully for 30 seconds, while it was mentioned also in the operational records, that the SVC has managed to maintain the voltage constant. In another literature, other utilities adopt control strategies that SVC or STATCOM devices are designed to be isolated during short circuits in the network [16]. Also the previous research recommended that TSCs shall be switched off after the fault clearance [16]. Each utility has the option to select the SVC operation during faults, based on the prevailing operating conditions. In this Saudi experience [24] the utility wants the SVC to contribute the needed MVAr power during the fault itself, or initial fault recovery, since the load is dominated by air conditions. In other places of the world and during winter climate the load would mainly be heaters, and during fault conditions they could be no need for SVC operation. The rising critique here that the SVC is designed to be used during fault conditions, as the authors confirmed that the SVC is a robust device during faults and during fault clearance [24].

6.2.5 SVC wide-area power oscillation damping control using PMUs

The role of power oscillation damping control through the assessment of wide areas was studied in Norway, using a static VAr compensator [6], [25]. The study encompassed "feedback signals from remote phasor measurement units (PMUs) in Norway and Finland are used to damp the critical inter-area modes through a large SVC unit located in south-east Norway". A comparison between two control design approaches: (i) model-based POD (MBPOD) – dependant on accurate system model and (ii) indirect adaptive POD (IAPOD) – which relies only on remote measurements is made. For MBPOD, optimisation approach is used to obtain the parameters of the controller while the IAPOD is based on online Kalman filter estimation and adaptive pole-shifting control. It is shown that the IAPOD yields almost similar performance as the MBPOD with very little prior information about the system [25]. Meanwhile, the research compared the performance across multiple tie-line outages, attempting to deduce the most optimal approach to wide area controls. The potential usefulness and applications of these developments have been used and researched in depth in recent years, as wide area signals used to optimize power oscillation damping control effectiveness. The increasing potential of technology throughout the evolution of power systems instrumentation has led to the examination of the possibility to adopt closed-loop damping control for wide-area signals. Although conventional control concepts and solutions are continually used and considered for future developments, primarily due to the level of precision which has evolved through numerous integrations and on-going practice. But this method is becoming increasingly inflexible in relation to the increasingly dynamic technology and broad range of innovative features [6], [25].

Analysing the implementation of damping in key 'inter-area' modes across a SVC, the authors examined feedback signals, the optimization of parameters within their fixed structure controlled (based on a combination of pole-shifting and Kalman filter estimation), and a comparison of MP and IA power oscillation damping (MBPOD and IAPOD) [6], [25]. Following their analyses, the authors determined that both damping approaches give rise to similar results, further stating "the transient behaviour of SVC susceptance and voltage is slightly inferior for an IAPOD both in terms of larger and higher frequency variations".

6.2.6 Wide area monitoring, protection and control system in GB

The content of [26] published in 2006 is mainly focusing on the modelling, analysis and control techniques of FACTS controllers and their future R&D applications. The controller

applications cover various power-system phenomena comprising steady state voltage and power flow control, voltage and reactive power control, voltage stability control, small signal stability control [26]. The FACTS controllers including IPFC, GUPFC, VSC HVDC and M-VSC HVDC, etc., have been modelled and used for flow compensation and power quality control in power system [26]. The book's input is a collective effort from the authors' practical R&D industrial experience in the modelling, simulations and control design of FACTS [26].

The same research trend was followed by the same research leader at Imperial College London. The work is an interesting piece of collaborative applied research in Wide Area Monitoring, Protection and Control (WAMPAC) took place simultaneously at three British universities: University of Manchester, Imperial College, and University of Strathclyde with the SUPERGEN FlexNet Consortium [1], [26]. The mentioned research addressed the design and development of an optimal WAMPAC architecture, communication infrastructure and real-time application in GB power grid operation and planning [1], [26]. The technology is named by the researchers as 'Synchronized Measurement Technology (SMT)' [26], because it can provide synchronized time stamped measured signals to the controllers, using the global positioning system (GPS). This technology has also been tested successfully in this R&D project where wide area monitoring system was applied with three PMUs installed at the three mentioned universities.

The Data Concentrator (DC) was installed in Ljubljana (Slovenia) and it acquired data from all PMUs using standard internet communication network [26]. The WAM presented in the paper is a commercial system known as 'FlexNet' helped to identify opportunities for better optimisation of GB network performance [26]. The research used 'Improved Recursive Newton Type Algorithm', to better estimate inter-area oscillation damping and frequency. The researcher claimed that this research has supported the future application of real-time dynamic protection and control schemes through the improved WAMPAC [26]. A combination of this smart application and the other PMUs, SVC compensation controlled via synchrophasors application [12] can be studied for potential application in Qatar to improve the system voltage profile and monitor and control the network loading.

6.2.7 Synchrophasors for improved interconnection operations

This research discusses application of synchrophasors in Saudi Arabia transmission network [27]. The introduction of this applied research stressed the fact that network disturbance and blackouts occurred at different locations demonstrated the need for simple

situational awareness for system operators for sustained stability and increased operation efficiency [27]. According to these researchers, the synchrophasors can improve the visualization of system conditions and wide area control. Data streaming in a standard format in synchrophasors was used in improving the SCADA (Supervisory Control & Data Acquisition) data quality, as well as in providing automatic checks of state estimation calculations [27]. The paper explained how system parameters such as voltages, angles, power flows, and breaker statuses can be seen well in real-time rather than delayed by scan rates and calculations. Power system phenomena in terms of oscillatory modes, damping ratio etc. can be calculated, displayed for operators use, and correlated.

The authors claimed that 'one of the main blackout causes in the wide areas, that the system operator was using non-real time information to monitor real time operations in his area' [27]. The standard SCADA data is retrieved by slow sequential time scan of 1-5 seconds making the situation impossible to see system oscillations [27]. The research conclusions claimed the need for synchronised monitoring and control systems as the best solution for large scale visualisation. It has exhibited the experience of other utilities on using synchrophasors in visualisation of system dynamic performance. Synchronised measurements can boost real time processing in relays, processors and other equipments which lead to high speed control actions in manual and automatic modes. The new result, as per the researchers, is the new method they presented for the voltage stability assessment of transmission corridors [27].

The synchrophasor technology discussed above can benefit QPTS in many aspects, including the provision of fast detailed information of the incidents in the first 5 cycles after faults. There was a partial disruption of electricity supply in part of QTPS, due to a fault in one of the transformers, which was cleared in less than 5 cycles (100 m-seconds) and the SCADA system showed no detail results within this short period, rather than only a trace of voltage drop in the faulty phases and recovery. The synchrophasor technology can also work fine with FACTS devices in controlling the compensation as explained in the paper [12] and in this thesis.

6.2.8 PSS and FACTS devices controller for damping of power system oscillations

The dissertation [28] completed researching the potential for low frequency electromechanical oscillations to impact transmission lines' transference capacity and stability of power systems. The thesis is emphasizing the reduction of this potential through the implementation of PSS (power system simulator) and FACTS devices for damping oscillations

[28]. Similar to other studies in this area, the author acknowledged the capabilities of the devices in general power system improvement, but the study provided more focus on the ability to develop advanced PSS and systematic techniques for FACTS devices' damping controller design [28]. According to this researcher, an intelligent control strategy which combines the knowledge of system identification, fuzzy logic control, and the neural networks are applied to the PSS design. A fuzzy logic based PSS is developed and tuned by neural network strategy. The proposed PSS improved the damping of power system oscillations over a conventional PSS. But the same control strategy is not satisfactory for the FACTS damping controller design, mainly because of the different locations and roles of FACTS devices in power system oscillations compared to PSS. Additionally, a systematic approach provided to design damping controllers, an examination of the challenges in feedback control, using the PRONY method to establish a low order plant transfer function, strategy for changing the controller gain in accordance with transmission line loading condition (for improved damping in UPFC, and SVC), and simulation results relevant to these areas [28]. The researcher asserted that "the UPFC brings quite a few challenges to power system simulation and study including power flow calculations, modelling of converter control and UPFC dynamics, interfacing UPFC with the power system for transient simulation program development and physical and operating constraint modelling".

The research work presented design techniques for power system stabilizers and controllers, for the purpose of damping oscillations for FACTS equipment, recommending the integration of PSS in damping controllers with excitation systems. Generally speaking, the PSS has been found to perform superiorly to FACTS controllers in damping local oscillatory modes, while the design presented, successfully integrated neural network theory, fuzzy logic control, and system identification. An assessment of the strategy determined that it is more ideal for PSS design than controlling FACTS, but continuing research could address the weak areas for improvement in either area [28].

Further commenting on damping, according to research, FACTS devices are normally installed on the high voltage transmission lines that are far away from any generator. They do not affect the power system oscillations in the same way as PSSs. Instead, they do that indirectly by affecting some of the power system network parameters. Therefore, unlike PSS, it is difficult to derive fuzzy rules for damping controllers for FACTS devices, further pointing out "PSSs use the local generator speed signal as their input and this signal is a good indicator of power system oscillations, especially local oscillatory modes". On the other hand, single generator speed does not contain as much information about inter-area oscillatory modes as do

transmission line local signals like power, current and voltage. Therefore, sometimes it is hard to damp out inter-area mode oscillations using PSSs only [28].

A more recent knowledge after this dissertation [28], revealed that, a series FACTS controller with a damping controller ought to be able outperform a PSS on a generator if designed correctly (so a TCSC, for example) since it can modulate power directly instead of indirectly as is the case with a PSS [16]. There have been many TCSCs installed for this purpose in Brazil, Sweden and India [16].

6.2.9 Small signals analysis of damping performance of IPFC and UPFC controllers

The research discussed the dynamic behaviour of IPFC and UPFC in a common reference system [29]. The small signal model of the interline power flow controller is developed and validated using electromagnetic transients simulation [29]. The paper made comparison for the damping capabilities between for IPFC and UPFC. The research stated that the series branches of these FACTS devices segment the network, creating a new structure that could be used to improve the damping without requiring design of a tuned feedback controller [29]. Since the IPFC has two series branches (VSCs) compared to the UPFC which has one series branch, the IPFC has greater potential for improving the network's dynamic performance [29]. The results of this research have concluded that the effect of installing an IPFC or UPFC in a constant power mode is similar to that of disconnecting the transmission line that contains the series branch. This resulting modification in the network structure introduces significant changes in the corresponding mode frequencies as well as mode damping [29]. The transmission network can also improve more the damping performance with proper allocation of series branches with controllers. This is attributed to the change in the network structure rather than by tuning of controller parameters as in the case of PSS, requiring no use of designing the feedback damping controller [29]. However it has been recommended with proper damping, controller can modulate the performance of the FACTS device. The results have a final observation that the IPFC can provide better damping improvement compared to UPFC.

Considering the last conclusion, the GPUFC device modelled and studied in this thesis can have a better performance compared to IPFC, because the GUPFC has two series branches and one shunt branch and the latter can control the local and remote voltages (using PMUs). This case study in the reference can be extended further to include the performance of GUPFC.

6.2.10 Power-flow control and power-quality enhancement in interconnected networks

The main objective of the PhD [30] is to explore the real interest and potential of a Unified Power Line Conditioner (UPLC) when used for interconnecting MV distribution grids. The writer claimed that UPLC is very versatile power electronic apparatus, and represents a very appropriate circuit for interconnecting distribution grids. The researcher considered UPLC as a universal topology that combines the capabilities of both UPFC and UPQC [30].

In this PhD thesis [30], the Autonomous Demand Area Power System (ADAPS) is discussed in details. The ADAPS concept was developed by the Central Research Institute of Electric Power Industry (CRIEPI), Japan, motivated by the large-scale penetration of distributed generation (including fuel-cells and photovoltaic) expected in Japan [30]. The 6.6 kV power distribution system of Japan is serving high power demand cities in urban areas and with a massive DG insertion would generate power flow congestions and voltage fluctuations in distribution lines [30].

The vision of CRIEPI, that the ADAPS are integrated as the segment that includes the distribution system at 6.6 kV and a primary system at 66 kV. According to the author, the meshed structure is controlled by means of back-to-back MVDC devices named Loop Power Flow Controllers (LPC) by the authors. The whole system is controlled by an operation control system (OCS) and the communication network consists of sensors, demand/supply interfaces, optical fibres, media converters and hubs [30]. The thesis addresses how the dual challenges of controlling the power flow and power quality could be achieved simultaneously using a static power electronic device.

6.2.11 Power flow calculation with GUPFCs connected in a power grid

The authors of [31] released the invention of new method to run load flow subroutine using conventional Newton-Raphson method, incorporating a model of generalized power flow solution into a power grid [31].

The disclosed method claimed to apply the generalized power flow solution model to calculate the power flow solution with FACTS devices such as STATCOM, UPFC, and GUPFC in a single framework [31]. The invented algorithm is designed to incorporate the control variables of the shunt VSC into the state vector of Newton-Raphson power flow. The

new increment of state variables with the generalized power flow controller preserved the quadratic convergence characteristic of the Newton-Raphson power flow algorithm [31].

The Newton-Raphson model contains different data inputs including bus types (slack, load and generator buses), bus loading conditions, lines parameters, reactive power limits etc. The new in this research is the generalized power flow controller comprising a shunt voltage sourced converter in parallel with a bus and series branches having a sending-end and a receiving end [31]. A shunt coupling transformer connecting the power flow controller to the grid is, being modelled as an equivalent circuit of shunt voltage source converter in series with impedance. Each series branch is modelled as a series voltage source converter and a series coupling transformer (series voltage source in series with impedance). The DC capacitor is hosted between voltage source converter and the shunt voltage source converter and the series jointly connecting and sharing the same DC bus [31].

In this thesis, the same internationally accepted standard software (PSS®E) is used for modelling and analysis of the case studies. Versions 31, 32 and 33 of this Siemens software have a common power electronics data input card that can be customised to model different FACTS and HVDC devices. This software is tested and verified by the supplier and also by various utilities around the globe for correctness and preciseness. So the research work conducted saved the effort and time to program or model any power electronics devices, while focused mainly on efforts to get more useful results from the analysis on a real power network (QPTS). The PSS®E software has already contained all power flow methods including Newton Raphson, Decoupled and Fast decoupled techniques etc. Therefore the FACTS and HVDC models used in the Cases Studies Chapter are embedded in the PSS®E power flow algorism using one of the mentioned methods [1], [2], [3].

6.2.12 Online simulation benefits for operation of large power systems

Another critical element of research and development in power systems online elements is simulation [33]. Estimation denotes the generation of approximations, while simulations are the medium for testing structures amid developments for real-life equipment. Successful planning and operation of power systems and system interconnections depend largely on the engineer's skills to provide safe, reliable and economic solutions. Simulation technologies provide useful means for the design, operation and analysis of the power system, assisting in making reasonable decisions for a reliable configuration. Due to powerful software and advanced real-time simulators, it has become possible to simulate dynamic behaviour of large

power system [33]. Simulation technology has further facilitated the assessment of the growing alternating and direct current projects proposed and implemented across a range of remote generation systems. The changes in technology and in the demand for different forms of energy have given rise to the development of systems designed to distribute power generated from solar, wind, hydro, nuclear, and geothermal facilities [33].

The planning stage of simulation projects requires meeting demands identified during the analysis phase, while these may include assessments of the functionality and dimensions of equipment within the system. The rise of power system capacity and applications has been paralleled by a rise of tool development, and some of these are capable of streamlining conventional software simulations with real-time simulations. The authors reported on the potential for NETOMAC to be used to decrease network size, another increasing demand in order to transfer parts from a large power system simulation in form of a reduced network into another program or into a real-time simulator, which cannot handle the full power system [33].

These authors pointed out that the simulation capacity in 2004 had reached a high level, as programs at this time were capable of real-time simulation while features and capacity were being improved at an exponential rate. The most influential improvements noted at this time were new models, new technologies, and new applications. Also during this time, the real-time simulation was increasingly converting to (purely) digital technology from analog (or analog-digital combinations), as this change compounded with the demand for real-time applications was assumed to be affecting all areas of power system software and simulation development [6], [33]. The abilities of developers and demands from users were assumed to be the limiting and driving factors, and these authors concluded that the results of simulation analyses are limited by the talent of engineers assuming the research (regardless of technology) [6], [33].

Streamlining can facilitate the detailed analysis of commutation, related to individual device switching in LCC HVDC and can be extended to an extent to FACTS and VSC HVDC. RTDS is a simulation tool that can help in performing this analysis [16]. Combination of FCATS and HVDC is not unique, as there have been papers and theses proposing this since the late 1990's. Nobody has actually installed a STATCOM with a HVDC link yet although many papers have proposed it. LCC links use synchronous condensers, even in new installations, not STATCOM [16].

6.2.13 Optimal location of FACTS devices using Genetic Algorism (GA)

Genetic Algorithm (GA) is an optimization search technique based on the nature of random selection and genetics. The GA first generates encoded initial population randomly and then select, till crossover and mutation are reached the maximum generation [34]. In the paper [34], the researchers had claimed a novel algorithm for allocation of multi-type FACTS devices based on Genetic Algorithm (GA) using a multi-objective optimization function. They advised that the proposed algorithm tested on IEEE 5 and 6 test systems and WSCC (Western System Coordinating Council) 9-bus power system has decreased the loss of system about 25% [34]. At the conclusion, the paper also claimed that the test of multi-type FACTS devices has led to improvement in security and reduction in losses without increasing the total cost of power system [34]. Figure 16 gives an overall view of investment ($/kVar) compared to rating of TCSC, UPFC and SVC (in MVAr).
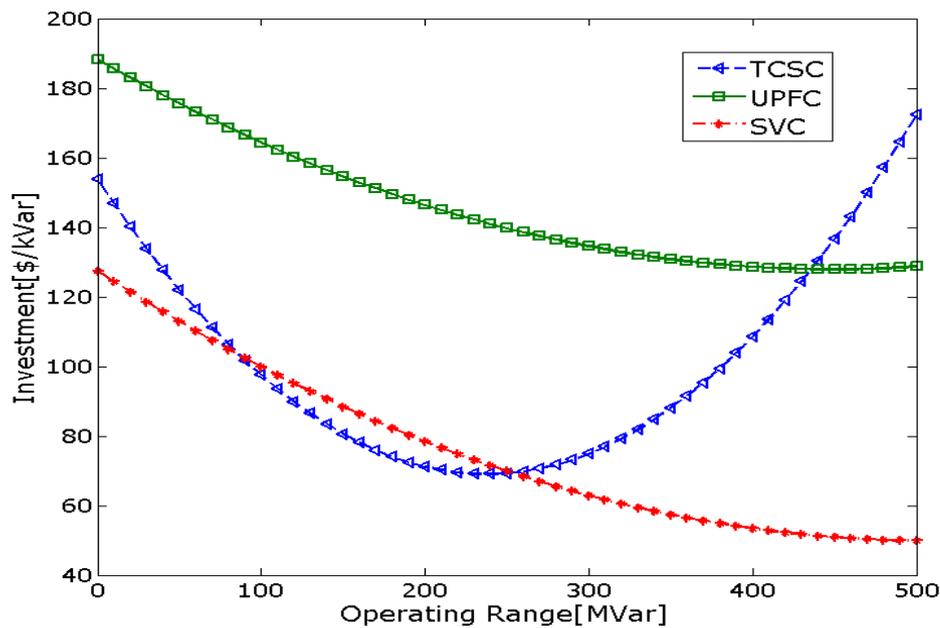
Figure 16: Ranges of investment cost for TCSC, UPFC, SVC [34]

The critiques to this piece of research fall into two issues, the first is the reduction of losses to 25% which doesn't look so real in physical power systems. The second critique is that with all the benefits to the tested network, but still it is 'without increasing the total cost of power system'. Obviously there shall be a cost of using multi-FACTS devices and the new technology of power electronics costs more than the conventional power system development of the same rating (Figure 16). However the paper should have compared both costs to give an option for selection.

In another research paper [35], steady state models of UPFC, TCSC and TCPST have been selected for simultaneous optimisation of the location, type, cost, and parameter values. The research presented optimum FACTS allocation using genetic technique for two objectives; reactive loss minimization and voltage stability improvement. Other objective is the cost to find the optimum locations and sizes of different FACTS devices. The results of the study confirmed that power system performance is improved by optimum allocation of FACTS devices. Case studies conducted with, IEEE 30-bus and 118-bus systems are not in real physical networks such as QPTS, presented in previous chapters [35]. The authors claimed that of the most of the FACTS research was focused in the enhancement of transmission capacity while, the research didn't examine fully the minimisation of reactive power loss along with improvement in voltage stability margin. The researchers proposed a GA search technique to determine the optimal location of FACTS devices in transmission network to enhance the voltage stability margin and minimize the reactive power loss of the power systems.

In this thesis, improvement of voltage stability margin is discussed using STATCOM and the minimisation of active and reactive losses in the compensated lines comes as a by-product of the reduced transmitted power (active and reactive). In other words the enhancements of transmission capacity or local MVAr compensation bring other benefits to power systems in terms of losses optimization and voltage support. The theory behind this losses optimisation is well developed, however Appendix-E, tests the individual research carried as part of this thesis to optimise the power losses using the B-Coefficients technique.

The research work advised that the use of FACTS technology could be a cost-effective option for power delivery and could minimise capital investments cost when selecting the optimum number and placement of these devices [35]. The paper used genetic algorithm, to identify the optimal number and location of FACTS devices in the IEEE 30-busbar power system. It is reported in [35], that the simultaneous use of different FACTS devices is the most efficient method to enhance the transmission system transfer capacity. In finding the optimum location for a FACT device generation costs, transmission losses, line overload and the costs of installation and maintenance are considered [35]. The research claimed that the algorithm finds the cost-effective location for the device.

Although the research conducted is not recent (2004), however, the researcher reached results earlier than, what has been discovered in more recent papers. Similar to other research

in the area, they use MATLAB tool for the analysis on the standard IEEE 30 buses system. It is very rare in the academic research fields to find simulation carried using the PSS®E software on a real exiting transmission system.

6.2.14 State estimation of power system with FACTS and HVDC

Other estimation through their application of their recursive least squares technique; the research has developed a model for integration within a system using a UPFC controller, and used an IEEE 14-bus system for assessment [36]. The states selected within the UPFC, claimed by the researcher as a new approach to power system state estimation with UPFC names as the power injection model. The research mentioned that the model is effective for generating data through estimations. Contributions to the existing knowledge base in power system estimation through their application of recursive least squares technique (RLS); asserting this method is entirely unique to applications in the field. The authors developed a model for integration within a system using a unified power flow controller, and used an IEEE 14-bus system for assessment [6], [36]. Asserting this research design produced evidence of an effective methodology, the validity of the developed algorithm, and the ideal nature of the states selected within the unified power flow controller, the authors presented a new approach to power system state estimation. The methodology they presented made use of the LAV estimator. The results of the research proved that the model is ideal for generating data through estimations.

The research conducted in [79] described how an algorithm applied in the estimation of phase angles, amplitude, frequency, and other signal characteristics in power systems. It focused in the estimation of distorted power system signal parameters, pointing out that the method can be applied to controlling many electrical parameters and to online power electronics including FACTS, HVDC etc. [6], [13].

6.2.15 Optimal allocation of FACTS devices using Bees Algorithm (BA)

The idea of 'Bees Algorithm (BA)' emanated from the physical movement of bees searching for food. The honey bees fly in different directions in gangs to cover a large areas containing food [36]. There are many researchers conducted useful work for applying the BA. In one of the researches the BA was used to find the optimal location of FACTS devices to achieve the economic generation and dispatch in the restructured electricity market. In 2010, the paper [36], suggested BA to decide the optimal locations of FACTS devices to maximize the available transfer capability (ATC) of power transmission (and hence the transactions)

between generations and loads in restructured power system. The research explained the algorithm uses a novel method that combines the simultaneous search of the FACTS location, parameters and types [36]. Two studies simulated the thyristor-based TCSC and SVC, repeating power flow to evaluate the feasible ATC value within allowable limits real and reactive power generation, line thermal, voltage and FACTS operation [36]. The model used the IEEE30 bus system to verify the algorithm for enhancing the ATC and validated the results using Genetic Algorithm. The research conclusions indicated that when the FACTS with proper parameters combined with the optimum location could increase the ATC. The researchers confirmed that BA is very efficient for this kind of nonlinear integer optimization [36]. The same researchers carried similar initial study in 2009, using other more FACTS devices including the UPFC and TCPST. The same conclusion received in both researches stating the BA and GA gave similar results.

As a critic, the BA like other research location optimisation techniques is more versed in theoretical content. More practical approach is to use the allocation techniques associated with some international, utility standard softwares. The PSS®E software [88] used in this thesis has its own location optimisation techniques called optimal power flow (OPF). The PV, QV analyses conducted, explain the use of optimisation function of this software [88]. The results from these analyses have used in the Case Studies Chapter. The function can use different objectives including the best allocation of capacitors banks, reactors, FACTS, voltage or power flow control.

6.3 Literature Review of Online Energy Systems

6.3.1 Online power conversion system technology

Other researchers proposed a method to develop and integrate single phase online UPS systems, presenting a combination of circuit plans, implementation processes, theory, and potential for systems using this technology [44]. The design included an integrated directional AC/DC converter, thereby providing active power filtering and power factor correction for the system. Beyond this, the authors further provided recommendations for operations across the input state, the event of input power failure, and full functionality [44]. The input stage is designed for the converter, allowing rectification, power factor correction across standard AC line operation, and active power filtering across outage modes. Active power filtering can continue through input power failure while offering reactive power. In the output stage, this

technology transmits power from the battery to the critical load, and the power capability is superior to standard online UPS systems. The presented plans analysed for the UPS system, assessing multiple circuit models and the strategies for design and implementation [44]. Expanding a case for their development and implementation opposed to the conventional technology, the authors provided a combination of theory and simulation results to support their argument and conclusions. A laboratory prototype of the technology was used in these simulations supporting the functionality and potential for their system. The technology can be applied or tested as part of the battery storage and PVs case studied in Chapter 7.

6.3.2 Online monitoring structures in power transmission lines

The paper examined the use of an innovative power supply for online monitoring structures in power transmission lines [71]. The method for supplying power is ideal, drawing energy from the electromagnetic effects generated from standard transmission. This relates to fundamental theories of physics, as the current generated down any wire or power line generates some magnetic field perpendicular to the flow of the electricity. This is an effective energy that can be harnessed if technology worthwhile of investment could avoid this 'waste' of energy while diverting it back into the system. Using a custom designed Rogowski coil, the authors proposed a method to harness these magnetic fields surrounding the transmission lines, thereby converting it to electricity to power elements of a power station. Although this could be used in a number of ways, the authors provided plans for harvesting the energy to use in powering online monitoring systems. The authors presented circuit designs, theory, strategies and methods for implementation and use, considerations for overvoltage and impulse line current, and an analysis of feasibility and reliability were presented. All of these are entirely viable and potentially beneficial across Qatar lines. The research, ultimately concluded "experimental tests, including the, short-circuit and impulse-current tests, have been conducted on the power supply to verify its performance under different operating conditions. Test results show that the power supply is capable of providing stable outputs with no saturation and low heat generation for the entire range of line conducting currents and can sustain severe conditions such as abnormal impulse currents [6], [71]. This conclusion suggests that further research could optimize methods or uses of such technology or strategies, while demonstrating the practicality, benefits, and potential for transmission systems such as Qatar's in adopting the method. Clearly, this technology and the relevant methods provide an ideal path to efficiency, while an investment in the machinery and installation could provide (or 'save') energy that could potentially reimburse the investment by multiple times over as it allows the nation to

meet a greater percentage of energy needs through improved net output. Naturally, energy used by the system powered from these devices allows the energy which would normally be used to remain free for distribution elsewhere [71].

6.3.3 Online control on ESS and wind-diesel system

Other research has provided evidence of potential improvements by way of energy storage and management, which could be integrated into online systems [72]. Naturally, the ideal implementation would depend on budgeting factors, although the technology described by [6], [72] reveals a clear benefit. The research presented an analysis of energy storage systems that can be integrated with power systems to addresses variable power generation sources. While this is generally only an issue with uncommon sources of energy such as wind power, the design and strategy proposed and recommended offers insight into combining technology, amid the additional establishment of flexibility for systems using multiple energy sources. Energy storage system power must be controlled using multiple time frames to achieve established objectives, with a dual level structure of control compatible with online implementation. The method was analysed through a combination of theoretical exploration and simulation. They concluded that a controller possessing the capacity to minimize dump load, maximize energy storage system utilization, and restrict diesel ramp rates is proven to be superior to available controller technology, which is compatible with online systems. Both the mechanisms of managing the energy hold potential for benefit, particularly in the areas of Qatar where energy storage is most desired, while the flexibility for additional energy sources of smart grids is further desirable [6], [72].

6.3.4 Online diagnosing shorted turns on the windings of power transformers

One of the most important elements of online systems is fault assessment, while systems capable of monitoring an entire network, identifying faults, and further attempting to locate causes and solutions of faults are of great potential benefit. In a more recent analysis of these areas, researchers studied the relationship between interturn faults in power transformers with network failure, emphasizing the impact of the progression of fault severity, detection, on- and offline testing, and problem solving through online systems [6], [73]. According to the authors, "the main problem with SFRA as one of the well-recognized diagnostic tools for detecting winding faults is its restriction to the domain of offline testing since the method requires injection of a test signal into the transformer windings through the high-voltage

bushings. To address the difficulties arising from this issue, in this contribution, a new technique for online transfer function monitoring of the power transformers windings through a quite simple, economic, and non-invasive capacitive sensor installed on the surface of the transformer bushing is presented. Interturn faults with various levels of severity were imposed on the winding of a 35-kV/400-V, 100-kVA oil-immersed distribution transformer to evaluate the feasibility and sensitivity of the method" [73]. Analysing this technique through a controlled experiment, the authors concluded that modern online monitoring systems are practical while capable of perceiving even minimal interturn faults (as low as 0.2%) across windings. Moreover, it was recommended that such systems be integrated with power systems to increase the capacity to detect warning signs, thereby reducing the potential for network failure while improving the health assessments of transformers. These same benefits could be realized in Qatar systems, with compounded benefits when integrated with the improvements recommended and the previously analysed research [6], [7].

6.3.5 Online small signal stability PMUs based analysis of multi-machine systems

In another recent study published in the 2011, extended research provided a methodology for analysing stability online, providing strong conclusive evidences of benefit [6], [74]. These authors researched online signal stability assessments, using synchronized PMUs information on power system that contains multiple machines. Their proposed and assessed method does not require data regarding the line impedance, network configuration, or generators, while it uses a combination of least square estimation and ambient data to develop a reduced admittance matrix. Analysing their presentation with theoretical analysis and an evaluation of strategically designed simulation results, the authors determined that the recommended method has potential for benefits across a range of differing system types, while it can further be used to assist operational personnel with monitoring the stability of signals in the system [74].

6.3.6 Online smart alarm processing system for digital substations

Online monitoring, fault detection, and methods for designing these systems while generating alarms were further assessed by the researchers presented recommendations for an online intelligent alarm-processing system [6], [75]. This system was based on the design of the digital substation; alarms were developed in accordance with IEC standards. The two modules for parallel operation in the online development were presented and evaluated. The

authors provided a method for using alarms to notify users of the presence of alarms which has clear benefit, to locate the presence and potential causes of false alarms, to locate missing or dysfunctional alarms, and potential implementations in a case scenario complete with an established software program [75].

6.3.7 Online power estimation using an on-chip bus performance monitoring units

In this study, the researcher analysed another aspect of online power system management, assessing modern aspects of quality power estimation, efficient power management, indirect power management, and using performance monitoring units for quality online power estimation [6], [76]. Realizing that current CPU performance monitoring units (PMUs) only assess the functions conducted within the core and cache (contributing to a restriction of accuracy for system wide power estimation in both on- and off-chip memory). The authors proposed an on-chip bus PMUs which effectively processes the functions of both on- and off-chip components [76]. This on-chip bus (OCB) PMUs further compiles the data across separate storage devices, while online software converts the stored data into power data (using linear power models). Additionally, an algorithm designed to optimize the processing of the OCB PMUs is proposed, while the authors assert its effectiveness in reducing the amount of data processing required for effective compilation, conversion, and operation. The accuracy of the power estimation through this system was compared to the power estimation of conventional hardware measurements and cycle-accurate estimation, proving substantial accuracy facilitating the ultimate recommendations [76].

6.3.8 Current phasor measurement in a power system state estimator

Three inclusion techniques for measuring current with phasor measurement units examined in power system states, using a combination of conventional and comprehensive formulas, the Jacobian matrix, and other performance estimation [6], [77]. The authors presented an outline for combining estimations across hybrid states, phasor measurement units, and integrating conventional techniques for each of the three methods used. Through the experimentation, it was determined that each method has unique benefits while there was no superior 'all-purpose' method. Moreover, the authors reported the behaviour of elements in terms of general influences and the potential for "ill conditioning" to have affected the state estimator gain matrix, as this was found to be a considerable factor [77]. It was asserted that the 'Monte Carlo' technique is one which is ideal for simulating and generating sample

measurements, and discerning the average variation of estimated states. Meanwhile, it was determined that the Jacobian matrix is ideal for identifying convergence behaviours and issues. While on the basis of the simulation results, it is observed that the inclusion of the real and imaginary part of the current phasor gives better performance in terms of the accuracy of the estimator and convergence characteristics [77].

6.3.9 Online estimation of maximum power transfer limits (Thevenin equivalent parameters)

Examining the online approximation of power transfer limits, stating the use of the Thevenin equivalent has risen in popularity (due to its lack of complication) [78]. The research study was designed to provide a model for investigating the Thevenin equivalent parameters, while the potential for this method was examined, assessed, and discussed while simulation results and a predictor-corrector framework were also presented [78]. The predictor-corrector framework was suggested for the purpose of improving accuracy, while the method was tested through a basic linear network as well as two larger and more complex systems. The simulation determined that these methods are in fact effective, and are ideal in using for online estimations of power transfer limits for weak load buses [78]. Acknowledging the challenges associated with developing accurate estimations of Thevenin equivalent parameters, the authors asserted that the significance of their research was evident in this alone, stating that an effective approach to determine the Thevenin equivalent would be valuable for existing processes and future research initiatives. Fortunately for them, the authors were able to present an analytical model for generating and examining the Thevenin equivalent data for the case of maximum power distribution for online systems [78]. The applicability of this model was determined to be high, while recommendations for future research included decomposing the coupling term, implementation on a larger scale, increased efficiency and timeliness, and improving accuracy. Generally, this research proved that the model was not only functional but ideal, and could serve as the foundation or guidelines for existing online systems [6], [78].

6.3.10 Online estimation of distorted power system signal parameters

An algorithm, designed to incorporate Kalman filtering principles, applied in an analysis of estimation potential in the areas of phase angles, amplitude, frequency, and other signal characteristics in power systems [79]. Pointing out that the method can be applied to regulating digital automatic voltage, distribution static compensators, protection relays,

FACTS, and other areas of power electronics. The authors asserted that the algorithm is especially useful in combining generators to grids amid a demand for accurate and quick trait fluctuation detection [79]. It was further reported that the algorithm can benefit the examination of noise influence, computer influence, and high order harmonics; it was the intent of the study to examine these areas, and the authors conducted numerous simulations to illustrate both the nature of influence and the benefits of the algorithm method. Concluding, the authors prove that the method is in fact beneficial in conducting the outlined processes, as well as estimating multiple signal traits at the same time. It is capable of making accurate estimations in the presence of non-linear loads, noise, and other forms of substantial distortion. It is further reported that the drawbacks of applying the traditional Kalman method include a high sensitivity, although the improvements proposed were stated to have addressed this issue; a custom summation is conducted across the samples in order to generate a periodic output which is much less prone to complications. This signal is thereby less prone to being useless, and is less distorted than the original [79]. Reporting on the results of multiple simulation analyses, the authors prove how their technique is effective across a range of conditions. Considering this, the study shows how known theories and methods can be developed further to address complications or to generally improve processes and output. It provides a blueprint for the effective use of Kalman filtering amid the outlined conditions [6], [79].

6.3.11 Online PMUs estimation/application of power grid impedance matrices

Acknowledging the significance of grid impedance matrix estimation in safeguarding or analysing large power systems, the researcher reported on the potential for a recursive least-squares approximation algorithm for locating impedance values [80]. Basing their method on synchronized phasor measurements, the authors tested it across two power systems using data managed through MATPOWER, and tracked changing parameters. Case studies were carried out to estimate impedance, detect faults, and analyse voltage stability margins. Following the presentation of the recursive least-squares estimation algorithm (including a forgetting factor) for approximating impedance models, the authors pointed out that the case studies were in fact proof of their accuracy as well as the potential for applicability of impedance parameters in fault detection and stability monitoring [6], [80]. This piece of literature further recommended the analysis of techniques to address data loss, communication delay, and online approximation of grid parameters as areas ideal for progressive research. This study was yet another primary research initiative which demonstrated how existing methods could be improved for enhanced

output, while further recommending topics for similar improvement in future efforts to improve elements of online structure for power systems.

6.3.12 Online state estimation for fault detection and voltage sag

Fault identification and detection is often considered alongside other topics, and while its importance in power systems is high as a failure to properly address the area can be detrimental to development, a unique method for detection in estimation provided [81]. This research is another example of the combined emphasis on estimation and another category, while estimation and simulations are common areas used in primary research initiatives attempting to safely examine the potential of some process or element [81]. The researchers stated that one of the more desirable approaches to voltage sag approximation is an approximation of the instantaneous voltage, and an approximation of the traditional state amid the accessibility to redundant data. Meanwhile, the authors proposed approximation of voltages amid sag performance during a fault, while the topology of the system is shifting across the fault. As such, the matrix used in assessment must be reconfigured at the fault, and the authors suggest the use of a reportedly efficient technique for both detecting faults and assessing the grid topology. The method they present is based on traditional error detection within a grid and residual assessments [81]. Using an IEEE I4 bus system, the authors prove the effectiveness of their theory and method, further reporting the significance of various elements in greater detail.

According to their initial discussion, the researchers report "power quality (PQ) monitoring is necessary to characterize electromagnetic phenomena at a particular location in a power system [81]. In some cases, the objective of the monitoring is to diagnose power quality problems, while in other cases, monitoring may be used in planning the installation of power quality mitigating devices. Economic impacts of power quality problems are significant in many load centres. In addition to resolving equipment disruption, a database of equipment tolerances and sensitivities can be developed from monitored data. State Estimation (SE) is one of the essential functions in Energy Management Systems (EMS)" [81]. The authors further state that they applied a weighted least square algorithm to solve equations spanning a wide network, while line currents and bus voltages were selected for linear measurement equations in voltage approximation. Meanwhile, the automation of substations is considered progress towards the development of a reliable system capable of 'healing' itself, and further reactors to events with ideal responses in real-time quickly. Such a system is asserted to be cost effective, and while it has not been possible until the rise of technologies occurring within a few years of

the study (communication technology in existence could not appropriately address the demands of substation automation), there were many areas in need of examination and assessment. At the time of publication, technology and communication practices had evolved to appropriately address the demands, with the most beneficial technology including global positioning systems (GPS), wireless communication, and intelligent electronic devices. This technology would further serve to reduce complications in monitoring wide areas, implementation in real-time, and synchronization, while the system can alter some aspects of the measurement matrix without altering dimensions [81].

Attempting to improve the processes used to locate faults in time domain voltage sag state approximation, the authors presented a novel and efficient method, ultimately concluding that their method was successful in generating a unique advantage. In their closing statements, the authors reported "the current based model allows a linear mapping between the measured variable and the states to be estimated. Residuals analyses are used to obtain criteria threshold [81]. The main advantage of the developed method is the fault detection and identification within just one step time after fault instance. A time-domain measurement model was considered for the voltage state estimation. The approach was tested on IEEE 14-bus system [6], [81].

6.3.13 Distribution systems state estimation

It is more common for researchers to analyse estimation in regards to its capacity for an evaluated method, and while the evaluation of the method is commonly a topic of research, the previously reviewed authors placed emphasis on fault detection. Other researchers have placed a greater emphasis on estimation, attempting to improve the nature of existing and future processes in another manner. A year prior to the previously reviewed analysis, other researchers studied the deregulation of power systems, the complications in the "operational philosophy" of distribution, and the potential to change the approach of network operation [82]. With this, these authors emphasized the potential for change using state estimation, designing a study aimed at discovering techniques for optimizing distribution [82]. The authors pointed out that, existing networks were passive by nature, and therefore, could only handle a limited amount of the total capacity for distributed generation. Thus, future developments should emphasize additional network restructuring capable of handling a rising amount of distributed generation. A combination of evolved technologies and techniques were recommended to accomplish such a feat. One possibility for improvement was a new approach

to general network operation, and improving controls, but this alternative could not appropriately address the entirety of the realized (and assumedly surmountable) challenges. Additionally, the authors recommended creatively engineered network structure housing these controls, integrating software functions such as optimized power flow and state estimation into the network's control hub, and custom sensor placement for each network. Despite the commonality of state estimation as a method used in systems analysis in general, such an integral yet custom role was stressed, as was the recognition of differences between transmission and distribution networks (especially in terms of topology and quantity of available network measurements). With this, it is accepted that the state estimation methods used for transmission systems are perceived as weak when related to the dynamics of distribution. The authors state "the potential benefits of using SE technologies in distribution network control have not been explored mainly because of the absence of adequate network measurements and also the lack of rigorous methodology and tools that could be applied on restricted measurements". The development of new distribution system state estimation (DSSE) is a challenging task as the tools to evaluate the quality of SE must consider a number of issues relating to measurement types, locations and numbers" [6], [82].

Concluding, the authors write that the performance assessment of state estimation methodologies prove that all methods ideal for transmission systems can be applied to transmission systems, while effective estimation demands major changes to the algorithms. Knowledge of noise traits improve the potential of effectiveness in development, while changes to existing methods demand detailed statistical modelling amid a scarcity of relevant measurements [82].

6.3.14 Improved power state estimation based on rectangular coordinates

Estimation also analysed, but focused on the evolution of the equivalent current measurement model, use of rectangular coordinate state variables, and bus voltage phasors [83]. Combining these elements, a new estimation technique is presented, while power assessments, the magnitude of voltage, and approximations of voltage buses are utilized in attempt to discern equivalent current phasor data. Through the presented approach, the authors point out that a formula for assessment is generated through a constant gain matrix and iterative computation [83]. Meanwhile, the authors propose simulations on IEEE systems (specifically, 14, 30, and 57-bus for numerical simulations) using these methods. The study

was able to successfully generate unique data in these areas, and this data was further compared to techniques applying polar forms of data to standard processes.

Generally, the study proved that the newer method demanded less time for computation, which is especially beneficial when applied across a large power system, while the study made many more specific revelations as well. Firstly, it was proven that the state estimation model can be used in linear measurement, by using bus voltages as state variables and converting power data to current data. As the authors point out, the gain matrix is treated as a constant in this case, and further affects the Jacobian matrix assessment; the benefits were observable across each of the three IEEE systems listed above, implying that similar benefits are obtainable in real-time applications using FACTS devices [6], [83]. This research initiative combined multiple aspects of theory and assessment in a way which further demonstrates the value of estimation, reducing computation time, and improving processes.

6.3.15 Dynamic equivalents of power systems with online measurements

While internet technology is among the more recent of technologies evolving in the history of power systems, online systems have provided recent enhancements to operations, and the technology continues to provide new functions and potential for future development. The ability for microcomputer equipment to measure and identify elements examined in online systems, and the researchers used this equipment across a range of field tests [84]. Applying the generated data to a dynamic response simulation, stability limit calculation, and comparing to existing data, the researchers were able to generate a range of unique results and meaningful analyses [84]. The final validation of dynamic equivalent (DE) had been utilized to generate and apply equal parameters to practical stability analyses. The equivalent parameters located and applied to the stability analysis and simulations, and the research concluded that the model was efficient and effective [84]. More specifically, they concluded that the equivalent and standard model do not show differences across ICTs, that the equivalent and standard models are close to each other and to existing values across the dynamic responses. There is also more influence on inter-area stability than intra-area stability for the equivalent parameters, and that their equivalent model requires less than 50 percent of the CPU time (also compared to the standard model). This study provided a useful methodology and structure for optimized and organized online system elements, while the continued analyses and technological developments continued to facilitate this progressive development of efficiency and effectiveness [6], [84].

6.3.16 Online collaborative voltage stability control of power systems

Five years would pass between the work of [84] and the beginning of research conducted in [85], while both applications and technology had evolved considerably over this time. Collaborative voltage stability control was examined in online systems, aiming to analyse effective methodologies for performance enhancement, efficiency, addressing operational uncertainty, voltage stability, information exchange, error-tolerant communication, and the deployment of multi-agent systems. The authors presented a framework for integrating power system controllers in online systems in a manner which facilitates benefits in the aforementioned areas, emphasizing the significance of error-tolerant communication and deploying multi-agent systems. The authors further provide results for their study of voltage stability within a New England power system (comprised of 10 machines and 39 nodes) [80], [85]. Moreover, a feasibility study provided data regarding a low-probability cascading faults, while the study overall provided a range of unique information as it expanded the knowledge base for online technology for power systems at that time.

In presenting their results and providing analytical discussion, the researchers revealed that the primary contribution of their literature piece stemmed from their feasibility study, as they defined it as novel concept in online power controls [85]. Beyond this, addressing the emphasis on collaboration and multi-agent systems, the study proposed an improved error-tolerant agent communication protocol. It was proposed that this was possible through the use of an algorithm optimizing information. Additionally, the study proposed the application of the nesting method of decomposition in graph theory, as this serves to effectively deploy the multi-agent systems. Moreover, this method serves to safeguard lesser functions surrounding power loads, which thereby reduces the chance of them collapsing amid cascading faults [85].

The researchers were also able to contribute to existing literature through a range of recommendations supplementing their descriptions of functionality and output. Asserting that there are many areas in need of further examination and analysis, the authors recommend that the practical applications of multi-agent systems, the potential for error or ineffective operations, and the improvement of control algorithms be considered as prime areas for enhancement and improved development. While the potential for this technology, related applications, and the additional developments were proven and outlined, the researcher recognized that the theory and technology have potential for still further applications and improved output [85]. As a final recommendation, the authors stated that the area of load shedding applied to collaborative online control, and the testing of a control algorithm for a

larger power system, are areas which would be targeted (by them personally) in future research. This combination of original information and recommendations thereby assisted the existing knowledge base in multiple ways, while the growing technological potential of both power systems and online controls is clearly evident [6], [85].

6.3.17 Online dynamic security assessment for proper power system control

In this research online dynamic security assessment can be used to enhance the real-time situational awareness for assessing different contingencies [86]. This allows the network operators to take fast preventive and corrective actions. The research comprised numerous contingencies, bulk power systems, and different dynamic operating conditions. The online dynamic security assessment study developed a data mining framework for using decision trees and a boosting technique [86]. The data mining framework has been processed in different stages from offline training stage to multiple decision trees built on collected training data, and an iterative algorithm [86]. The real-time update stage, discussed the decision trees together with a smooth tracking of the decision changes. Real-time PMUs are used to locate the current operating conditions into a timely security decisions in the online DSA stage. The authors claimed that test of the online dynamic analysis on a practical power system proved that the proposed approach is valid under a variety of realistic operating conditions [6], [86].

6.3.18 Online real-time hardware in the loop optimization using a simulation

More recently, the use of RTDS (Real Time Digital Simulator) has been expanded so that it can now handle an analysis of nearly any power system [87]. One way in which RTDS can be expanded is through the use of an optimization enabled electromagnetic transient simulation technique (OE-EMTP). Initially this technique was used to tune the HVDC control parameters. It was also used for optimization of the gating sequences in space vector modulation. The simulations were done for each case application. This meant that multiple simulations were necessary in most instances. A problem with traditional approaches to multiple simulations is that they are wasteful. This is true for the common Monte Carlo simulations. In order to overcome this problem, an optimization algorithm which is nonlinear can be used to guide the simulation. In this case, existing simulation programs can be used as objective function evaluators to help with optimizing the algorithm which is being employed. PSCAD software which is based on ENT-type programming allows for the optimization to be seamlessly incorporated into the simulations [87].

Unfortunately, even with the nonlinear optimization algorithm being used as a guide for the simulation, the time which is required for the computations increases with the size of the simulation. This means computational complexity increases with a higher number of iterations. Furthermore, there can be discrepancies between real-world implementation and model optimization. This means the conceptual model may be quite different than the real-world application. The controllers may suffer from parasitic filtering during the analog input and output stages. Finally, the controller conceptual model will not account for a number of issues associated with implementation. For example, the conceptual model does not account for floating-point representation of numbers, no ways, and limits of the signal quality [87].

In order to overcome problems regarding the use of RTDS for multiple simulations of real-world applications, a new approach was investigated by using OE-EMTP simulations [87]. This technique consists of combining the already existing capabilities for simulation of the EMT-type programs with optimization algorithms, which are nonlinear. This means that the EMT type simulation can be used as a way of evaluating the optimization algorithm since it is not part of the EMT-type simulation program. The optimum which is desired can be achieved through iterative steps, which are conducted using the optimization algorithm. During each trial, the parameters are adjusted in the optimization algorithm based on actual outcomes from prior steps. This is done with the objective of improving the desired outcomes. When the OE-EMTP technique is used with an EMT program which is off-line; the simulations are limited to conceptual models. In order to overcome this problem, a real-time simulation must be utilized as the objective function evaluator. This means that the RTDS is taking the place of the off-line EMT-program. The RTDS environment evaluates the candidate through the use of an externally derived nonlinear optimization algorithm in real time. This is more accurate than the purely conceptual models previously developed [87].

The optimization algorithm which is external uses output derived from the RTDS and executes the algorithm. This means there is a candidate for subsequent steps. This is done until the termination criteria for the specific algorithm are met. This is a new approach which offers at least two benefits. The first benefit is that the amount of time necessary for the optimization process is substantially reduced. This is due to the real-time execution and evaluation of the objective function. Another benefit is that the external optimization does not need to be fully understood. The OE-EMTP technique with an off-line EMT-type program would require

complete information regarding the optimization subject. This is not a limitation of the OE-EMTP when it is combined with the RTDS [6], [87].

6.4 Outcome of Literature Review

The chapter highlighted different FACTS devices including converters, compensators, advantages and disadvantages and their applications in today's power industry. The spreading literature emphasized that with the potential advancement in silicon carbide-SiC technology, many new power electronics applications would become techno-economically feasible. The analysis inspected that any utility when considering FACTS shall compare the various devices available, study and their design aspects for the best utilisation and optimum performance. Different design aspects can reviewed for use with FACTS in any utility. Transmission companies around the globe have increased their installations in the past few years of FACTS, and there are still far more orders of SVC, STATCOM and HVDC. There are still fewer than 20 TCSC's installed by different utilities [16].

The review of literature surveyed by the thesis showed that, the technology of power electronics (FACTS, HVDC, custom power devices) is moving fast. Some technologies outdated, even in a shorter time of less than 3-4 years when some of the authors' research papers were published [16]. For example, the design technologies discussed in Appendix-D for FACTS and customs power devices, such as direct and indirect controls are now obsolete and nobody uses this in new installations any more [4], [16]. As a critique and update to [16], the discussed technology is outdated, since there are existing converters using this, but it will not appear in the design of new FACTS devices. This extreme and aggressive development in this power technology would necessitate that the experts and engineers in this field shall keep abreast with its development on a daily basis.

Next chapter, exhibits more details in the case studies exploring different scenarios of online control that can be used with online power electronics devices.

Chapter 7: Case Studies: Power Electronics Applications in QPTS

This chapter is explaining the applied research initiative to fetch new solutions for QPTS challenges using online power electronics. Various studies were investigated, and this chapter describes three research case studies conducted on QPTS. The first case study covers the steady state power flow analysis carried out on the network revealing the impact of FACTS devices [2]. The second case study further analyses the steady state and dynamic responses of the QPTS with STATCOM device [1]. In the third case study HVDC transmission is modelled in the QPTS and the steady state and dynamic behaviour of the network are compared between HVDC, STATCOM and capacitor banks. The entire steady state and dynamic models for QPTS created in this research were using the Siemens PTI's PSS®E program [88]. The executive results of these case studies are published in the thesis's papers [1], [2], [3], [4], [5].

7.1 Case Study One-Voltage and Power Flow Control with FACTS in QPTS

7.1.1 Objective

The objective of this case study is to investigate the potential benefits of implementing dynamic control of voltages, power flows in QPTS. The planning strategy is to explore mid-term advanced solutions such as FACTS, HVDC, PVs, energy storage systems (ESS), and other renewable resources together with the present conventional practices, which are facing challenges in getting new rights of ways for new overhead lines and cables' corridors. The control of power flows and the voltage profiles in certain areas are the main concerns in the long term plan for the transmission power network. This section outlines the actual case studies and scenarios of voltage and power flow control conducted in the QPTS. The section also provides recommendations and conclusions for implementation.

7.1.2 The solutions

The planning and operational solutions considered are comprised of conventional transmission expansion options including conductor up-rating and fixed series capacitors (FSC). Non-conventional and innovative means of dynamic control of power flows and voltages are also considered. For example, FACTS devices, such as TCSC and GUPFC, are considered. These devices are modelled, tested and verified for power flow control and voltage

support in interconnected overhead lines feeding the same industrial area with different ratings and lengths. Comparison with other FACTS technologies such as SVC is also presented. The analysis assessed the potential to improve power flow imbalance between transmission lines and the voltage profile to enhance the network security and reliability for important industrial customers. Optimization techniques for the FACTS devices allocation and rating considering the voltage improvement and optimal power flow control are studied in general.

7.1.3 Simulation of the case study scenarios

To implement the discussed solutions, the following case study scenarios were conducted in this planning project. The case studies simulated can be summarized as follows:-

Case-1) Upgrade of the under-rated 132 kV overhead lines

Case-2) Upgrade of the under-rated 132 kV overhead lines and use of TCSC

Case-3) Upgrade of the under-rated 132 kV overhead lines and use of SVC

Case-4) Upgrade of the under-rated 132 kV overhead lines and use of GUPFC

The four case study scenarios were modelled, and analysed using the PSS®E program [88].

7.1.4 Power flow contingencies

As has been described before, there is a potential power flow imbalance between the two 132 kV overhead lines (OHLs) feeding Dukhan and Umm Bab industrial areas from different network sources. Refer to Figures in next section to see an indication of the potential imbalance and voltage profile concerns.

The power flow results for one contingency condition (switch-off the OHL between Al S'halah and GCC substations) are shown in Figure 17 for the year 2015 model. As it can be seen, the power flows and the bus voltages are within the acceptable limits. There is 80% loading on Al S'halah-GCC OHL (within the limit), while the line voltage is maintained within the allowable range +/- 5% [10].
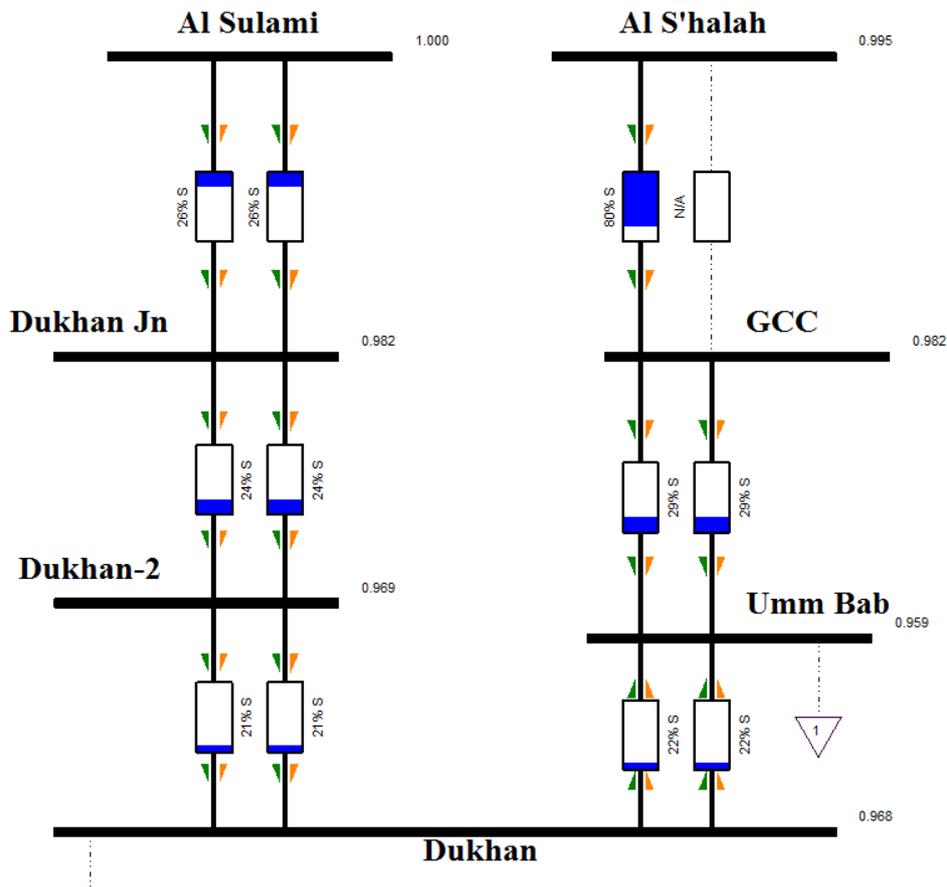
Figure 17: Contingency power flow case N-1 @ Al S'halah-GCC (2015 model)

When the area load is increased by 110 MW (at Umm Bab substation), anticipating the load growth beyond 2015 the lines exhibited appreciable loading and the imbalance between the two sources. This is evident at Figure 18, leading to violation of N-1 (73% loading) and voltage criteria in normal situation.

The loadings and voltage values for these cases (and for the cases to come) are shown in Tables I –III and IV- VI, respectively, placed at the end of all scenarios in this chapter.
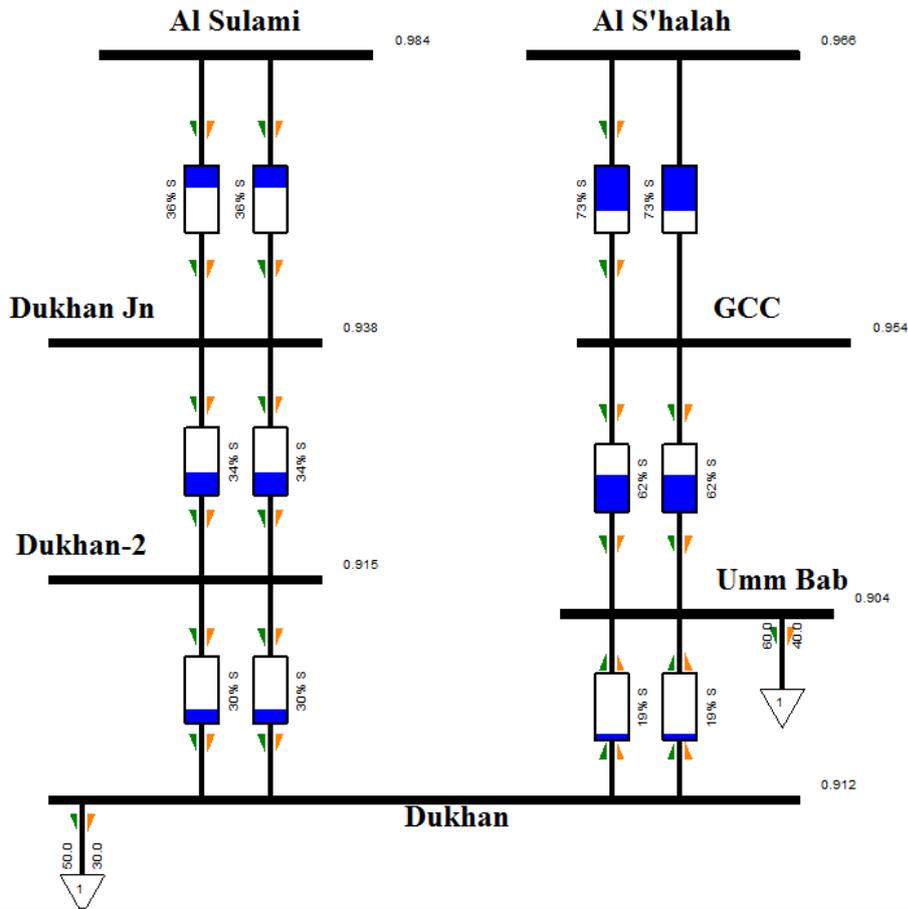
Figure 18: Normal case with increased load by 110 MW

Two N-1 contingencies, line switch-off with load increase, are shown in Figure 19. There is an evidence of violating N-1 criteria loading to 144% on Al S'halah-GCC OHL, and serious voltage violation with some buses drop to -12% or 0.88 pu [2].
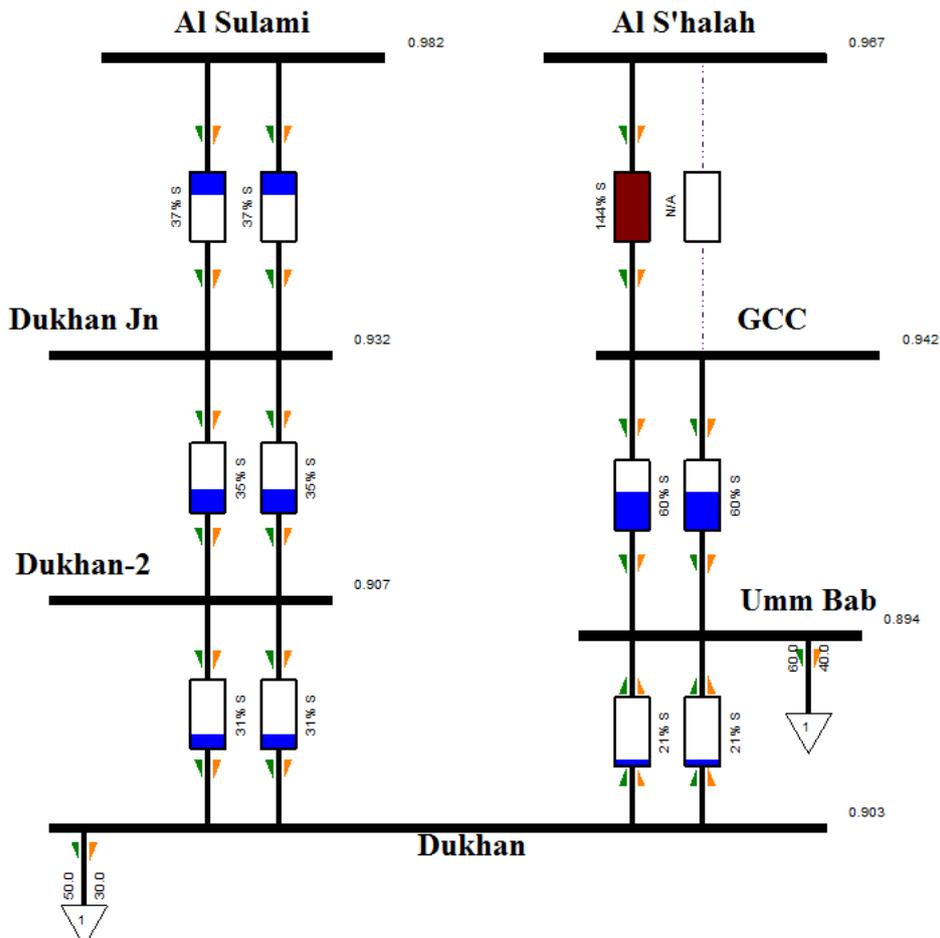
Figure 19: Contingency case - Al S'halah-GCC with increased load by 110 MW

To cope with this situation and to come up with an appropriate solution, different load balancing and voltage improvement techniques, are studied as discussed earlier and described in the next sections.

7.1.5 Application of different system improvement techniques

7.1.5.1 Uprating of the existing OHL capacity

Since there are restrictions to install new OHLs, one of the obvious conventional solutions is to up-rate the capacity of the under-rated 132 kV OHLs from 133 MVA to 265 MVA. In 2007-08, the Kahramaa decided to use ACCC (Alloy Composite Core Conductor) as a pilot project to upgrade part of the Al S'halah-GCC OHL 132 kV OHL to replace the existing ACSR conductor. By doing this, the OHL capacity was increased from 133 MVA to 265 MVA and the new ACCC conductors were installed and commissioned in 2012. ACCC conductor has high-strength and low-sag characteristics, which combined with its high-efficiency and

high-capacity, make it an ideal conductor for use in areas where high ambient temperatures and growing demand are prevalent [31]. The service history records gathered by the Projects and Control Centre departments of the Utility indicate that the conductors have been performing very well. The success of this conductor for use in Qatar has encouraged the Utility to upgrade the remaining existing 132 kV OHLs from 133 MVA to 265 MVA using the same technology or an equivalent one [2].

The power flow model is adjusted accordingly and the study results are shown in Tables I to III and IV to VI for thermal loadings and bus voltage profiles respectively. As can be seen from these tables, the violation of N-1 criteria is rectified; however, there are voltage violations at different buses under normal and contingency conditions, with voltage magnitudes falling down to -12% [2], [10]. Refer to Figures 20 and 21 for bus voltages and line loadings.
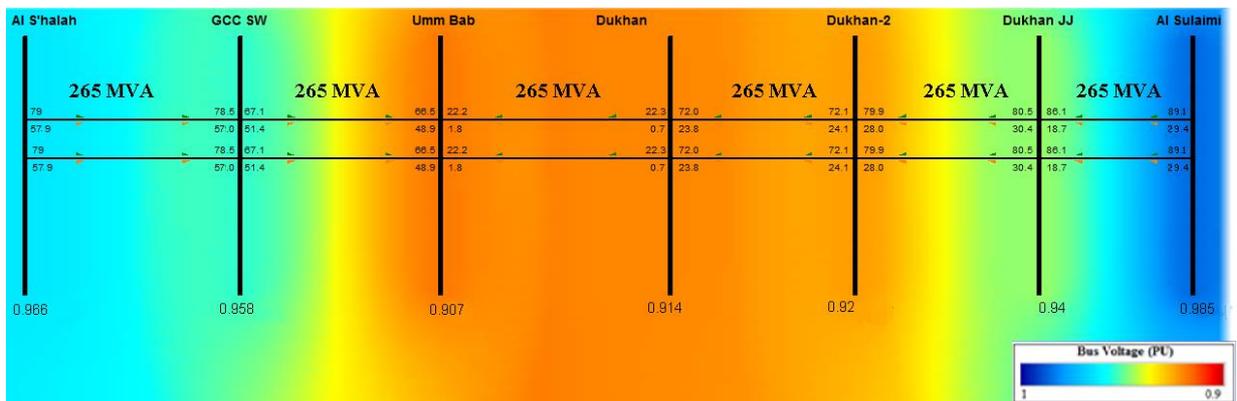
Figure 20: Voltages with OHL conductor up-rating to 256 MVA [2]
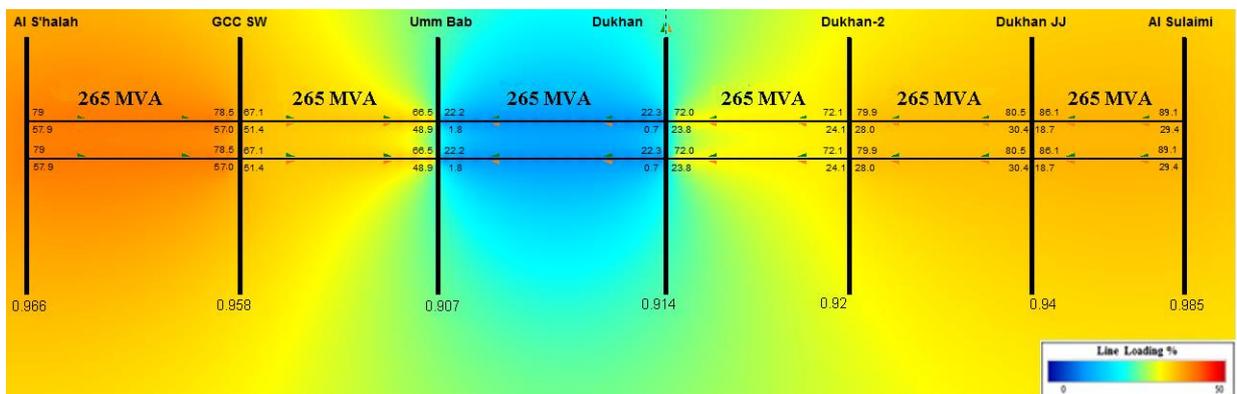
Figure 21: Power flows with OHL conductor up-rating to 256 MVA [2]

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7.1.5.2 Using SVC in addition to OHL uprating

These voltage violations indicate that OHL up-rating alone would not solve the problem and some sort of reactive support, either fixed or dynamic, would be required to adequately resolve the problem. The overhead lines reconductoring is further supported by adding a SVC at Dukhan bus to provide dynamic voltage support. The voltage profile has improved in the area to the satisfaction of the transmission code voltage criteria. The colour coding is still showing high loading in the shorter lines from Al S'halah to GCC and Umm Bab, due to flow imbalance. Refer to Figure 22 and Tables IV to VI.
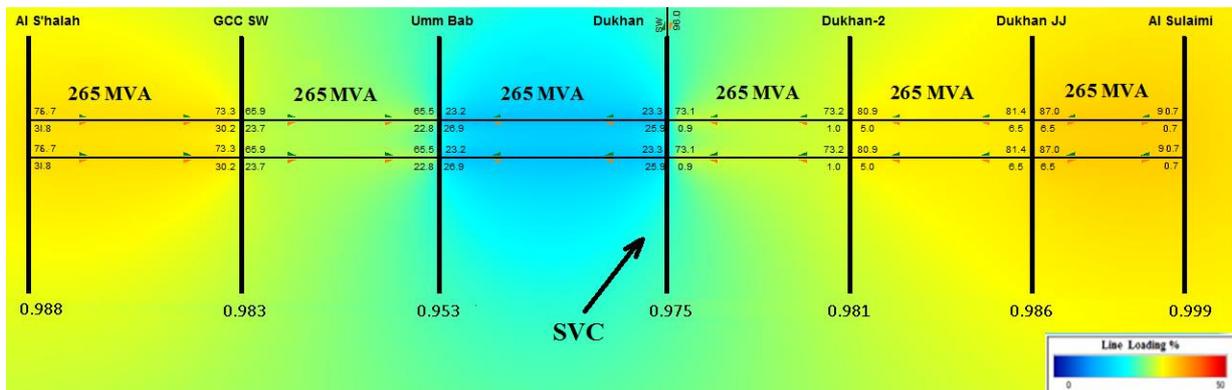
Figure 22: Power flows and voltages with conductor up-rating plus SVC [2]

7.1.5.3 Series Compensation (Fixed Series Capacitor- FSC)

To increase the power flow from the power stations in the Ras Laffan area, the OHLs between Al-Sulaimi to Dukhan JJ are series compensated using fixed capacitors. The line is compensated for 50% to avoid any probable risk of sub synchronous resonant- SSR. This is the longest section of the OHL from the Ras Laffan side and is selected to have a maximum impact of the series compensation.

The study results of this option for normal and contingency conditions are also shown in Tables I and VI. The results show how this solution slightly improved the voltage profile as compared to the conventional solution, but the Umm Bab busbar has seen a voltage of about 92.5% violating -5% voltage criteria. In addition, there is still voltage and loading violation (106.6% loading) following N-1 contingencies .Therefore, this solution option did not resolve the problem adequately.

7.1.5.4 Series Compensation (Thyristor Control Series Capacitor- TCSC)

The same scenario is repeated with 50% FSC, and 20% TCSC compensation. The N-1 loading violation has improved slightly from 106.6% to 103.8%; however some busbar are still exhibiting out of Code's limit values for voltages such as 0.93 at Umm Bab substation and 0.945 pu and Dukhan substation (Figure 23).
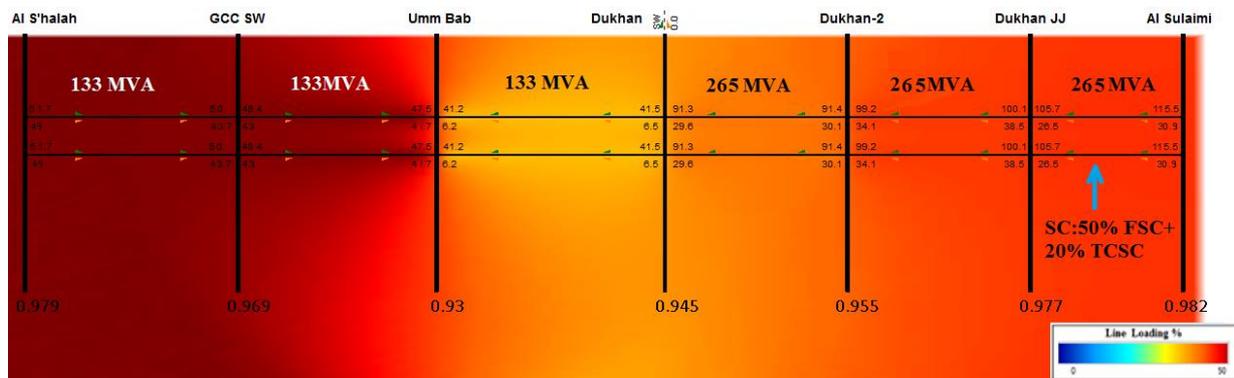
Figure 23: Power flows and voltages with series compensation using FSC and TCSC [2]

The simple mathematical equations explained in Chapter 4 "Compensation from FACTS and non-FACTS Devices" demonstrate how the series and shunt compensations work in real applications. More versatile FACTS devices need to be tested to compensate for both active and reactive power for further improvement.

7.1.5.5 Generalized Unified Power Flow Controller - GUPFC

The power flow model is modified with the GUPFC, which has each converter rated as 100 MW, 50 MVAr. Different locations for the installation of this device are studied and the results are summarized in the Tables I to VI. The results of location-4 are shown in Figure 24.
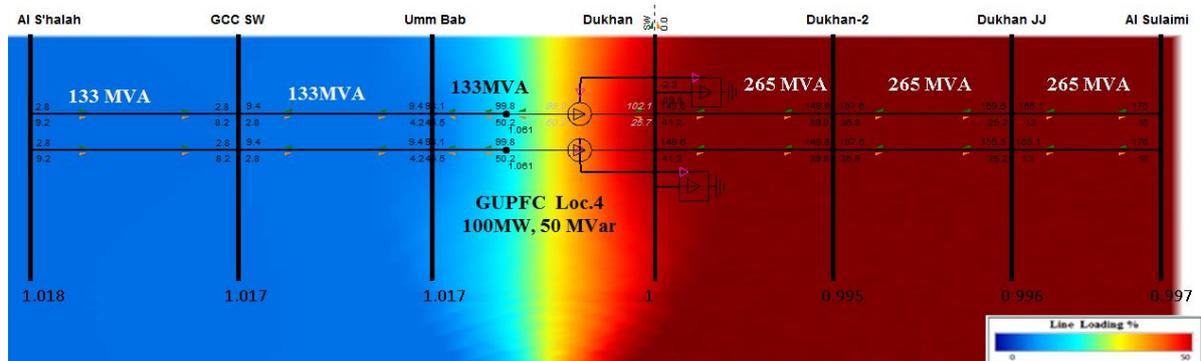
Figure 24: Power flows and voltages with GUPFC-Location-4, (100 MW, 50 MVAr) [2]

It is interesting to note that different locations give different performances in respect of voltage profiles and line loadings. It is found that the best location for the installation of GUPFC is at Dukhan. This location has not only improved the voltage profile of the network but also brought the line loading of Al-Shalah to Umm Bab line to within the limits under normal and contingency conditions. The location for this GUPFC is optimized using load flow scenarios investigated at the different four locations Al Sulami- Dukhan Jn, Dukhan Jn–Dukhan-2, Dukhan-2 – Dukhan, and Dukhan- Umm Bab. However, using a 100 MW, 50 MVAr GUPFC slightly overloaded the Al Sulami-Dukhan Jn line under the parallel circuit out condition, indicating that the rating of GUPFC needs also to be optimized. Critical contingency cases are carried out, particularly by switching off the OHLs Al S'halah-GCC and Al Sulami – Dukhan Jn. using the power flow model the GUPFC, each converter rated as 50 MW, 50 MVAr at location-4 (Figure 25).
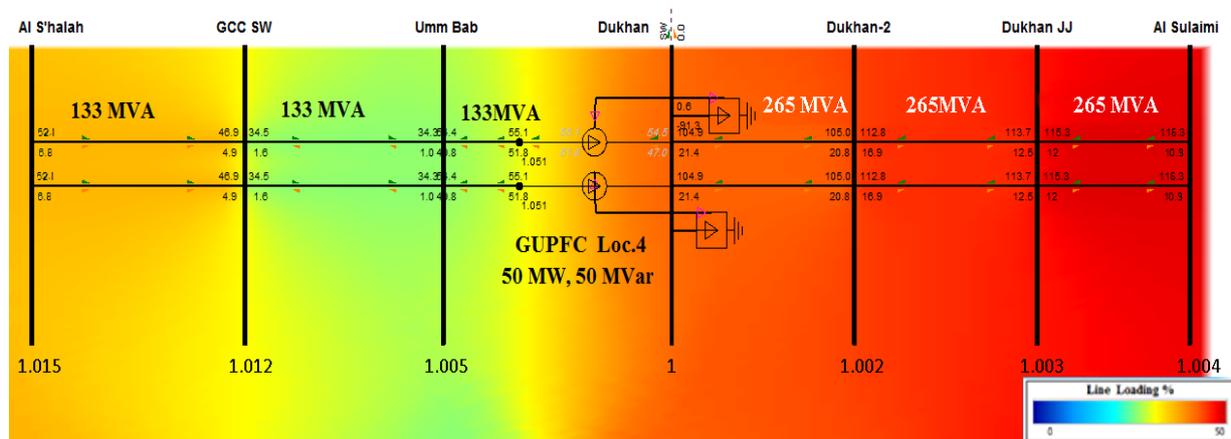
Figure 25: Power flows and voltages with GUPFC-Location-4, (50 MW, 50 MVAr) [2]

7.1.5.6 Optimal GUPFC allocation technique using software simulation

Using PSS®E [88], Power Voltage Curves (PV) and Reactive Voltage Curves (QV) analyses were performed to determine the optimal size of the GUPFC. The proper sizing of the GUPFC device is very important because low voltage is a major issue at Dukhan 132 KV bus and vicinity. These two analyses (PV and QV) are widely performed to determine the networks vulnerability to voltage instability and voltage collapse in order to properly size HVDC and FACTS devices. The PV and QV analyses assessed the voltage variation with active and reactive power change. The PV curve is a representation of voltage change as a result of increase in active power transfer between two systems and the QV curve is a representation of reactive power demand by a bus or buses as voltage level changes.

In PV analysis, PSS®E uses one power flow case to automatically create several power flow cases in the engine by gradually increasing the power transfer from one system to another with a user specified MW increment. As power transfer is increased, voltage decreases at the buses on or near the transfer path. The transfer capacity where the voltage reaches the low voltage criterion defined by the user is the low voltage transfer limit. The power transfer can still continue until the solution identifies a condition of voltage collapse. This transfer limit is the voltage collapse transfer limit. The PV analysis is used to determine the amount of MW power that the GUPFC can supply to the load at Umm Bab reliably.

In QV analysis, PSS®E creates the QV curve through a series of AC power flow calculations. By starting with the existing reactive loading at a bus, the voltage at the bus is calculated for a series of power flow as the reactive load is increased in steps until the power flow demonstrates convergence problems as the system approaches the voltage collapse point. The user can also specify a particular voltage or voltage range at a bus for the program to determine the minimum reactive power compensation required to keep the bus at the specified voltage levels or ranges. The output of the QV analysis is the QV curve, which is typically a convex curve. The bottom of the curve represents the voltage stability limit that is reactive power value at the bottom of the curve, is the minimum reactive compensation needed. At bottom of the curve, the change in reactive power with respect to voltage is zero. In other words, the derivative is zero. To the right of the bottom of the curve, where an increase in reactive power results to an increase of voltage, is the stable operating point. To the left of the bottom of the curve, where an increase in reactive power results to a decrease in voltage, is the unstable operating point.

Since the transfer of power reduces the system bus voltages, QV analysis was first performed to determine the reactive power need at Dukhan, and then PV analysis was performed with the determined reactive power size modelled at Dukhan. Figure 26 below shows the minimum amount of reactive power needed at Dukhan without any contingencies to keep its voltage at a minimum of 0.95 pu.
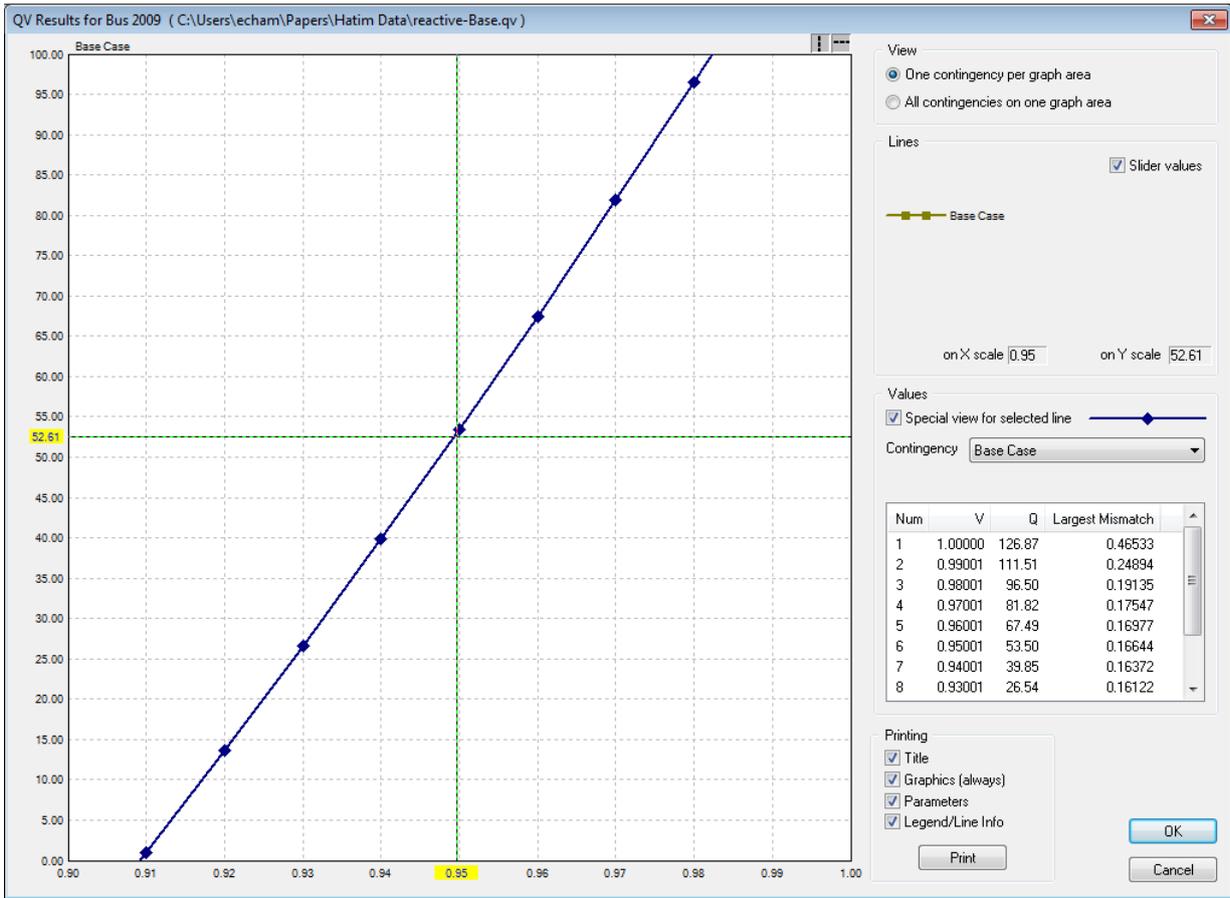
Figure 26: Reactive power sizing at Dukhan in system intact condition (PSS®E 2017/18 model)

The Figure above shows that the minimum reactive power needed at Dukhan without any contingency is about 52 MVAr.

Figure 27 below shows the minimum reactive power needed to keep the bus voltages at Dukhan and vicinity within ± 10% of 1 pu voltage following the loss of a single circuit contingency.
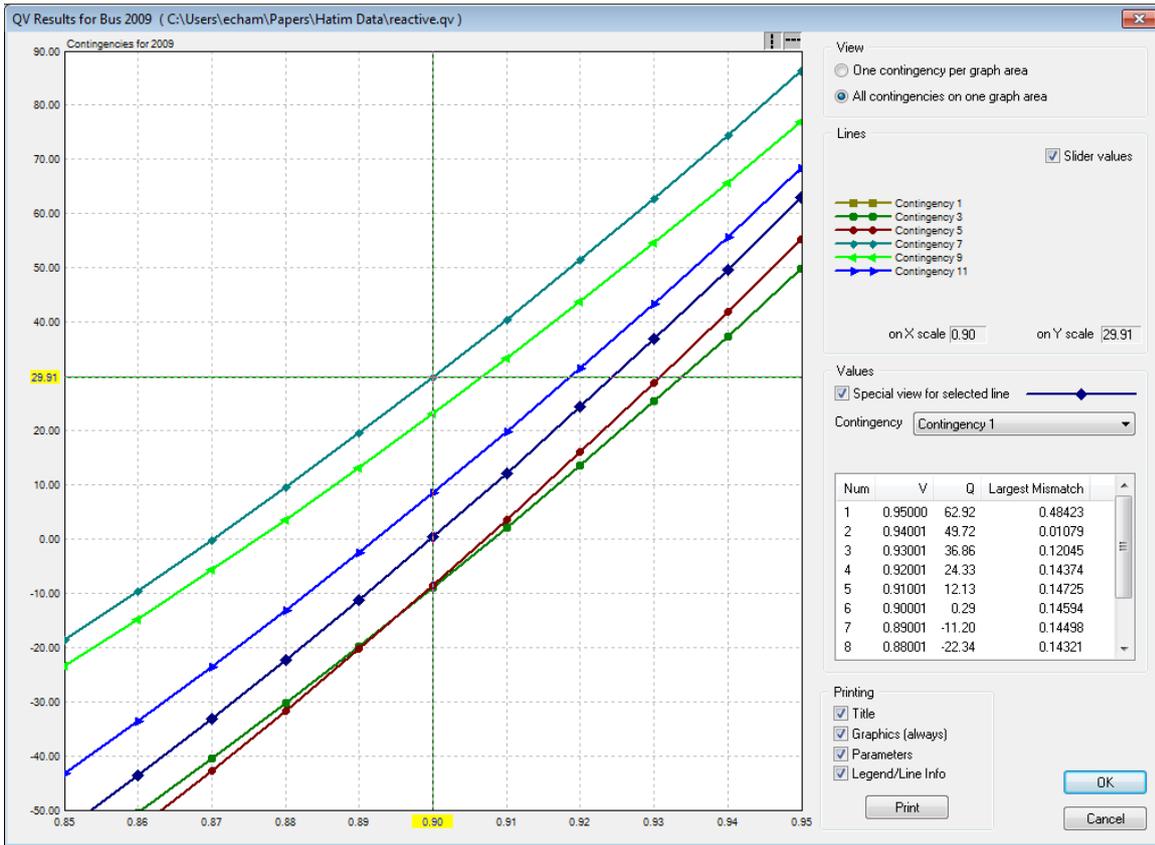
Figure 27: Reactive power sizing at Dukhan in N-1 contingency condition (PSS®E 2017/18 model)

From Figure 27, it can be confirmed that the minimum reactive power needed to maintain the bus voltage at Dukhan following the worst N-1 contingency is about 30 MVAr. Based on this, the optimal reactive power required at Dukhan is 50 MVAr, which is about the amount needed in system intact conditions as shown in Figure 26 to maintain the bus voltage at Dukhan at 0.95 pu voltage.

The case was then modelled with the 50 MVAr at Dukhan to perform PV analysis.

Figure 28 below shows the amount of power that can be transferred from Dukhan to Umm Bab in N-1 contingency scenarios.
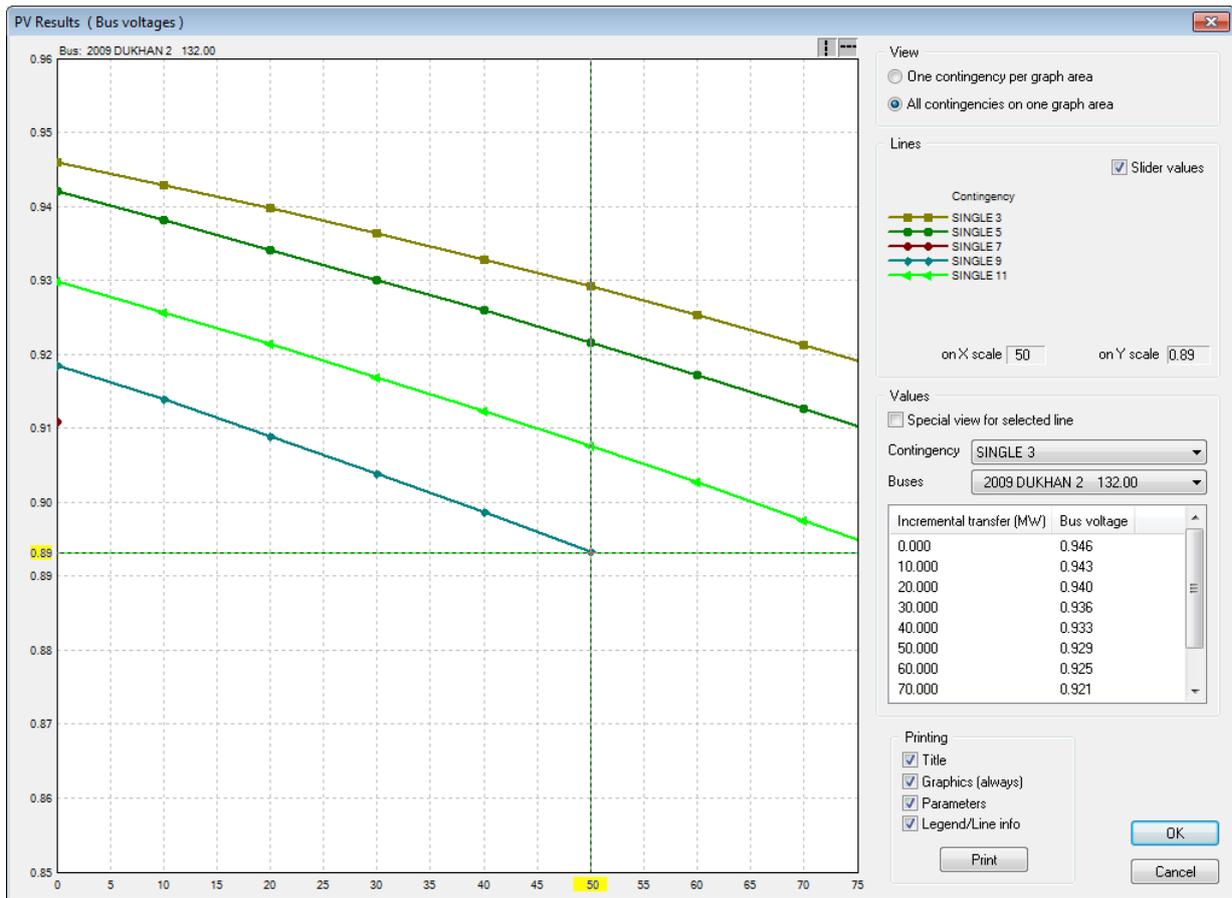
Figure 28: Power transfer from Dukhan to Umm Bab in N-1 contingency condition (PSS®E 2017/18 model)

From Figure 28 above, it can be shown that for the worst contingency, the minimum amount of power that can be transferred is about 50 MW. This transfer level happens when the bus voltage at Dukhan is above 0.89 pu but below 0.9 pu voltage. This difference in voltage from 0.9 pu is insignificant, so it is therefore assumed that the maximum amount of power that can be transferred from Dukhan to Umm Bab in N-1 contingency scenario is 50 MW.

Accordingly, from the QV and PV analyses, it was determined that the optimal size of the GUPFC should be about 50 MW, 50 MVAr. From the research in the published papers, this approach has not appeared from others in the published literature, and is a new contribution of this work. In this dissertation the approach is described in detail rather than just presenting results. The results found were very satisfactory under normal and contingency conditions as listed in Tables I-IV and depicted in power flow plots at Figures 29-31
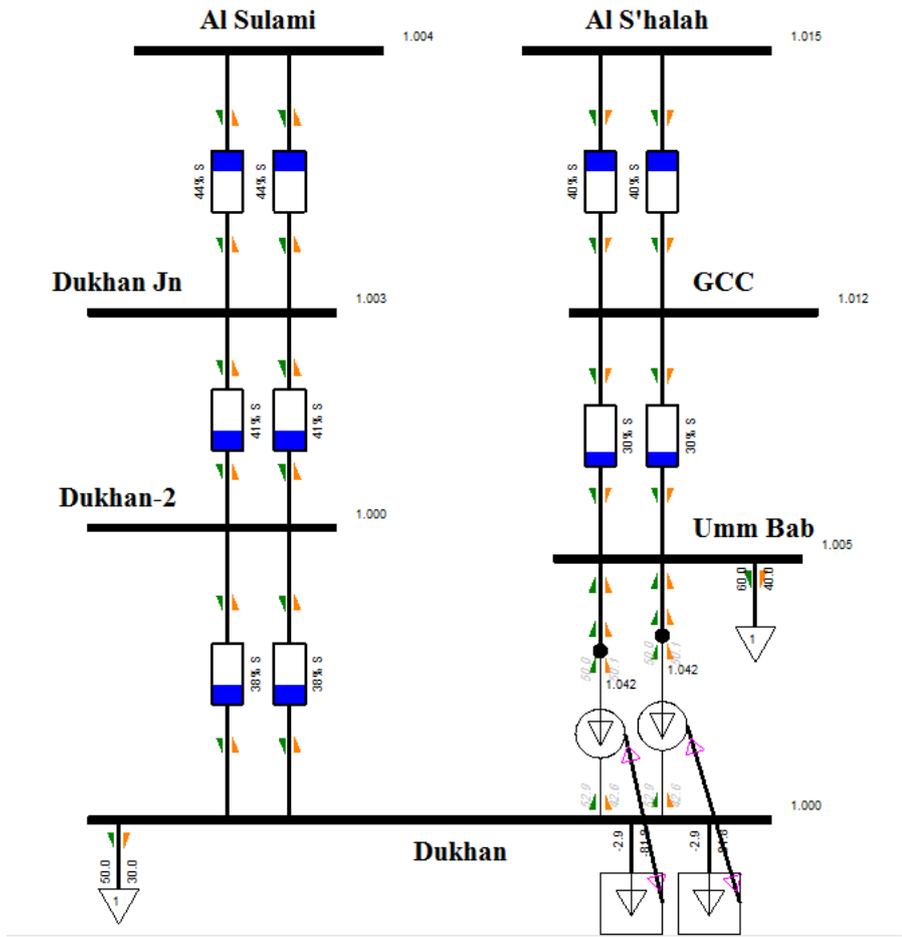
Figure 29: Normal case with GUPFC (50 MW, 50 MVAr)-Location-4, at Dukhan (PSS®E 2017/18 model)
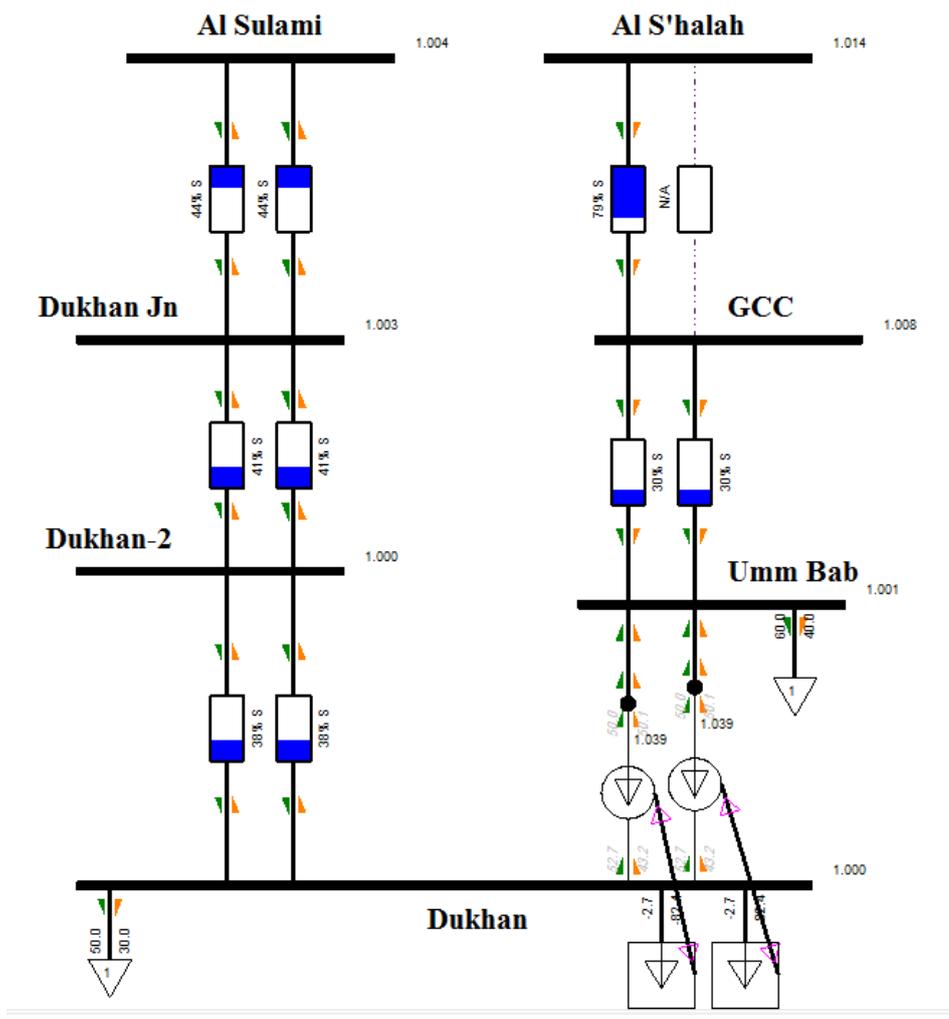
Figure 30: GUPFC (50 MW, 50 MVAr)-Location-4, at Dukhan (towards Umm Bab)- N-1 at S'halah – GCC
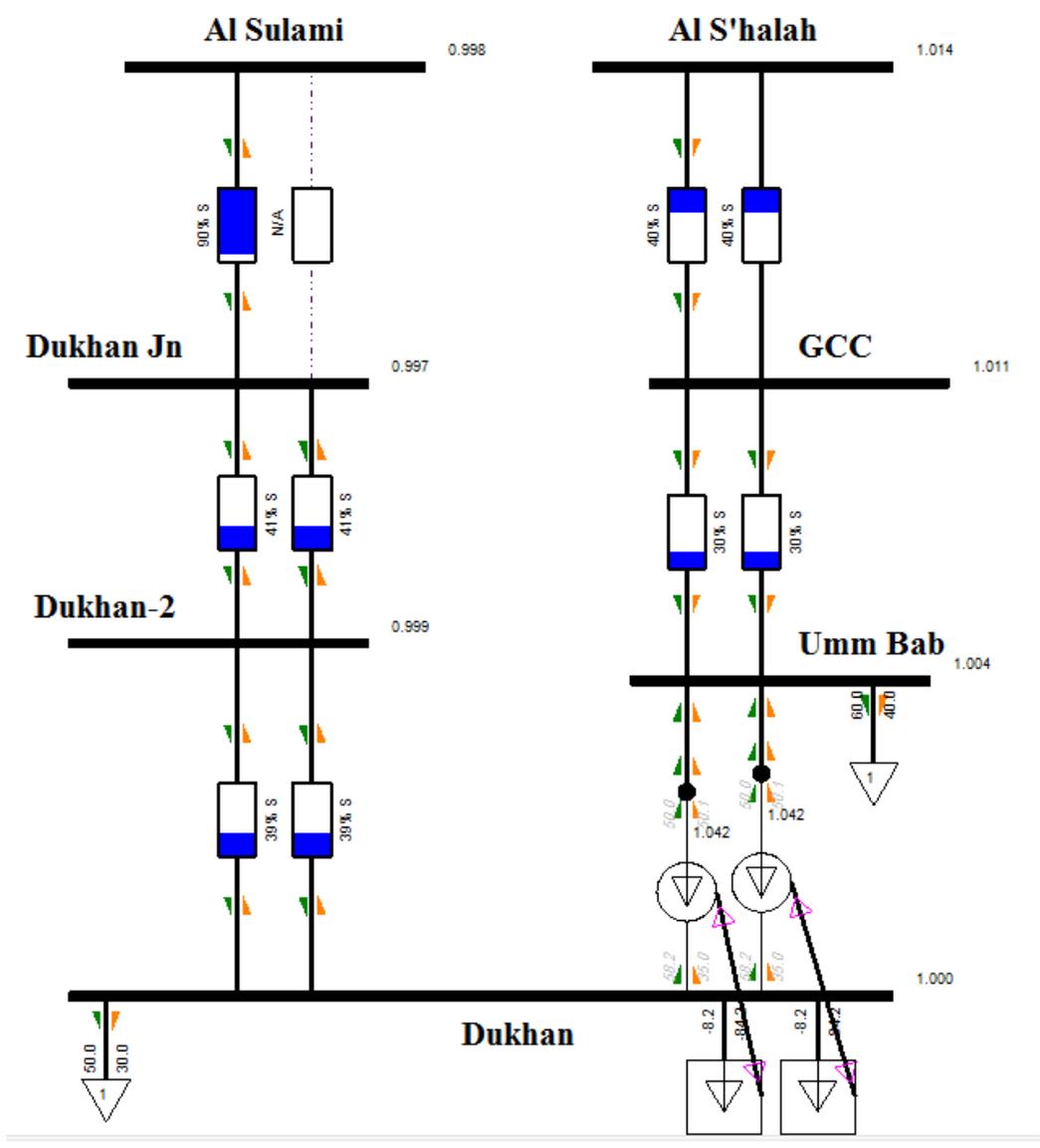
Figure 31: GUPFC (50 MW, 50 MVAr)-Location-4, at Dukhan, N-1 at Sulami – Dukhan Jn

Figure 32 shows the contingency when losing one series converter from the GUPFC. As can be seen the power flow is well shared between the two 132 kV OHLs forming the ring. The other series converter of the GUPFC simply operates as a SSSC. It is worth noting that this would be the normal response to this contingency, so the system would still have dynamic series compensation on one line and it is connected to the same bus [2].
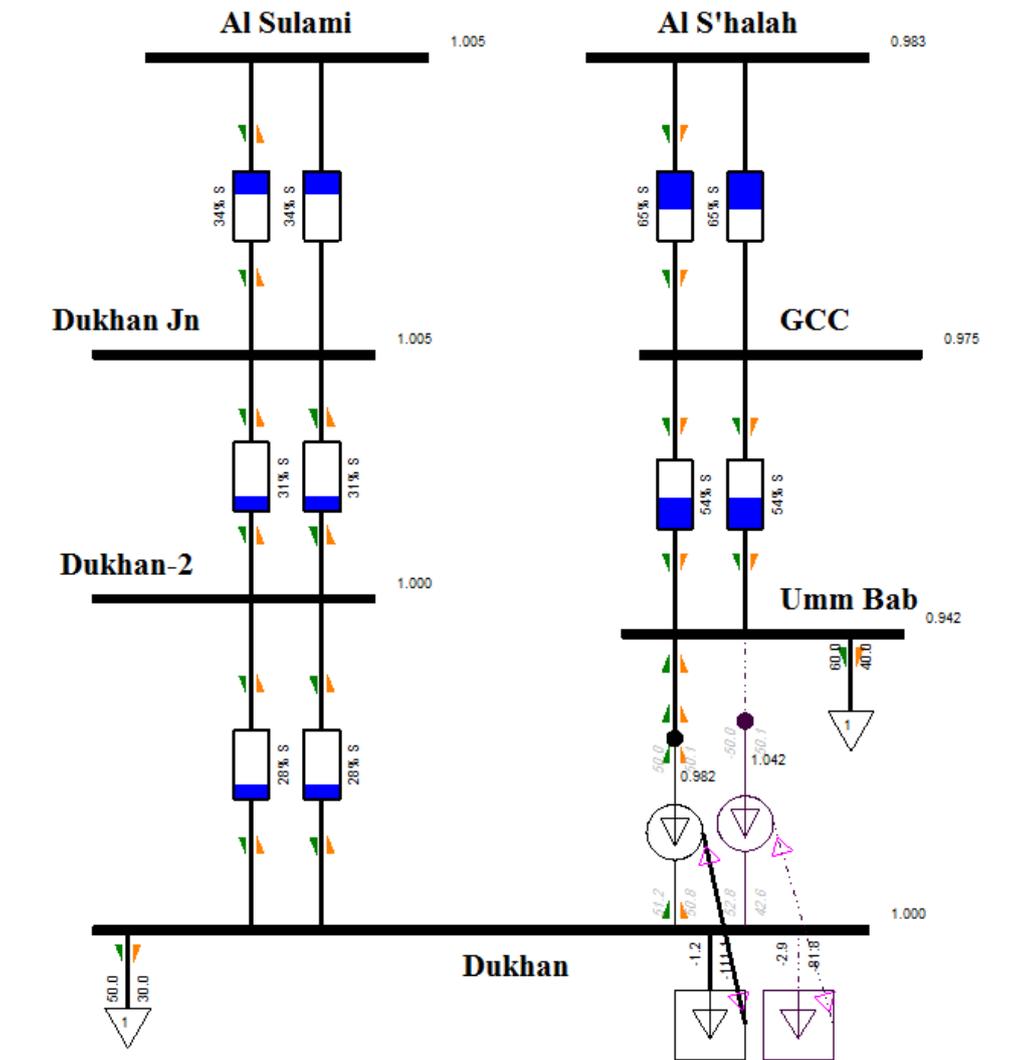
Figure 32: GUPFC (50 MW, 50 MVAr)-Location-4, at Dukhan, losing one converter of the GUPFC

7.1.6 Analysis of the case study

The analysis performed on QPTS 2015 model showed that the power flows and the bus voltages are within the acceptable limits on the two OHLs (from different sources) feeding the industrial area under study. When the load is increased by 110 MW anticipating conservative load growth in the area beyond 2015, the lines exhibited appreciable loading and the imbalance between the two sources occurred, leading to N-1 loading and voltage violations following the contingencies (Figure 33). The reference in the below figure is the line loading in normal operation and several contingencies, while the voltage values are inserted in the top of the bar without reference [2].
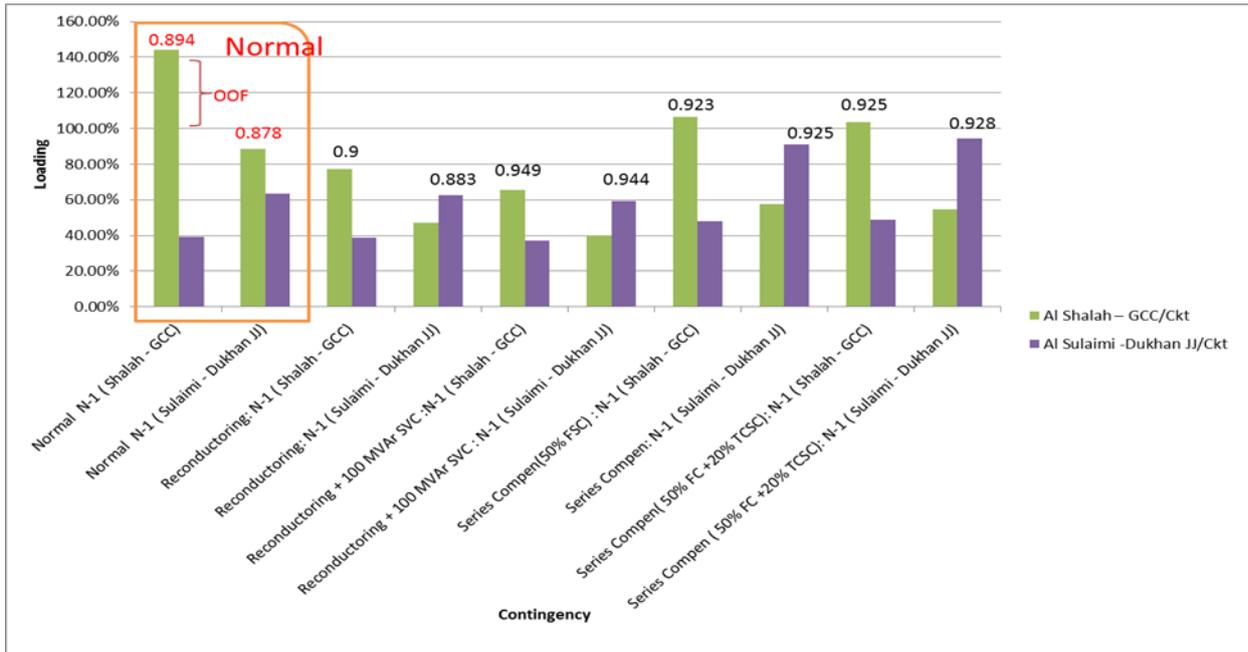
Figure 33: Line loading and voltages under normal operation and contingency (OOF: Out of firm)

Conventional mitigations such as up-rating of the line capacity solved the overloading issue but the low voltage problem still persists and some sort of reactive support would be required (Figure 34).
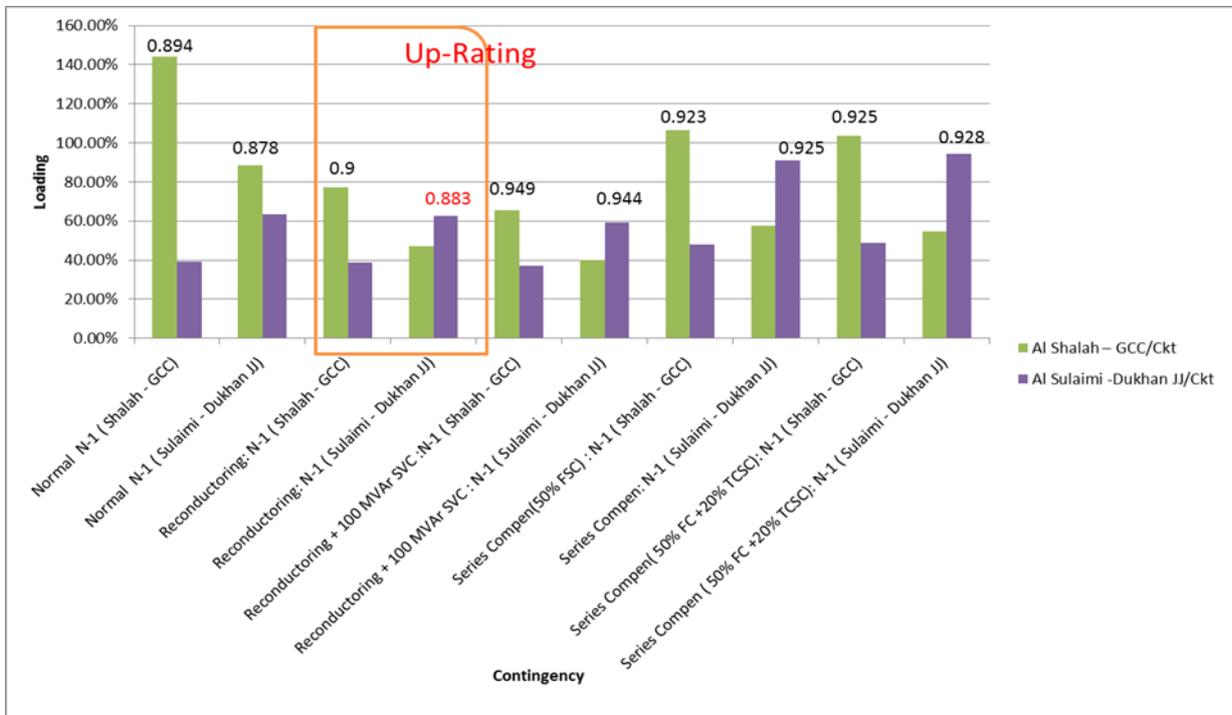
Figure 34: Line loading and voltages with OHL capacity up-rating, under normal operation and contingency

Use of a 100-150 MVAr SVC in the area in addition to conductor up-rating shows sufficient improvement in the network voltage profile, and this combination seems a feasible solution to resolve the problem (Figure 35). However, a STATCOM has better performance compared to a SVC, as it takes less space and produces more reactive output in low voltage conditions but is more expensive. The STATCOM is not modelled in this steady state study case, assuming that the shunt converter in the software is mainly for controlling the MVAr power at the bus. However the STATCOM is modelled in the dynamic case studies that will follow in this chapter.
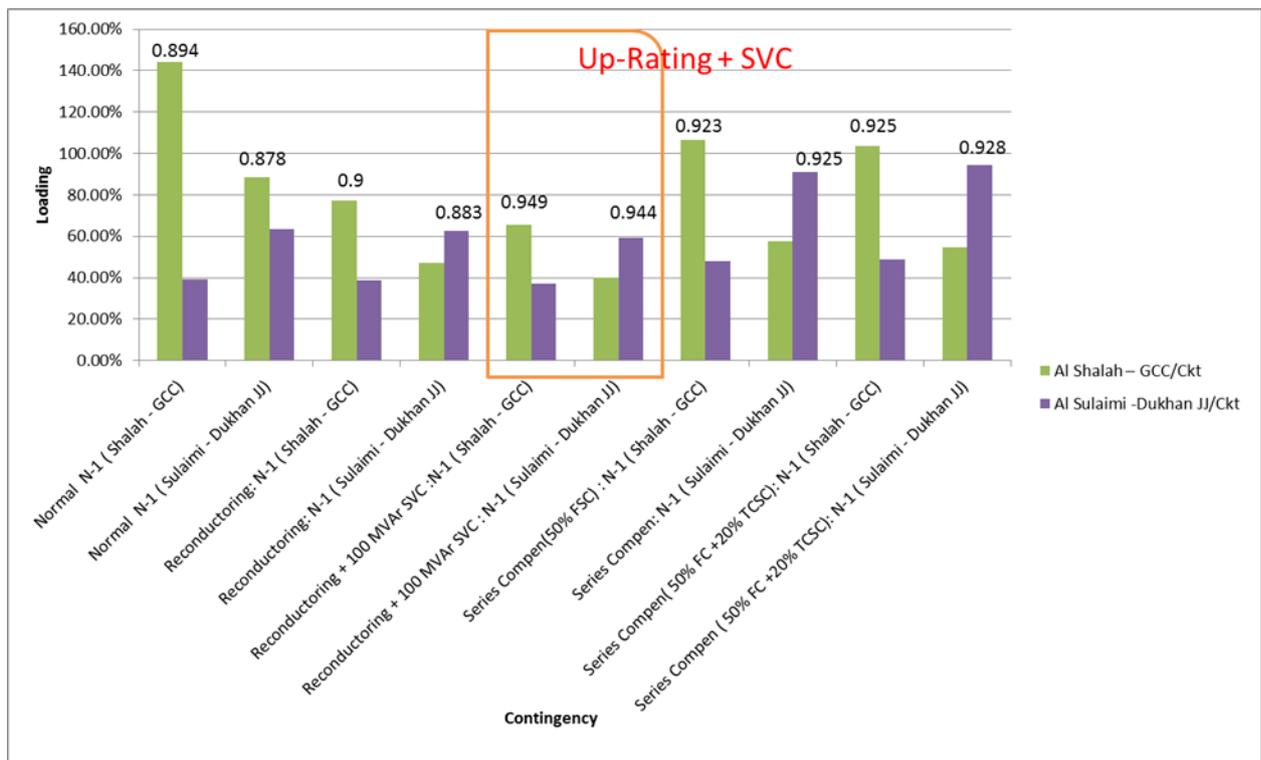
Figure 35: Line loadings and voltages with OHL up-rating plus SVC. Normal operation and contingency

Series compensation of the longest segment of the OHL is also studied to balance the power flow from the two sources, however, it is revealed that even with 70% of SC (50 % FSC + 20% TCSC) the overloading and low voltage problems are not fully resolved (Figures 36 and 37).
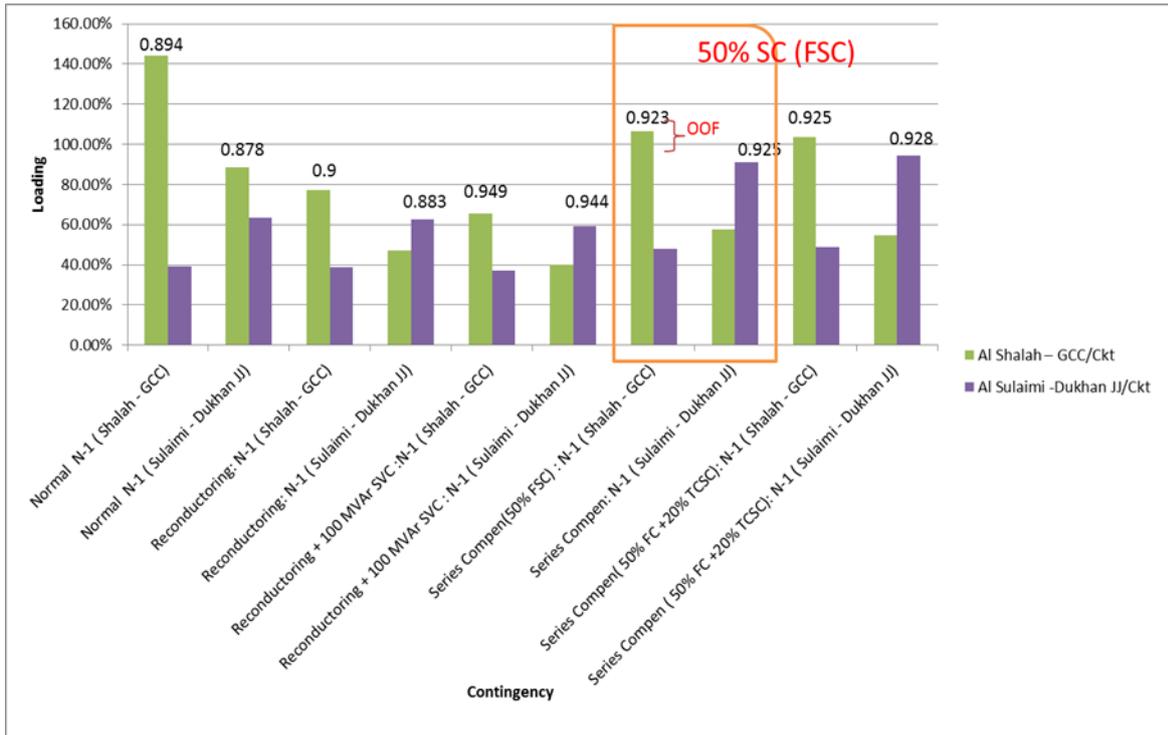
Figure 36: Line loadings and voltages with OHL up-rating plus FSC (50%)
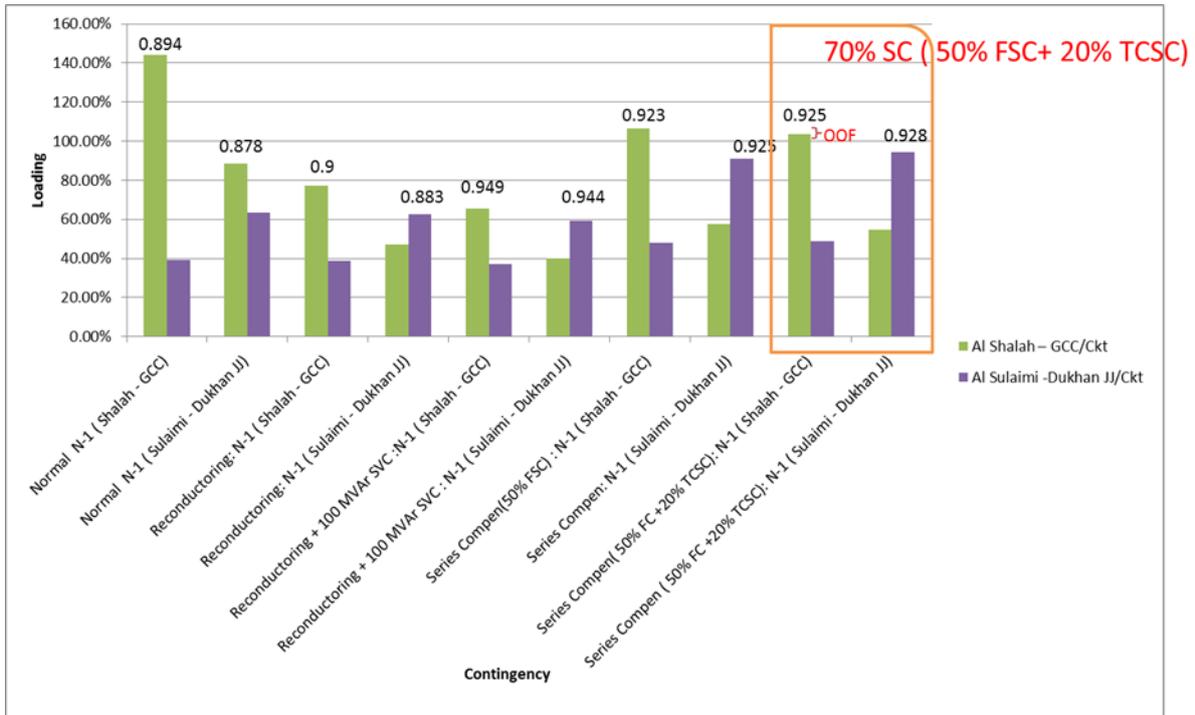
Figure 37: Line loadings and voltages with OHL capacity up-rating plus 70% SC (FSC 50%+TCSC 20%)

A GUPFC with a rating of 100 MW and 50 MVAr was tested in four locations to inspect the impact on power flows and voltages as shown in Figures 38-41. The network performance is improved considerably with the use of the GUPFC device with rating of 50 MW and 50 MVAr (Figure 42). This GUPFC rating is considered the optimum rating compared to the results achieved from the QV, PV analysis conducted using the PSS®E software. Further the installation location for the GUPFC is optimized using power flow simulations. It is found that the best location for the installation of GUPFC is at Dukhan which has improved both the network voltage profile and the line loading of Al-Shalah to Umm Bab line to within the limits under normal and contingency conditions. Also the power flow imbalance is improved and the load is shared well between the two 132 kV OHLs forming the ring (Figures 38-42).
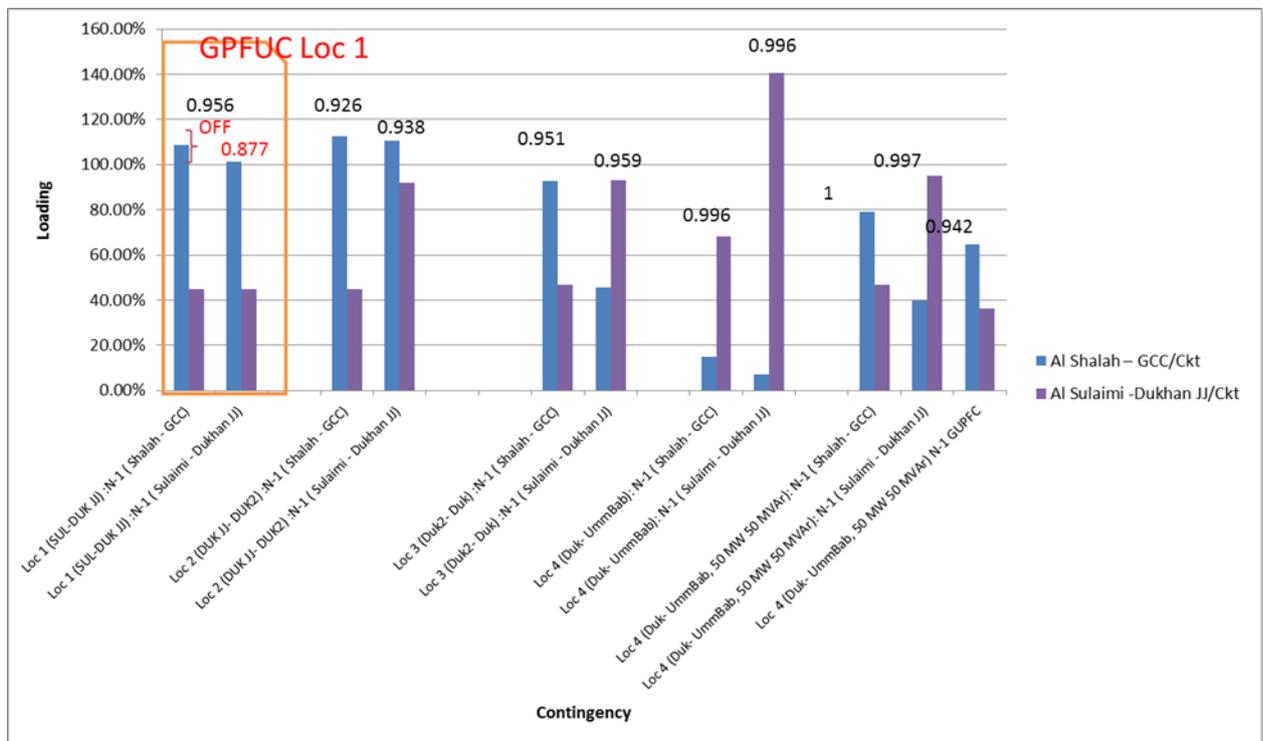
Figure 38: Line loadings and voltages with OHL up-rating plus GUPFC at location-1 (100 MW, 50 MVAr)
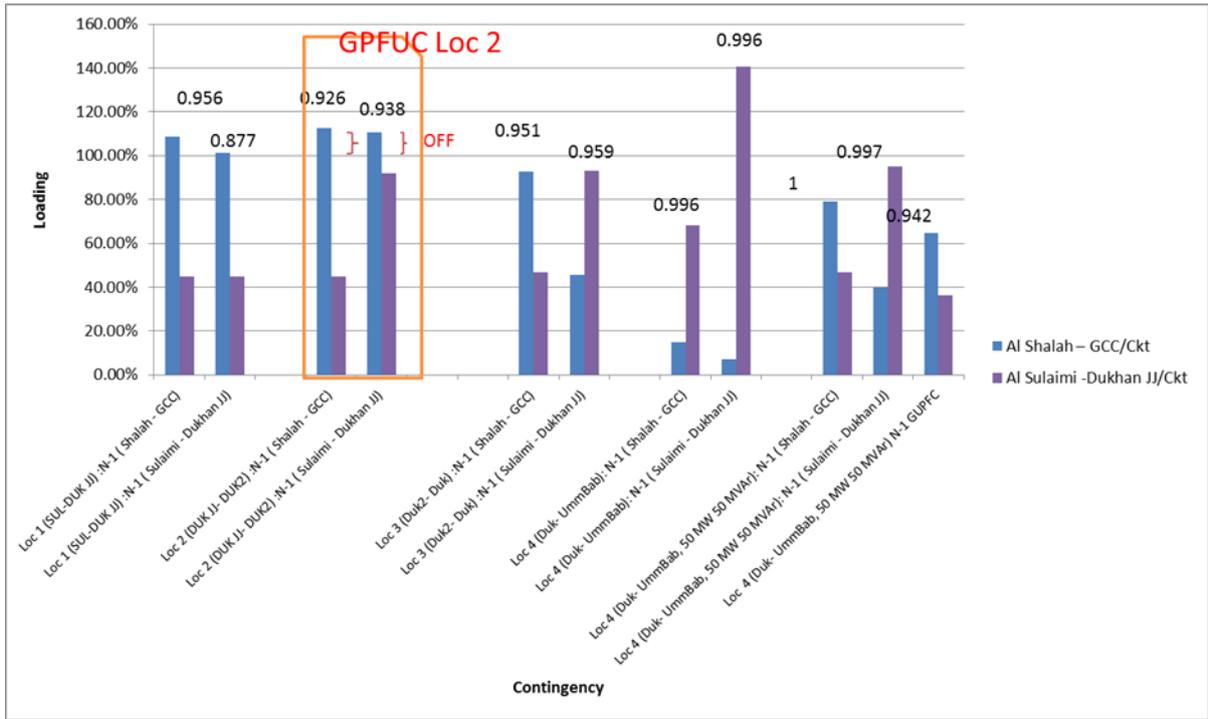
Figure 39: Line loadings and voltages with OHL up-rating plus GUPFC at location-2 (100 MW, 50 MVAr)
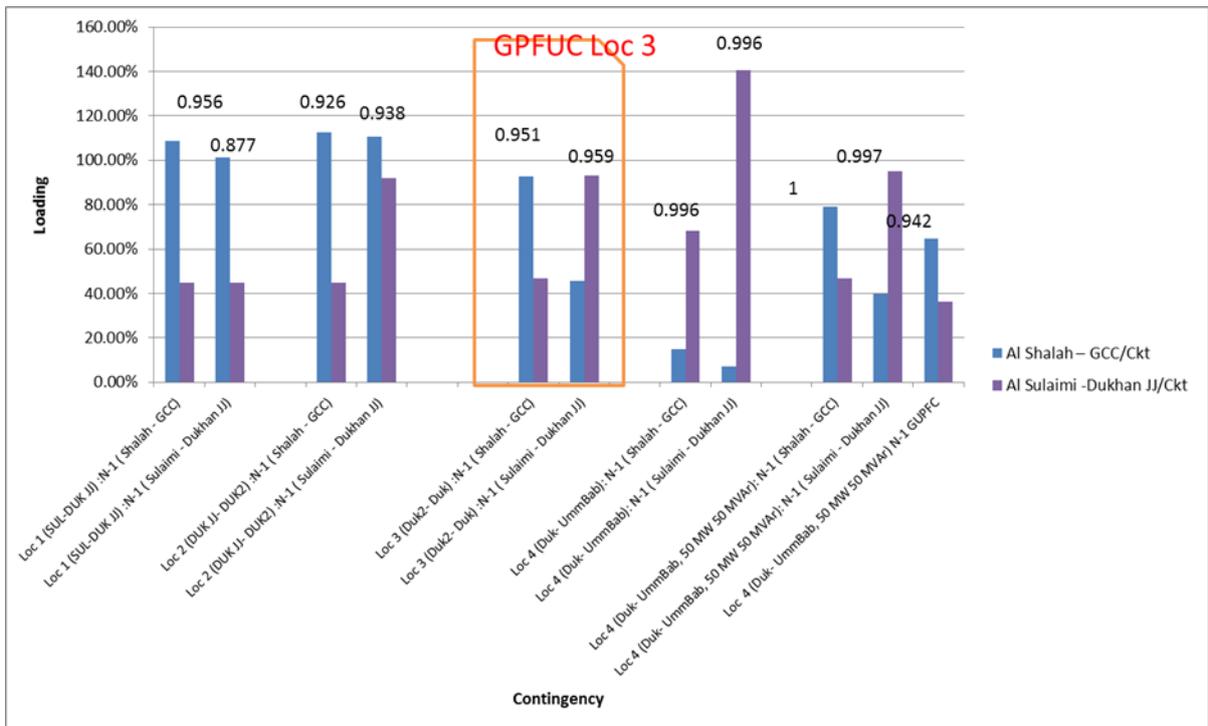
Figure 40: Line loadings and voltages with OHL up-rating plus GUPFC at location-3 (100 MW, 50 MVAr)
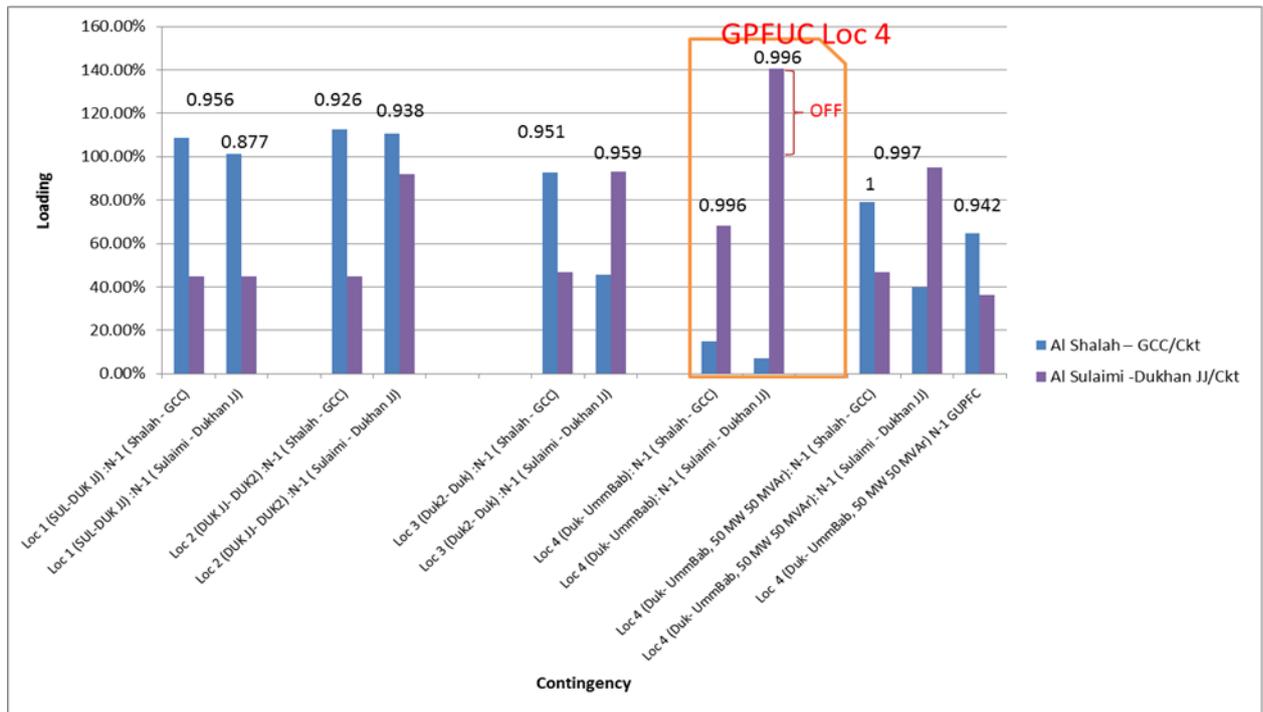
Figure 41: Line loadings and voltages with OHL up-rating plus GUPFC at location-4 (100 MW, 50 MVAr)

The selection of the 50 MW/50MVAr rating is found to be the optimal allocation for GUPFC from different combination of active and reactive power ratings. The applied research technique using Siemens PTI's PSS®E software simulation is unique to this dissertation (Figure 42). The PV and QV curves performed earlier in this chapter determine the optimal size of the GUPFC using more scientific calculation.

Figure 42 shows the results of this optimal allocation for GUPFC [2].
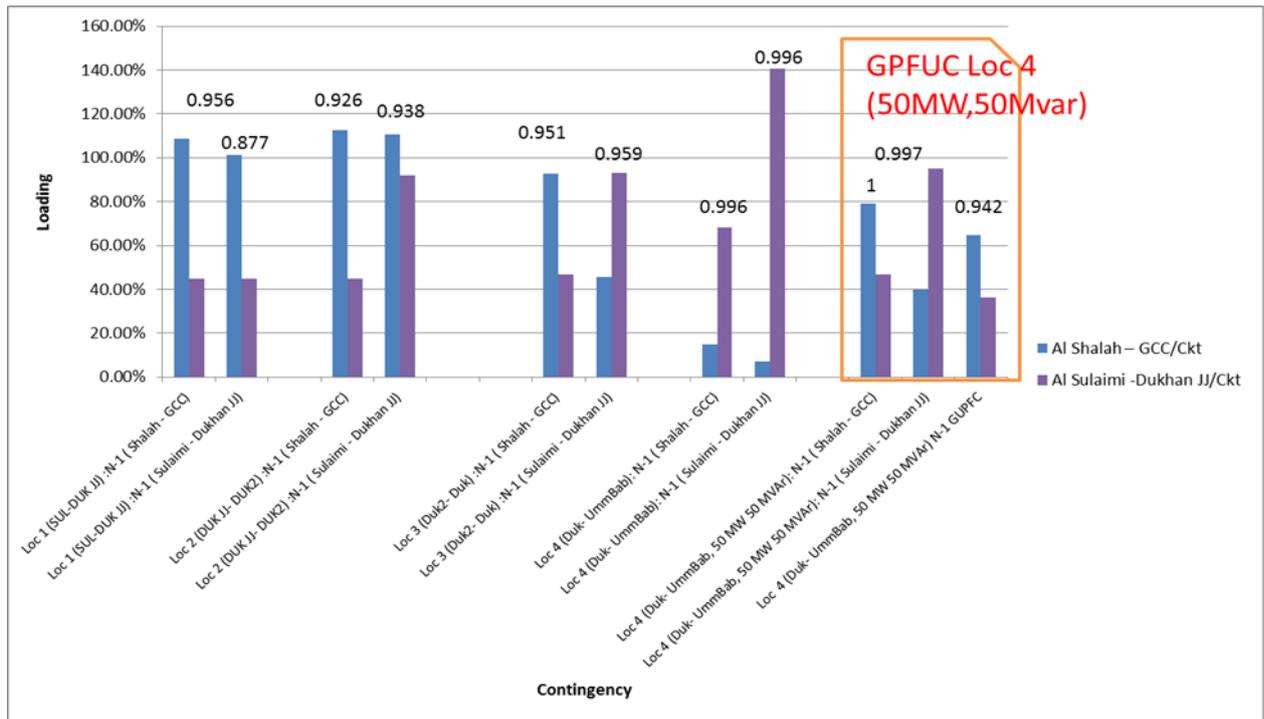
Figure 42: Line loading and voltages with OHL up-rating plus GUPFC at Location-4 (50 MW, 50 MVAr)

7.1.7 Concluding remarks

The two feasible options studied, i.e., reconductoring of the line with SVC and the use of GUPFC, need to be further complemented with dynamic and transient analysis to investigate their performance along with cost assessment. Also a business case report shall be prepared for this case study to provide a more techno-economic value to the results achieved. The report will assist QPTS with decision making with regard to investment in such new online power flow and voltage controls. This is a future work; however the dynamic model for the STATCOM is studied in the next section. Their recommendations and conclusions provide a solid argument for the rationalization of integration (in terms of benefit and potential). The studies suggest that GUPFC is a viable solution to alleviate the power flow constraints faced in the western region by increasing transfer from the north. The optimal allocation and selection of GUPFC ratings discussed in this case study chapter is a simulation technique using the PSS®E software [88]. The PV and QV analyses with voltage restriction and FACTS modelling appear to be rarely used in other applied research literature. The PV, QV explanation for this optimization may be well researched against the other known allocation theoretical techniques algorithms. The loading and voltage values are also shown in Tables I-VI.

Table I: Power flows results, OHLs reconductoring, 2015-2016 models [2]

Study Cases	Al Shalah – GCC/Ckt			Sulami -Dukhan JJ/Ckt		
	MW	MVAr	Loading	MW	MVAr	Loading
1.0 Normal (2016)	44.7	31.1	40.9%	66.1	4.8	26.5%
N-1 (Shalah - GCC)	87	61.2	80.0%	67.5	6.4	27.1%
N-1 (Sulami - Dukhan JJ)	57.4	33.2	49.9%	107.5	13.8	43.4%
2.0 Normal, 110 MW load increase	78.6	57.8	73.4%	89.7	30.6	37.9%
N-1 (Shalah - GCC)	153.5	115.2	144.3%	92.1	34.2	39.3%
N-1 (Sulami - Dukhan JJ)	96.6	67.2	88.5%	145.9	62.3	63.5%
3.0 Reconductoring)	79	57.9	39.2%	89.1	29.4	37.5%
N-1 (Shalah - GCC)	154.8	116	77.4%	91	31.9	38.6%
N-1 (Sulami - Dukhan JJ)	96.9	67	47.1%	144.6	59.9	62.6%
3.1 Reconductoring + SVC	76.7	31.8	33.2%	90.7	0.7	36.3%
N-1 (Shalah - GCC)	150.6	64.6	65.5%	92.6	2.4	37.1%
N-1 (Sulami - Dukhan JJ)	94.2	34.3	40.1%	147.8	11.6	59.3%

Table II: Power flows results- FSC and TCSC, 2015-2016 models [2]

Study Cases	Al Shalah – GCC/Ckt			Sulami -Dukhan JJ/Ckt		
	MW	MVAr	Loading	MW	MVAr	Loading
4.0 Series Compensation (50% FSC)	53.9	49.3	54.9%	112.8	30.8	46.8%
N-1 (Shalah - GCC)	104.2	96.1	106.6%	114.8	33.7	47.9%
N-1 (Sulami - Dukhan JJ)	57	50.9	57.5%	219.4	58.8	90.9%
4.1 Series Compensation, FC +TCSC	51.7	49	53.6%	115.5	30.9	47.8%
N-1 (Shalah - GCC)	99.9	95.2	103.8%	117.5	33.9	48.9%
N-1 (Sulami - Dukhan JJ)	52.7	50.2	54.7%	228	60.4	94.3%

Table III: Power flows results- GUPFC 2015-2016 models [2]

Study Cases	Al Shalah – GCC/Ckt			Al Sulami -Dukhan JJ/Ckt		
	MW	MVAr	Loading	MW	MVAr	Loading
5.0 GUPFC (100MW, 50 MVAr each)						
5.1 GUPFC Location 1 (Sul-Duk JJ)	66.7	25.4	53.7%	100	50	44.7%
N-1 (Shalah - GCC)	134	54.6	108.8%	100	50	44.7%
N-1 (Sulami - Dukhan JJ)	118.4	64.2	101.3%	100	50	44.7%
5.2 GUPFC Location 2 (Duk JJ-Duk2)	60.9	41.1	55.2%	111.2	17.6	45.0%
N-1 (Shalah - GCC)	122.3	85.9	112.4%	111.2	17.6	45.0%
N-1 (Sulami - Dukhan JJ)	121.8	82.2	110.5%	222.4	56.5	91.8%
5.3 GUPFC Location 3 (Duk2-Duk)	52.1	30.5	45.4%	116.4	-11.2	46.8%
N-1 (Shalah - GCC)	104.5	65.4	92.7%	116.4	-11.2	46.8%
N-1 (Sulami - Dukhan JJ)	52.1	31.6	45.8%	232.8	-5.9	93.1%
5.4 GUPFC Location 4 (Duk- Umm Bab)	2.8	9.2	7.2%	170	-10	68.1%
N-1 (Shalah - GCC)	5.8	18.8	14.8%	170	-10	68.1%
N-1 (Sulami - Dukhan JJ)	2.8	9.2	7.2%	351.4	17.3	140.7%
5.5 GUPFC Location 4 (Duk- Umm Bab, 50 MW 50 MVAr)	52.1	6.8	39.5%	116.3	-10.9	46.7%
N-1 (Shalah - GCC)	104.1	15	79.1%	116.3	-10.9	46.7%
N-1 (Sulami - Dukhan JJ)	52.2	6.8	39.6%	237.3	-5.1	94.9%
N-1 GUPFC	77.7	36.5	64.5%	90	-10	36.2%

Table IV: Busbar voltages, OHLs reconductoring, 2015-2016 models [2]

Study Cases	Shalah	GCC	Um Bab	Dukhan	Dukhan JJ	Sulami
1.0 Normal (2016)	0.995	0.988	0.964	0.971	0.985	1.001
N-1 (Shalah - GCC)	0.995	0.982	0.959	0.968	0.982	1.000
N-1 (Sulami - Dukhan JJ)	0.991	0.983	0.956	0.961	0.973	1.000
2.0 Normal (110 MW increased load)	0.966	0.954	0.904	0.912	0.938	0.984
N-1 (Shalah - GCC)	0.967	0.942	0.894	0.903	0.932	0.982
N-1 (Sulami - Dukhan JJ)	0.953	0.938	0.878	0.88	0.903	0.985
3.0 Reconductoring)	0.966	0.958	0.907	0.914	0.940	0.985
N-1 (Shalah - GCC)	0.966	0.950	0.900	0.909	0.936	0.983
N-1 (Sulami - Dukhan JJ)	0.953	0.944	0.883	0.884	0.907	0.986
3.1 Reconductoring + 100 MVAr SVC	0.988	0.983	0.953	0.975	0.986	0.999
N-1 (Shalah - GCC)	0.987	0.978	0.949	0.971	0.983	0.997
N-1 (Sulami - Dukhan JJ)	0.983	0.978	0.944	0.964	0.973	0.999

Table V: Busbar voltages- FSC and TCSC, 2015-2016 models [2]

Study Cases	Shalah	GCC	Um Bab	Dukhan	Dukhan JJ	Sulami
4.0 Series Compensation (50% FSC)	0.979	0.969	0.929	0.944	0.975	0.982
N-1 (Shalah - GCC)	0.98	0.961	0.923	0.939	0.973	0.979
N-1 (Sulami - Dukhan JJ)	0.976	0.966	0.925	0.938	0.969	0.982
4.1 Series Compensation (50% FC +20% TCSC)	0.979	0.969	0.930	0.945	0.977	0.982
N-1 (Shalah - GCC)	0.981	0.962	0.925	0.942	0.975	0.98
N-1 (Sulami - Dukhan JJ)	0.978	0.968	0.928	0.942	0.973	0.982

Table VI: Busbar voltages- GUPFC, 2015-2016 models [2]

Study Cases	Shalah	GCC	Um Bab	Dukhan	Dukhan JJ	Sulami
5.0 GUPFC (100MW, 50 MVAr)						
5.1 GUPFC Location -1 (Sul-Duk JJ)	0.995	0.989	0.966	0.993	1.033	1.000
N-1 (Shalah - GCC)	0.994	0.98	0.956	0.983	1.023	1.000
N-1 (Sulami - Dukhan JJ)	0.952	0.937	0.877	0.88	0.905	1.000
5.2 GUPFC Location 2 (DUK JJ-DUK2)	0.982	0.973	0.939	0.957	1.000	1.003
N-1 (Shalah - GCC)	0.98	0.962	0.926	0.945	1.000	1.003
N-1 (Sulami - Dukhan JJ)	0.982	0.973	0.938	0.957	1.000	1.000
5.3 GUPFC Location 3 (Duk2-Duk)	0.992	0.985	0.960	0.984	1.003	1.003
N-1 (Shalah - GCC)	0.991	0.977	0.951	0.976	1.003	1.003
N-1 (Sulami - Dukhan JJ)	0.992	0.985	0.959	0.984	0.998	0.998
5.4 GUPFC Location 4 (Duk-Umm Bab)	1.018	1.017	1.016	1.000	0.996	0.997
N-1 (Shalah - GCC)	1.018	1.015	1.014	1.000	0.996	0.997
N-1 (Sulami - Dukhan JJ)	1.018	1.016	1.015	1.000	0.984	0.985
5.5 GUPFC Location 4 (Duk-Umm Bab, 50 MW 50 MVAr)	1.015	1.012	1.005	1.000	1.003	1.004
N-1 (Shalah - GCC)	1.014	1.008	1.001	1.000	1.003	1.004
N-1 (Sulami - Dukhan JJ)	1.014	1.011	1.004	1.000	0.997	0.998
N-1 GUPFC	0.983	0.975	0.942	1.000	1.005	1.005

7.2 Case Study Two-Steady State and Dynamic Analysis of FACTS on QPTS

7.2.1 Introduction

In the previous chapter only the steady state operation of FACTS in QPTS including the SVC model at Dukhan substation is considered. One of the challenges that face transmission planners and operators is the steady state and dynamic control of voltage and power flow. Reference [1] presents the results of a case study conducted to investigate the performance of fixed capacitors and a STATCOM, in controlling the bus voltages of QPTS, during a fault. The key comparison is with a STATCOM versus capacitors, not a STATCOM versus no compensation at all. So the fixed capacitor option is included in the analysis to make it a realistic comparison, expecting the performance can be corrected to an extent with this option.

This case study outlines the analysis conducted to inspect the viability of fixed capacitors and STATCOM in steady state voltage maintenance, as well as in dynamic voltage recovery following the application of various faults to the system [1]. The SVC and the STATCOM perform the same basic function of maintaining the bus voltage by controlling the reactive power at the bus. Therefore the steady state results from STATCOM analysis in this chapter could be compared with the steady state analysis for the SVC conducted in the previous chapter.

The PSS®E software is used to model and analyse QPTS in both steady state and dynamic system studies [88]. The system voltage profile and power flow are basically influenced by the physical characteristics of the transmission system. The transmission grid can work smarter if the network physical constraints are countered through the use of smart devices to control voltage and power flows.

The system bus voltages are also dependent on whether the reactive power compensation can be injected or drawn locally at the buses or imported from a distance source. As a result of this relationship, inadequate reactive power in a part of the system could result to voltage depression of the system's bus voltages. FACTS can be utilized in the transmission system to assist in improving the voltage profile for such systems.

7.2.2 Power flow imbalance and low voltage

Figure 43 shows the power flow and bus voltage results in normal condition for system load conditions beyond the year 2015 without any reinforcements.
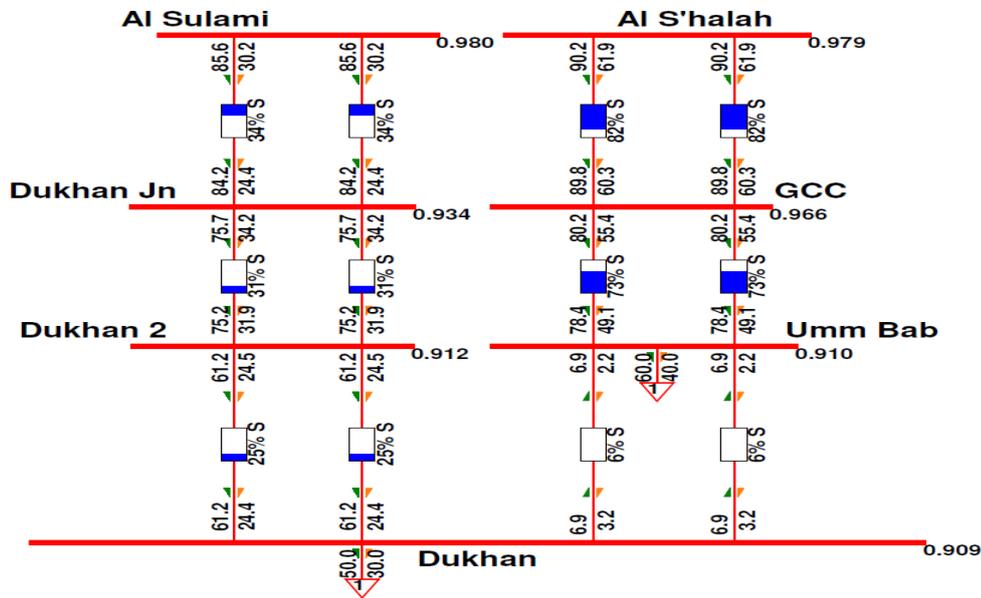
Figure 43: Normal case without fixed capacitor, STATCOM and without reconductored lines
(PSS®E QPTS Model – Beyond 2015)

As shown in Figure 43, each of the circuits of Al S'halah-GCC 132 kV OHL is loaded at 82% of its rating in normal condition. The loss of any one of the circuits will result to a thermal overload of the other circuit [2], [3]. This will result to a violation of N-1 criteria. Furthermore, Figure 43 shows that some of the bus voltages are below 0.95 pu, which is a violation of the voltage criteria in normal conditions [10].

7.2.3 Smart power grid in Qatar: Application of STATCOM and composite conductors

The widespread perception in the industry is that smart grid is mostly about the deployment of smart meters and smart LV applications. A significant part of a smart grid entails the application of modern technologies in power transmission operation and control. In fact, the conventional transmission grid can be converted into a smart grid with the application of FACTS devices. The trait of smart grid is the creation of operating conditions flexible enough to enable system operators to control the flow of both active and reactive power flows, and hence the magnitudes of voltage and phase angles, instead of the experiencing undesired

power flow loops controlled by the network resistances and reactive impedances [1]. The evolving smart grids are assumed to continue in their development and capacity, likely replacing many aspects of existing networks in the future. FACTS devices can serve to provide a solution to networks that is further conducive to the implementation of wide area control [22]. Additionally, other technology which can facilitate the implementation of these smart grids includes energy storage devices capable of assisting in the transmission and distribution of generated power. There are also smart technologies useful in implementing renewable energy to power systems, the use of phasor measurement units communicating synchrophasors data for large scale control and monitoring, and technology facilitating improved online analyses of grid control and transmission coordination.

7.2.4 Upgrading the overhead lines using composite conductors

Upgrading of the existing OHL from 133 MVA to 265 MVA by reconductoring of the 132 kV lines from Al S'halah –GCC –Umm Bab – Dukhan was discussed in the reconductoring section of the 132 kV lines [2]. Therefore this study assumes that the mentioned OHLs have the new rating of 265 MVA in 2015-2017. This is an ideal planning approach considering the challenges of getting new rights of ways for new overhead lines. It is worth-mentioning that, although the OHL upgrade has solved the thermal overload issue, it did not solve the low voltage issue [1], [2]. This study will show how voltages can be depressed at Dukhan and Umm Bab areas under certain loading conditions and how the installation of a STATCOM device can improve the voltage profile for these regions.

7.2.5 Capacitor for steady-state voltage control

One of the most feasible options to address the power flow imbalance and low voltage problems mentioned in the previous section is the installation of a 100 MVA fixed capacitors or STATCOM device at Dukhan 132 kV bus together with the reconductoring of the mentioned lines [2]. The basic case is to assess the impact of 100 MVAr capacitors in both the steady state and dynamic states and then compare the results with the STATCOM performance. Figure 44 shows the voltage profile and thermal loadings of the lines in normal condition, following the capacitor installation. From the figure, it is evident that the bus voltages are within the allowable voltage range of ±5% and that each of the circuits at Al S'halah-GCC is loaded at less than half of its thermal rating. A loss of any one of the circuits

will not result to a thermal violation of the other circuit, thereby maintaining the N-1 criteria [2], [3].
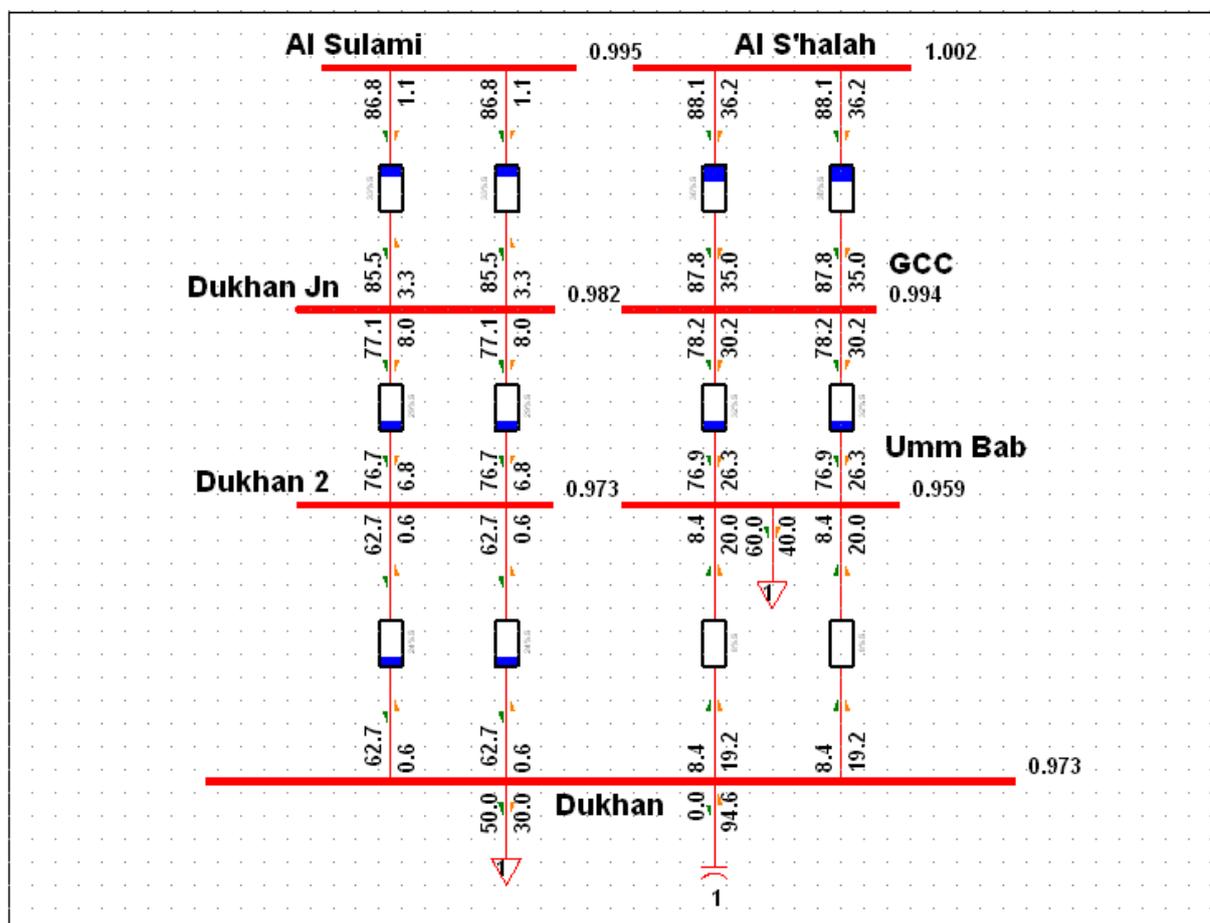
Figure 44: **Normal case with capacitors and reconductored lines (PSS®E QPTS Model – beyond 2015)**

7.2.6 STATCOM for steady-state voltage control

The next option is to assess the power flow imbalance and low voltage problems when a 100 MVA STATCOM device is installed at Dukhan 132 kV bus together with the reconductoring [2]. Figure 45 shows the voltage profile and thermal loadings of the lines in normal condition, following the installation of the 100 MVA STATCOM device and the reconductoring of the mentioned lines. From the figure, the shown bus voltages are within the allowable voltage range of ±5% [23]. Similar to the capacitor banks response, each of the circuits at Al S'halah-GCC is loaded at less than half of its thermal rating, maintaining the N-1 criteria [2], [3].
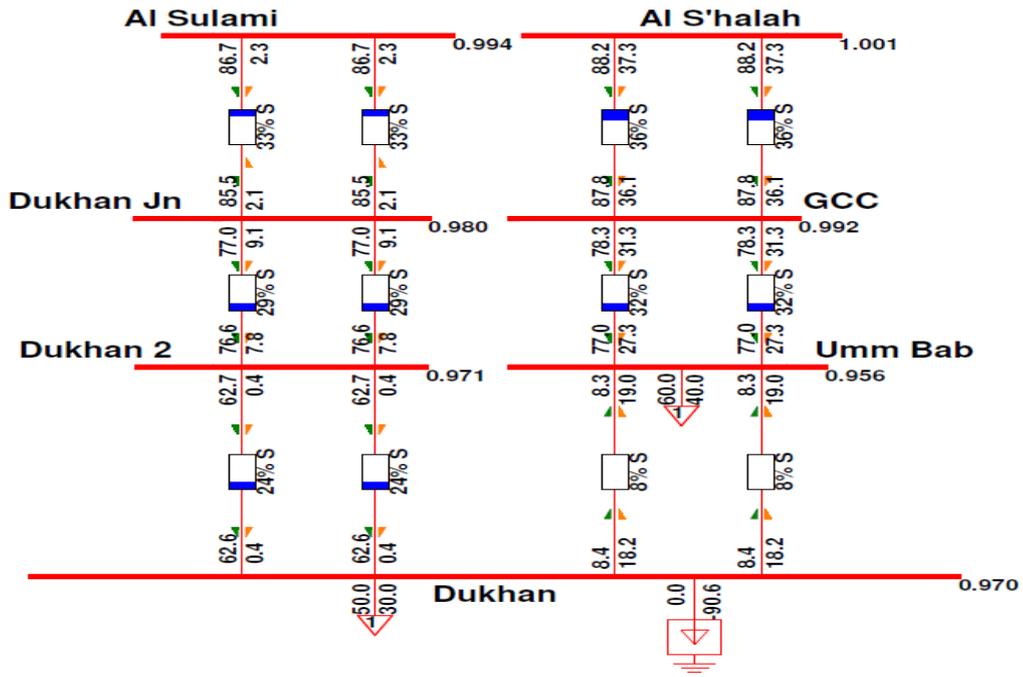
Figure 45: Normal case with STATCOM and reconductored lines (PSS®E QPTS Model – beyond 2015)

From the above analysis, the performance of capacitor banks and the STATCOM; is almost the same in steady state condition. This is an obvious result, because the STATCOM injects a pure reactive power at the bus to boost the voltage similar to the capacitor bank function. The following discussion is related to the dynamic response of both devices at the time of a fault close to the busbar connecting them [1].

7.2.7 STATCOM for dynamic voltage control

As mentioned in the case study-1, in steady state and power flow analyses, the installation of a 100 MVA SVC device at Dukhan 132 kV combined with the upgrade of the 132 kV lines were found to be the most feasible solution to the expected operational problems at Dukhan and Umm Bab areas. However, a STATCOM is capable of providing dynamic reactive power support, which is a key for justifying its cost. This section will explore the dynamic response of the system with the STATCOM present. The standard Siemens PTI's PSS®E FACTS Device Static Condenser, CSTCNT model, was used to model the 100 MVA STATCOM in the PSS®E for dynamic simulation. In order to look at the impact of the STATCOM device on the dynamic voltage recovery of the network following disturbances, two cases were compared, one with the STATCOM modelled and the other without the STATCOM modelled. Figure 46 shows the STATCOM control diagram taken from the Siemens's PSS®E documentation [88].
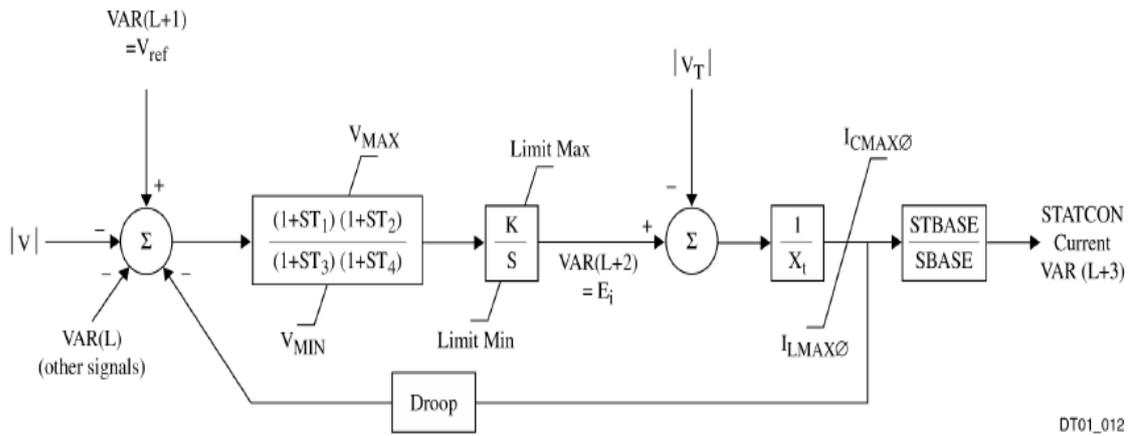
Figure 46: Siemens PTI's PSS®E STATCOM closed loop control model [88]

The integration step size used for the dynamic simulation was ½ of a cycle (0.01 seconds for a 50 Hz system). Before any of the disturbances were simulated, the dynamic simulation was run without any disturbances to confirm that the system was in steady state in initial condition. Figure 47 shows the machine rotor angles of QPTS unit at Ras Laffan power plant in steady state condition without re-enforcements, with a fixed capacitor at Dukhan 132 kV bus, and with a STATCOM at Dukhan 132 kV bus. Figure 48 shows the voltage profile of the system at Dukhan and Umm Bab 132 kV bus in steady state condition without re-enforcements, with a fixed capacitor at Dukhan 132 kV bus, and with a STATCOM at Dukhan 132 kV bus [1], [10].
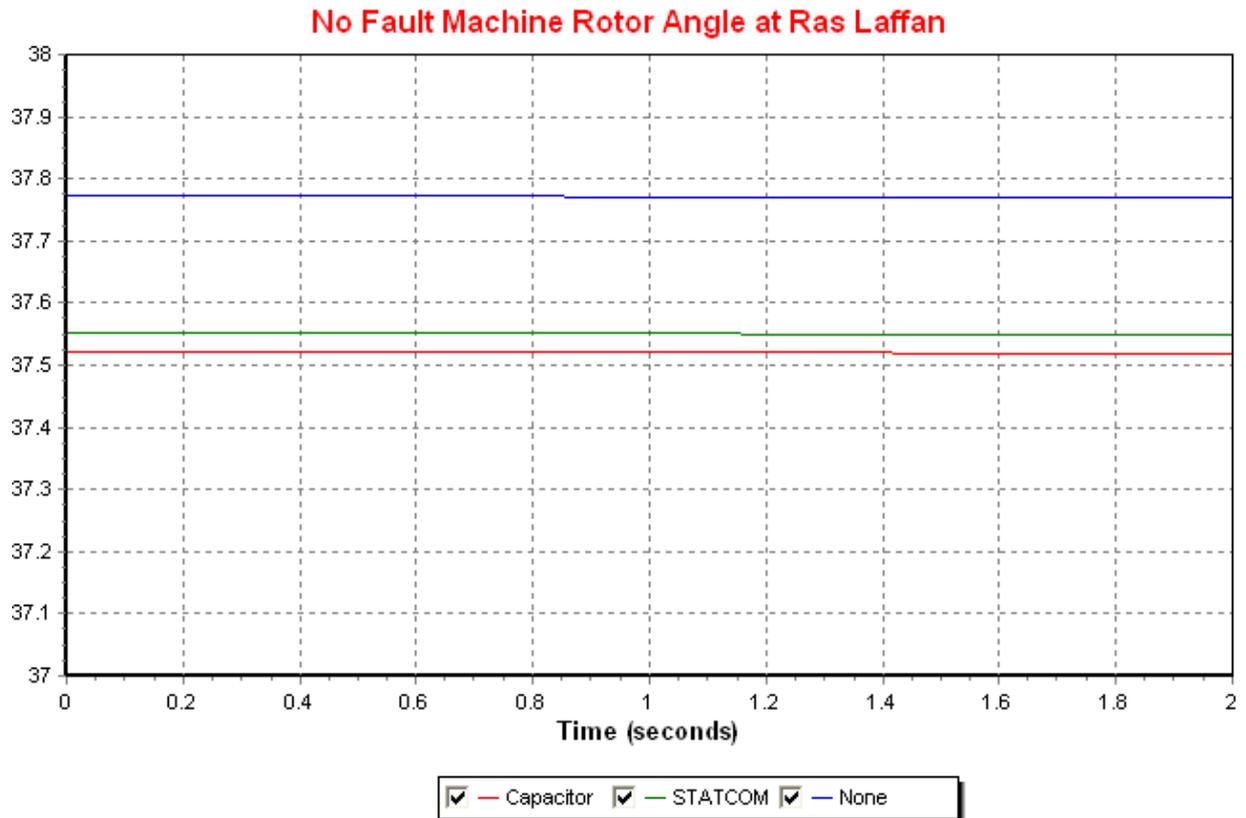
Figure 47: Machine rotor angle (degrees), with STATCOM, and with capacitor in steady state condition
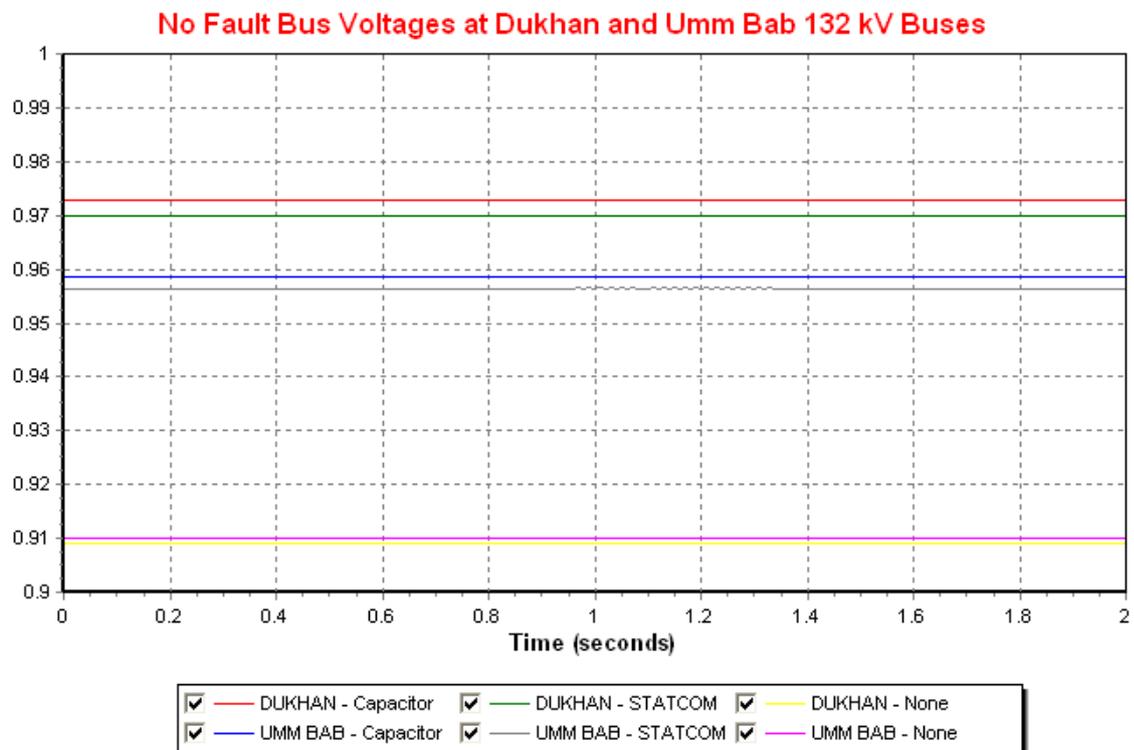
Figure 48: Bus voltages (pu), with STATCOM, and with fixed capacitor in steady state condition

The results shown in Figures 47 and 48 confirm that there are no oscillations in steady state conditions. Figure 48 shows that the bus voltages at Dukhan and Umm Bab 132 kV are within the allowable voltage range of ±5% in steady state when a STATCOM or a fixed capacitor is installed at Dukhan 132 kV bus, while outside the range when there are no re-enforcements [10]. This verifies the results of the previous case study-1. After confirming that the system is working fine in steady state condition without any disturbances, three contingencies were simulated to show the response of the system to disturbances and to compare the performance of the modelled 100 MVA STATCOM device at Dukhan 132 kV bus to that of the 100 MVAr fixed capacitor modelled at Dukhan 132 kV bus and to that of the case without any re-enforcement. These dynamic simulations were performed with a 0.1 second steady state period followed by the application of the appropriate disturbance. The contingencies simulated are:

1. Three phase fault at Dukhan 132 kV bus (Contingency-1), cleared in 9 cycles (0.18 seconds).
2. Three phase fault at Al Sulami 132 kV bus at one of the 132 kV line end of Al Sulami – Dukhan Jn. (Contingency-2), cleared in 9 cycles by disconnecting one of the circuits between Al Sulami – Dukhan Jn 132 kV.
3. Three phase fault at Al S'halah 132 kV bus at one of the line ends of Al S'halah – GCC 132 kV line (Contingency-3), cleared in 9 cycles by disconnecting one of the 132 kV circuits between Al S'halah – GCC.

Contingency-1 was simulated because the STATCOM device is modelled at Dukhan 132 kV bus, as such, this fault will have the most impact on the performance of the STATCOM. Contingencies-2 and 3 were simulated because the mentioned circuits are main sources of supply from Al Sulami and Al S'halah substations. They were simulated before in the power flow and steady state analyses of the SVC device in the preceding case study [2]. The STATCOM vendors would design the controls to shutdown the STATCOM for self-protection for a close-in fault. Any order for a STATCOM would need to specify the ability to stay on line for a close in three phase fault [16].

Figure 49 shows the rotor angle of QPTS unit at Ras Laffan power plant without re-enforcement, with a fixed capacitor at Dukhan 132 kV bus, and with a STATCOM at Dukhan 132 kV bus following contingency-1. There is significant acceleration during the fault but the machines stay in synchronism and the oscillation is damped out after a few seconds. The

system is stable without any re-enforcement, with a fixed capacitor, and with a STATCOM modelled.
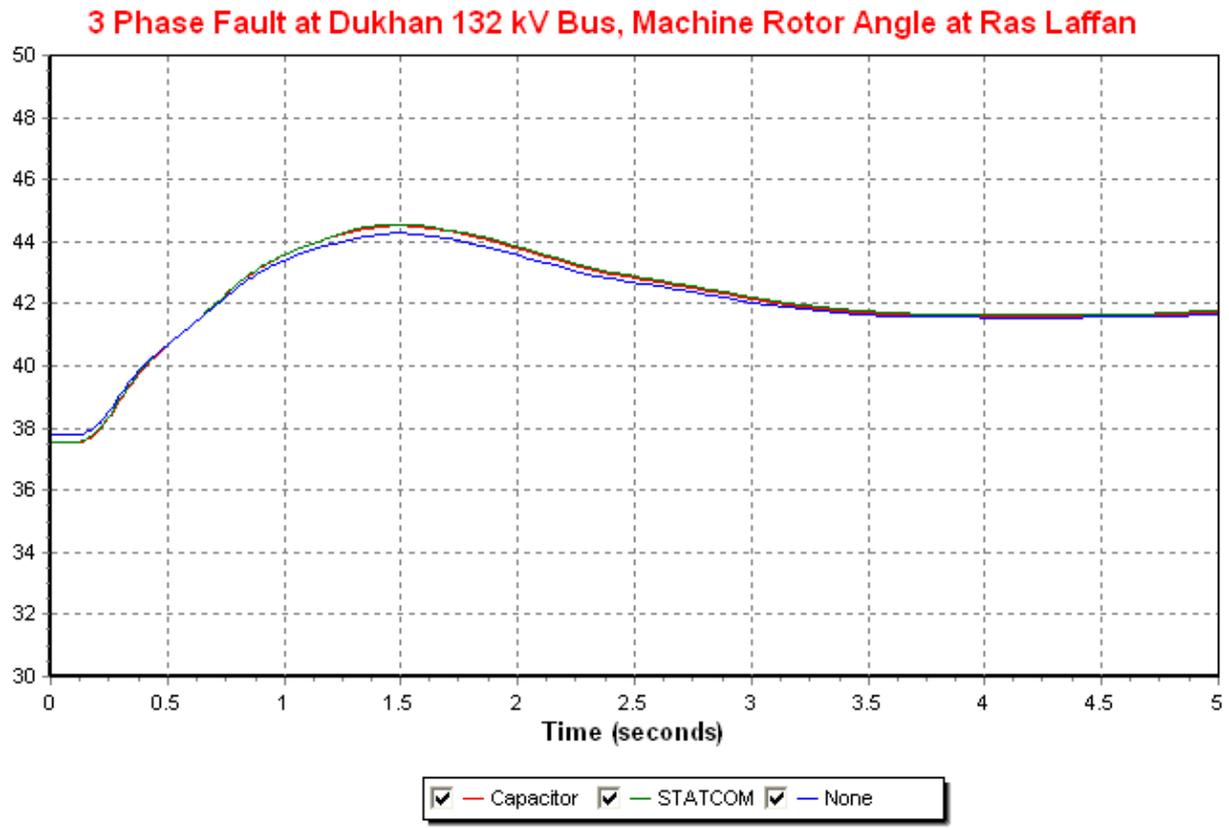
Figure 49: Machine rotor angle (degrees) at Ras Laffan following contingency-1

Figure 50 shows the results of the voltage profile at Dukhan 132 kV bus, following contingency-1 including the three scenarios; without any re-enforcement, with the fixed capacitor modelled at Dukhan 132 kV bus, and with the STATCOM modelled at Dukhan 132 kV bus. The result shows that the bus voltage at Dukhan 132 kV recovers quickest to 0.9 pu voltage with the STATCOM modelled. After the fault was cleared at 0.28 seconds, the bus voltage at Dukhan 132 kV with the STATCOM modelled recovered to 0.9 pu at 0.4 seconds, with a recovery time of 0.12 seconds. With the fixed capacitor modelled, the bus voltage at Dukhan 132 kV recovered to 0.9 pu voltage at 0.415 seconds, a recovery time of 0.135 seconds which is ¾ of a cycle longer than that of the STATCOM. Without any re-enforcement, the voltage at Dukhan 132 kV recovered to 0.9 pu voltage at 0.5 seconds, a recovery time of 0.22 seconds, which is five cycles longer than that with the STATCOM modelled.

Furthermore, the steady state bus voltage at Dukhan 132 kV with the STATCOM modelled is above 0.95 pu while that without any re-enforcement is below 0.95 pu, a violation of steady state operation [10]. As such, the STATCOM has improved the voltage performance

of the sub-transmission system. However, the performance of the STATCOM is slightly better than that of the fixed capacitor. The steady state problem can be solved for far less cost without a STATCOM, using a capacitor bank, however the main issue remains within the dynamic voltage support during faults which is addressed in this case study [1], [16].

Figure 50: Voltage profile of Dukhan 132 kV bus following contingency-1

Similar to Figure 49, Figure 51 shows the rotor angles of QPTS unit at Ras Laffan power plant without any re-enforcement, with a fixed capacitor modelled at Dukhan 132 kV bus, and with a STATCOM modelled at Dukhan 132 kV bus following contingency-2. As in Figure 51, there is significant acceleration during the fault but the machines stay in synchronism and the oscillation is damped out after a few seconds. The system is stable without any re-enforcement, with a fixed capacitor and with a STATCOM modelled.
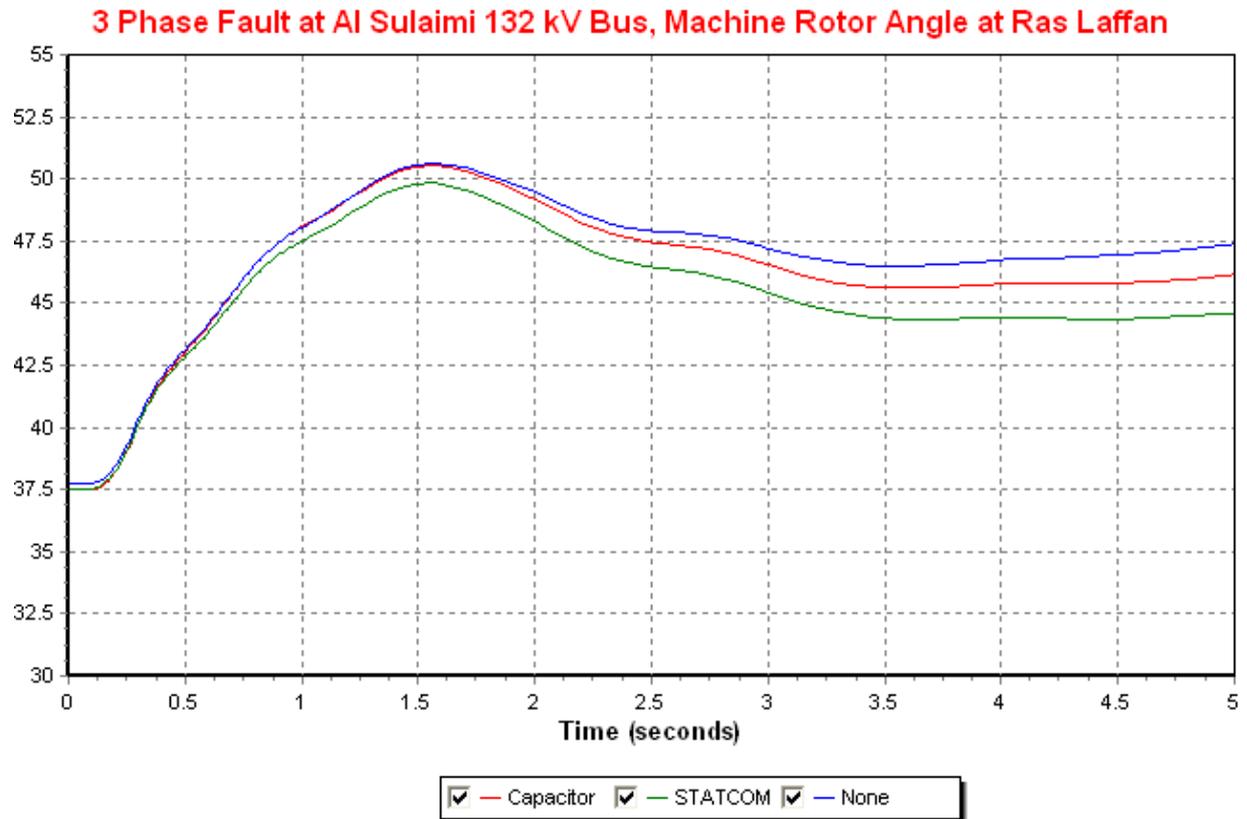
Figure 51: Machine rotor angle (degrees) at Ras Laffan following contingency-2

Figure 52 shows the voltage performance of Al Sulami 132 kV bus without any re-enforcement, with a fixed capacitor modelled, and with a STATCOM modelled following contingency-2. Similar to contingency-1, the voltage profile and recovery after the fault is cleared, with the STATCOM modelled is almost identical to that with the fixed capacitor. The voltage profile and recovery after the fault is cleared with the STATCOM modelled is better than that without any re-enforcement. The impact of the STATCOM on the voltage profile is less in contingency-2 than in contingency-1 because the fault location in contingency-2 is electrically farther from the STATCOM than that in contingency-1.
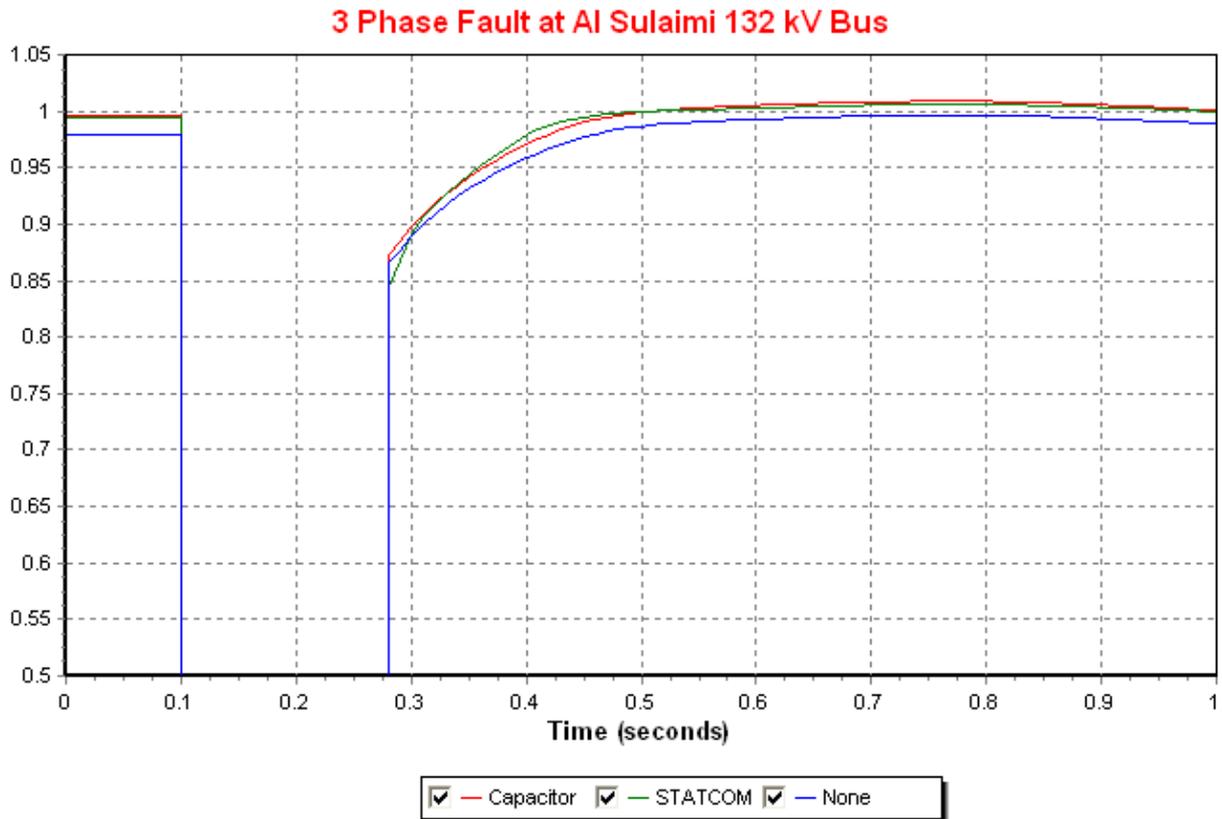
Figure 52: Voltage profile of Al Sulami 132 kV bus following contingency-2

Figure 53 shows the rotor angles of QPTS unit at Ras Laffan power plant without any re-enforcement, with fixed capacitor modelled at Dukhan 132 kV bus, and with the STATCOM modelled at Dukhan 132 kV bus following contingency-3. As in Figure 51, there is a significant acceleration during the fault but the machine stay in synchronism and the oscillation is damped out after a few seconds. The system is stable without any re-enforcements, with fixed capacitor modelled, and with the STATCOM modelled.
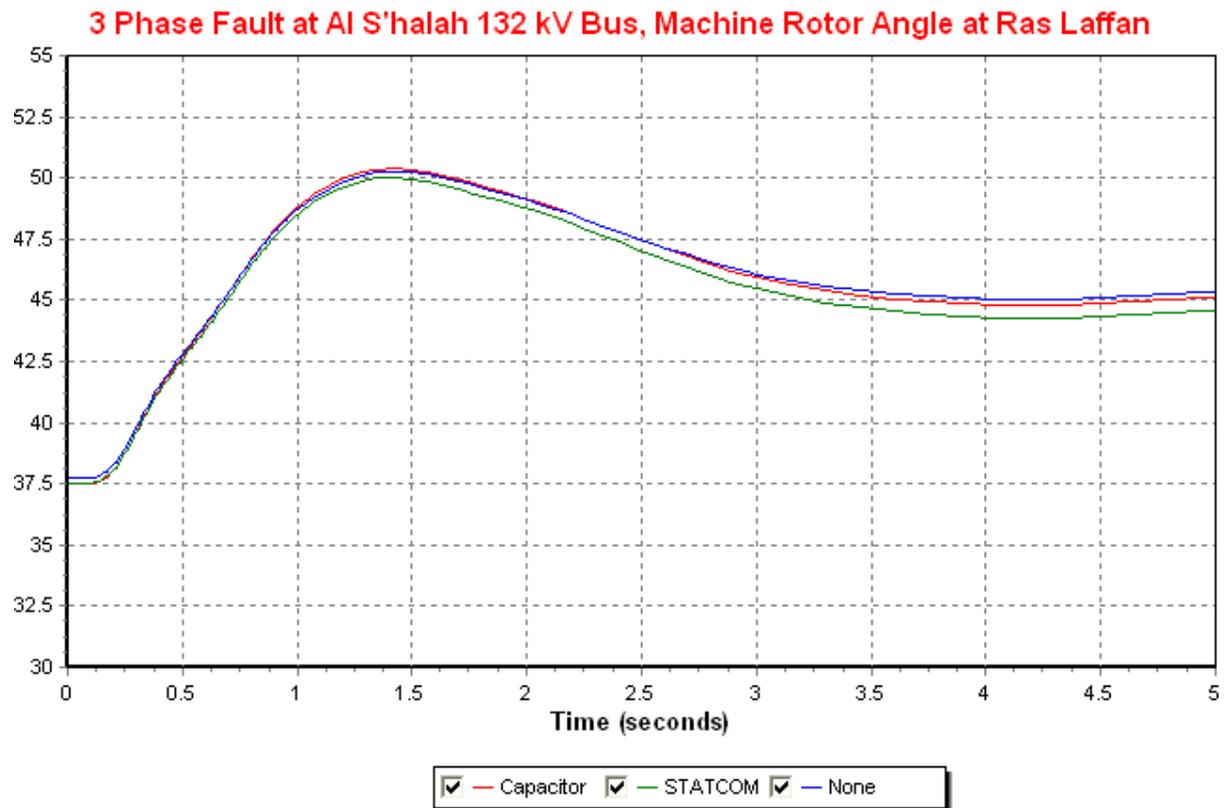
Figure 53: Machine rotor angle (degrees) at Ras Laffan following contingency-3

Figure 54 shows the voltage performance of Al S'halah 132 kV bus without any re-enforcement, with fixed capacitor, and with STATCOM modelled following contingency-3. As in contingency-2, the STATCOM helped to improve the voltage profile and recovery time following the disturbance [1]. The STATCOM and the capacitor performances are almost identical.

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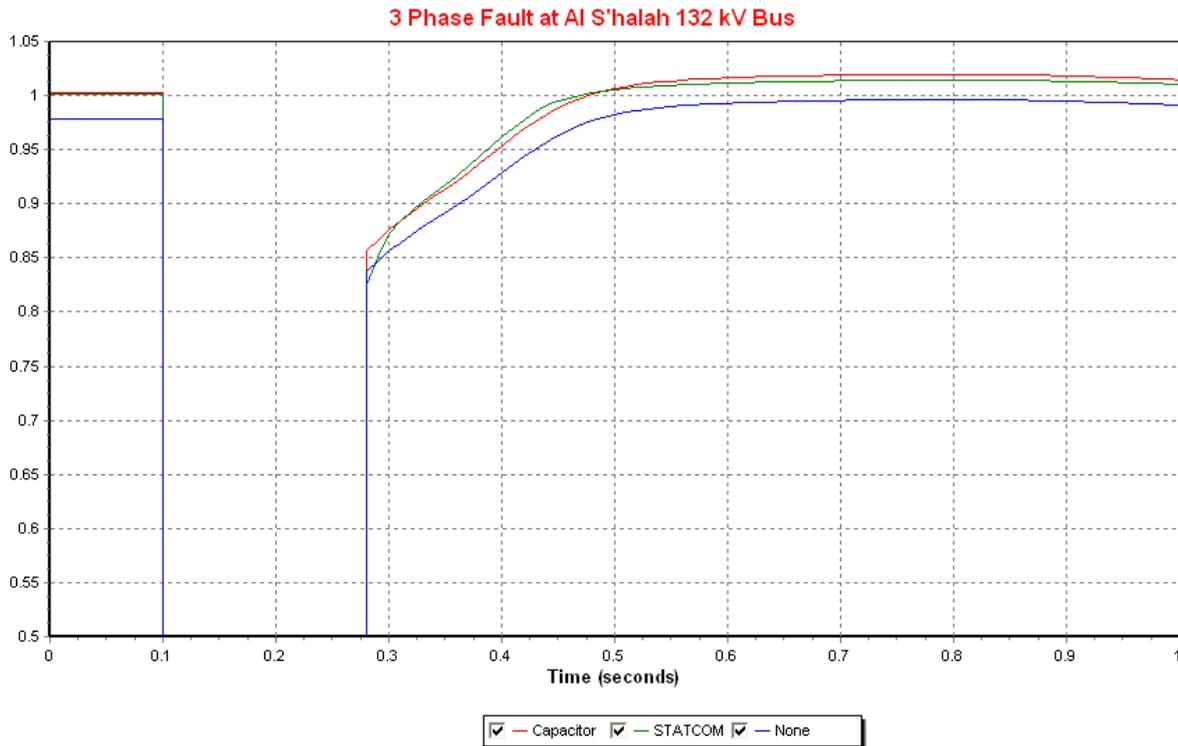
Figure 54: Voltage pu profile of Al S'halah 132 kV bus following contingency-3

It is important also to look at the current and reactive power output of the STATCOM to make sure the simulated STATCOM is performing realistically. The current output can only exceed 110% for a short time (a few cycles) unless the specified in the purchase contract. Performing a case with fixed capacitors ought to have similar results, but it would address likely objections to the STATCOM [16].

Therefore STATCOM current is also measured during the course of the three contingencies as shown in Figure 55. The STATCOM current profile looks different compared to the voltage profile. In contingency-1, for a fault at Dukhan bus where the STATCOM is connected, the current dropped when the fault occurred from about 1 pu to zero. When the fault cleared the current reversed it direction to the value of -1.25 pu and then returned to about 1.2 pu and stayed at value for about 20 ms (1 cycle). They continued on the stable value of about 0.9 pu. In case of the other contingencies (2 and 3, fault at Al Sulami and Al S'halah), the STATCOM current increased indicating that the STATCOM is feeding the remote fault or perhaps the load in that remote area. When the fault cleared the STATCOM current for these two contingencies followed the same pattern as for contingency-1 described above.

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The reactive power generated by the STATCOM is anticipated to follow the same voltage pattern, since 'Q' is proportional to the 'V' [4], [16]. The reactive power for the STATCOM could also be measured by the PSS®E.
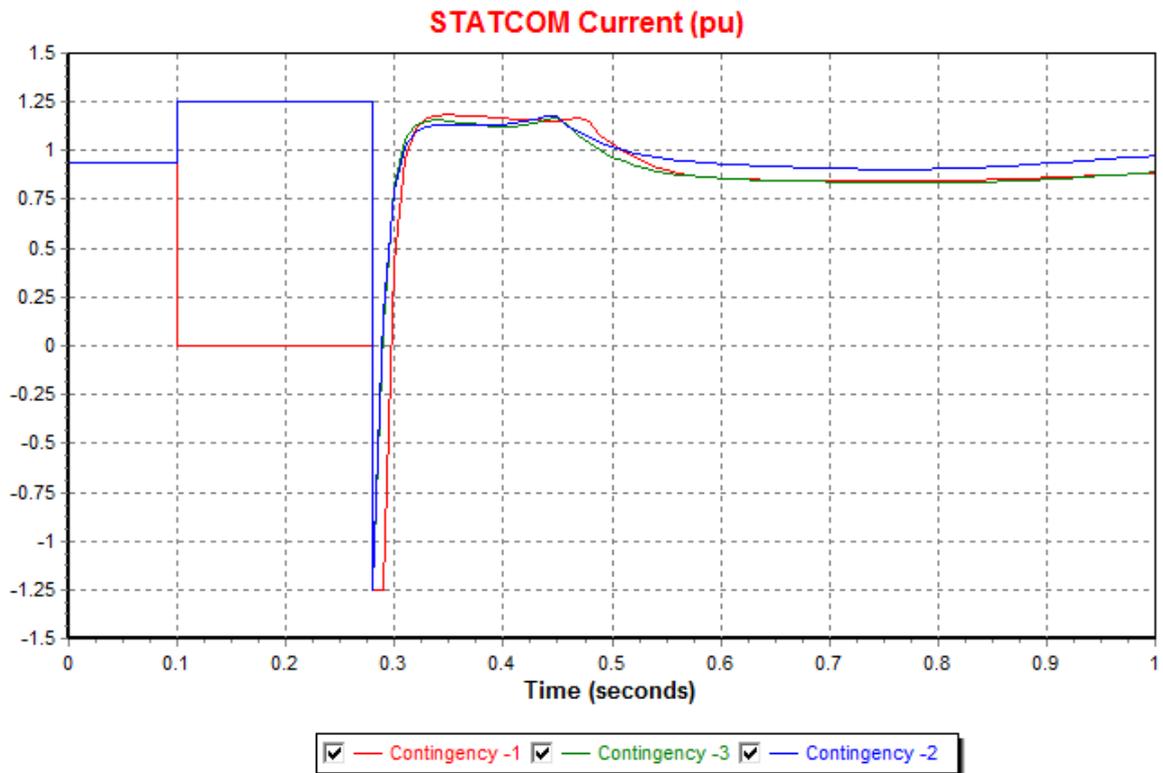
Figure 55: STATCOM current pu profile for the three contingencies

7.2.8 Green benefits of using composite conductors and STATCOM

According to the CTC Global Newsletter [11], the world consumes over 20 trillion kWh of electricity annually, and more than 1.2 trillion kWh are lost to transmission losses. The ACCC conductor is one of the smart technologies used to reduce line losses, thereby reduce electricity costs and decrease emissions [11]. It appears that, Kahramaa is the first utility in the Middle East to use this type of conductors by replacing the existing conductors in one of its 132 kV OHLs. The ACCR conductor is another technology from 3M, analogous to ACCC that can be used to achieve the same objectives. These conductors have the ability to reduce line losses by one-third or more. If these conductor technologies are widely deployed, they could potentially reduce CO_2 emissions by over 290 million metric tons every year [11]. This energy is equivalent to saving 466 million megawatt hours, which is the generation equivalent of 53,267 megawatts. Considering oil-energy, a Btu conversion rate of 42%, the energy saved would be equal over 1.9 billion barrels of oil annually [1], [11].

In this case study, the injection of 100 MVAr locally by the STATCOM removes the needs for the same amount of reactive power to flow through the conductors (ACCC or conventional). The saved capacity in the overhead lines could be used to deliver more active power and push the conductor to work more towards dynamic level. This means more power can be delivered from the bulk generation in the North of Qatar to feed loads instead of adding local generation at the south-west. Also, reactive power flow through the overhead lines increases line current, and in turn is increasing power losses. Therefore, power losses can be reduced by providing reactive compensation locally. The reduction of power losses will reduce the output of power generations, thereby reducing emission [1].

There is an operational practise to optimise active power losses in any transmission network through generation scheduling. For any system consisting of many plants, there is an optimum economic operation for any loading condition on the system (Appendix E). Transmission losses can be made as minimum as possible through the continuous scheduling of the loads amongst the system plants. One of the old commonly used method for dealing with losses optimization is the B-coefficients or loss-coefficients method. There are many load flow solutions usually needed before optimized losses are obtained (Appendix E). Siemens PTI's PSS®E software has an Optimal Power Flow function that can optimise the power losses, along with locations of capacitor banks, etc. The theory of losses optimisation technique is discussed in Appendix E using the B-coefficient method and A-constants calculations.

7.2.9 STATCOM compensation controlled via synchrophasors

Southern California Edison (SCE) has a practical application where the operation of SVC is used to control both local and remote busbar voltages by utilising synchrophasor based voltage measurements [12]. They claimed that SCE project is the first application of closed loop control of SVC using synchrophasor measurements. The authors also concluded that when an SVC is coupled with information available from synchrophasor based wide area monitoring; it can be a very cost effective solution to maintain voltage stability of high voltage transmission network [12]. The project also recommends the integration with other systems of energy management and state estimation.

The advantage of the synchrophasor technology, is that it can provide synchronized measured signals to the controllers, time stamped via global positioning system (GPS). This provides the control systems for FACTS devices, the ability to act on information from remote buses in addition to local measurements, enhancing the ability to solve system problems through local actions. The synchrophasor technology is also called synchronized measurement technology (SMT). This technology has also been tested successfully in an R&D project in Great Britain, where a wide area monitoring system is applied with three PMUs installed at three universities [13].

The measurements are compiled by a data concentrator (DC) installed in Slovenia. The DC acquires data from all PMUs by standard internet communication network. A combination of both practices from USA and GB can be applied in Qatar to improve the system voltage profile, with the STATCOM replacing the SVC, and controlled via synchrophasors.

7.2.10 Concluding remarks

The study simulated various fault conditions in the network and analysed how the STATCOM responds to recover the system voltage after each fault clearance. The study also highlights how the system performance can be enhanced with a synchrophasor based control system controlling the STATCOM. The main assumption to the study is the implementation of a capacity upgrade of existing overhead lines feeding the STATCOM bus by using smart conductors (ACCC) in 2015-2017. From the power flow and steady-state, the reconductoring of the 132 kV lines from Al S'halah – GCC-Umm Bab-Dukhan together with the installation of 100 MVA fixed capacitors or 100 MVA STATCOM device at Dukhan 132 kV bus was found to be one of the most feasible solutions studied so far. The option has solved the 132 kV power flow imbalance and low voltage issues at Dukhan and Umm Bab areas. Dynamic simulation analysis was performed to analyse the impact of this solution option on the system's voltage performance. The analysis has shown that the fixed capacitors or the STATCOM helped improve the system's voltage profile in both steady state and dynamic modes. They have similar performance; however the STATCOM has a faster response in dynamic. It is recommended that Kahramaa to follow this case study with more analysis including cost analysis to decide whether to install the fixed capacitors or STATCOM at Dukhan 132 kV bus (or at Dukhan-2).

For the obvious benefits to the system, the operation performance of the STATCOM can be further enhanced with its compensation controlled based on voltage measurements from remote buses via synchrophasors to work in a wide area monitoring and control (WAM, WAC) modes [1], [12], [13], [26]. The Research Chapter elaborates more on the technology of WAM, WAC and potential implementation in QPTS.

As noted above, the steady state problem can be solved for far less money without a STATCOM, however, performing a case with fixed capacitors ought to have similar results, but it would address likely objections to the STATCOM.

The previous case studies focused on the detailed analysis of the impact of the FACTS devices (SVC and STATCOM) in QPTS. The next case study will summarize testing carried out on the impact of HVDC (alone or with STATCOM) in the QPTS.

7.3 Case Study Three-HVDC and STATCOM Performance in QPTS

7.3.1 Introduction

As a follow up to the previous FACTS analysis, this case study compares the operation performance between HVAC and HVDC. Siemens PTI's PSS®E software is used in the case study for modelling of HVDC equipment and also used for the analysis by subjecting QPTS to different faults types at various locations. The following section gives more details of this case study.

7.3.2 Modelling and analysing HVDC links in Qatar's Transmission System

The previous study has concluded that the installation of a 100 MVA STATCOM or fixed capacitors at Dukhan 132 kV bus will mitigate the low voltage problems in the area [1]. From here on, this report will assume that only a FACTS device (a 100 MVA STATCOM) has been installed at Dukhan 132 kV bus as part of the re-enforcements.

A traditional solution to mitigate uneven loop flows is to re-dispatch generation or to upgrade the ratings of the affected transmission lines. However, since there are no local generation near the Dukhan and Umm Bab areas, the dispatch of remote generation will have minimal effect, if any, in controlling the flow of power. Furthermore, the upgrade of the lines

at Dukhan and Umm Bab will mitigate the thermal overloads in the area but it will not control the flow of power.

The most effective way to control the flow of power in this scenario would be the application of an HVDC technology LCC (or classic) versus VSC HVDC. As such, in this analysis, the double transmission lines from Al S'halah to GCC 132 kV network have been replaced by two HVDC links, each with a capacity of 130 MW. Replacing the existing transmission lines with HVDC links will eliminate the need for new right of way for the HVDC links. Furthermore, an HVDC line of the same rating as the transmission lines, need a narrower right of way [14].

To transfer the total amount of power from the HVDC links (260 MVA for both links), the two parallel transmission lines from GCC to Umm Bab 132 kV has been upgraded to 260 MVA. In this case, the loss of one line from GCC to Umm Bab 132 kV will not limit the transfer of power from the HVDC links in order to avoid thermal loading violations [10]. For reactive power compensation, about 200 MVAr of capacitor has been installed at the inverter end of the HVDC links (GCC 132 kV bus). This has further improved the voltage profile in the area. Most likely the reactive compensation is in the form of harmonic filters if it is LCC HVDC, however VSC HVDC can supply reactive power and doesn't need reactive compensation [16].

Figure 56 shows the power flow and voltage profiles of the Western Ring with re-enforcements (the addition of HVDC links and STATCOM) in system intact condition for peak load conditions beyond the year 2015.
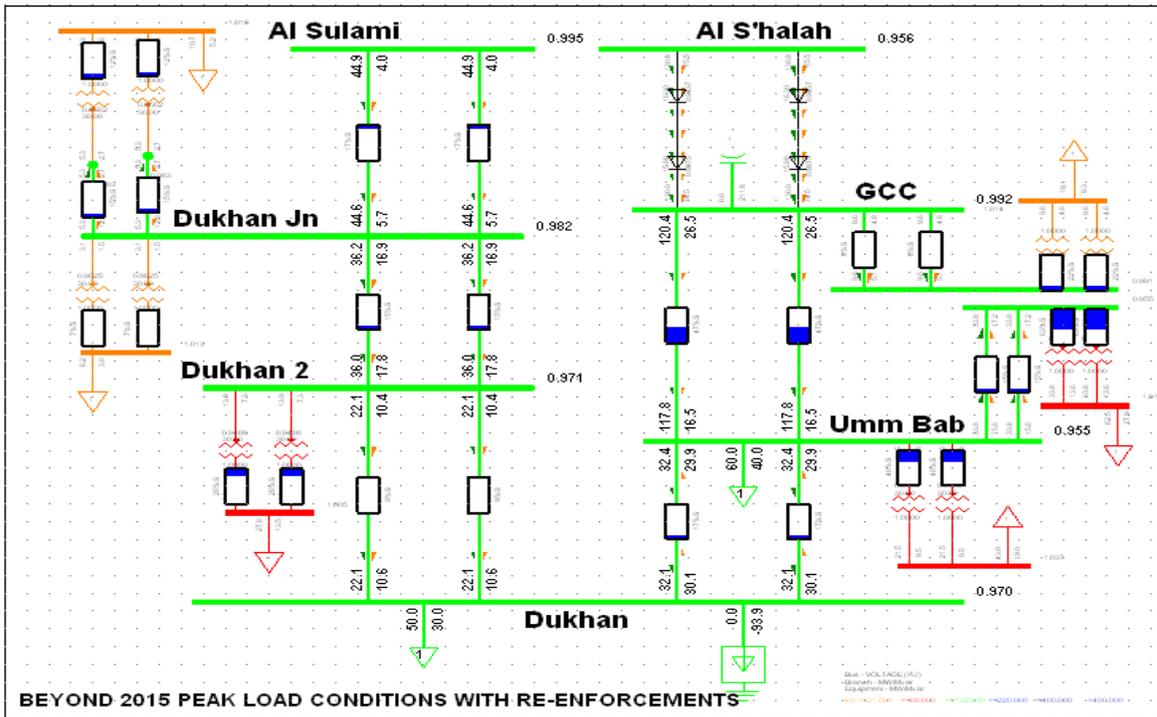
Figure 56: Normal case with STATCOM and HVDC (PSS®E QPTS model – Beyond 2015)

As shown in Figure 56, each of the circuits of Al S'halah-GCC 132 kV OHL is loaded at below 50% of its thermal rating in normal condition. The loss of any one of the circuits will not limit the maximum power transfer of the HVDC links. In addition, there are no voltage violations in the Western Ring [10].

Dynamic analysis has been performed on the cases with the STATCOM and HVDC and without the HVDC to determine the impact of the installation of the HVDC lines at Al S'halah to GCC 132 kV network on QPTS. The analysis has found that the HVDC lines have no negative impact on the reliability of the grid. Dynamic simulations were performed with a 0.1 second steady state period followed by the application of the appropriate disturbance. The contingencies simulated are:

1. Three phase fault at Dukhan 132 kV bus (contingency-1), cleared in 9 cycles (0.18 seconds).
2. Three phase fault at Al Sulami 132 kV bus (contingency-2), cleared in 9 cycles.
3. Three phase fault at Al S'halah 132 kV bus (contingency-3), cleared in 9 cycles.

Figures 57 to 59 below show the machine rotor angles with the STATCOM modelled alone and with both the STATCOM and the HVDC modelled following contingencies -1, 2 and 3 respectively.
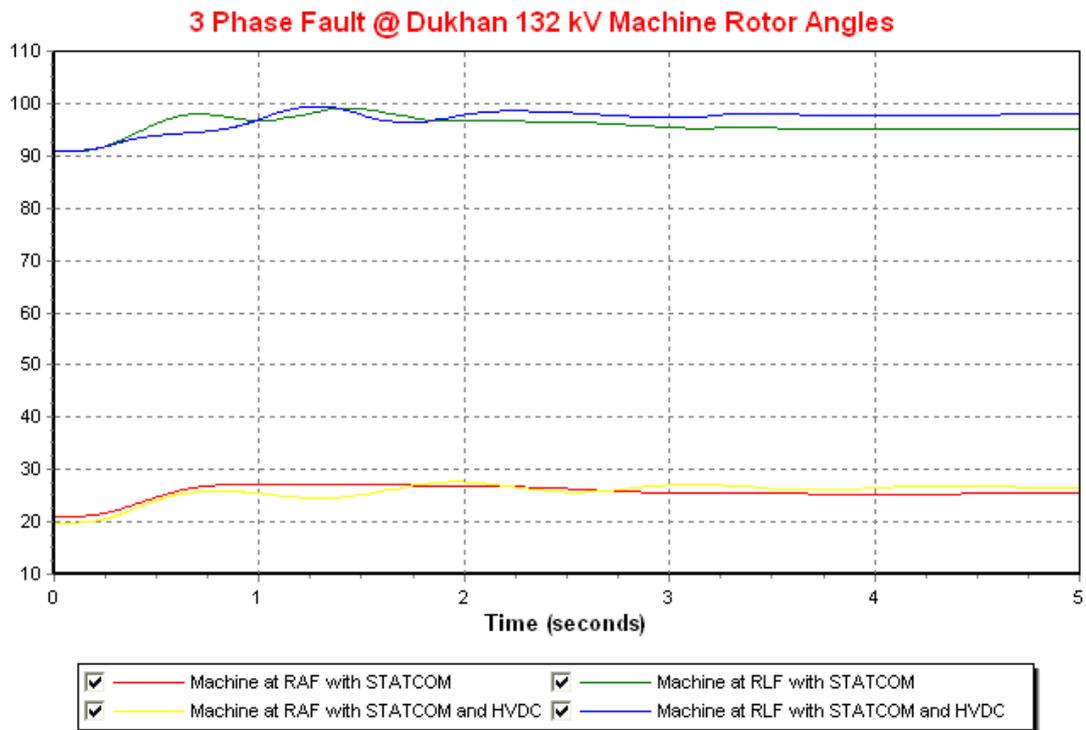
Figure 57: Machine rotor angles (degrees) following contingency-1
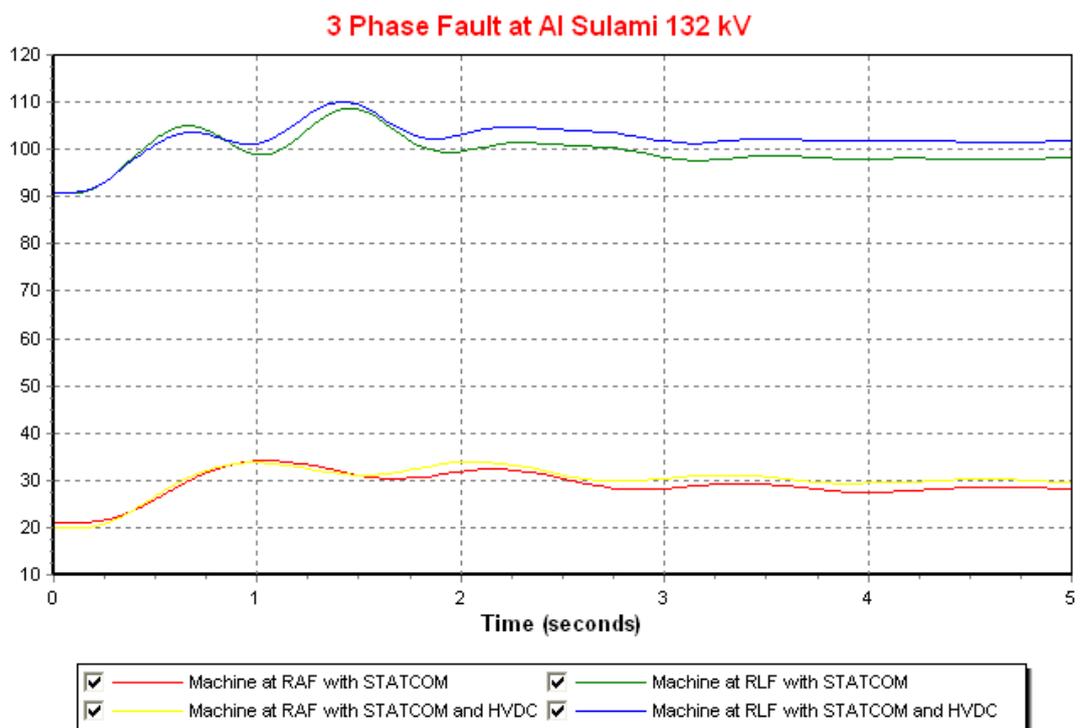
Figure 58: Machine rotor angles (degrees) following contingency-2
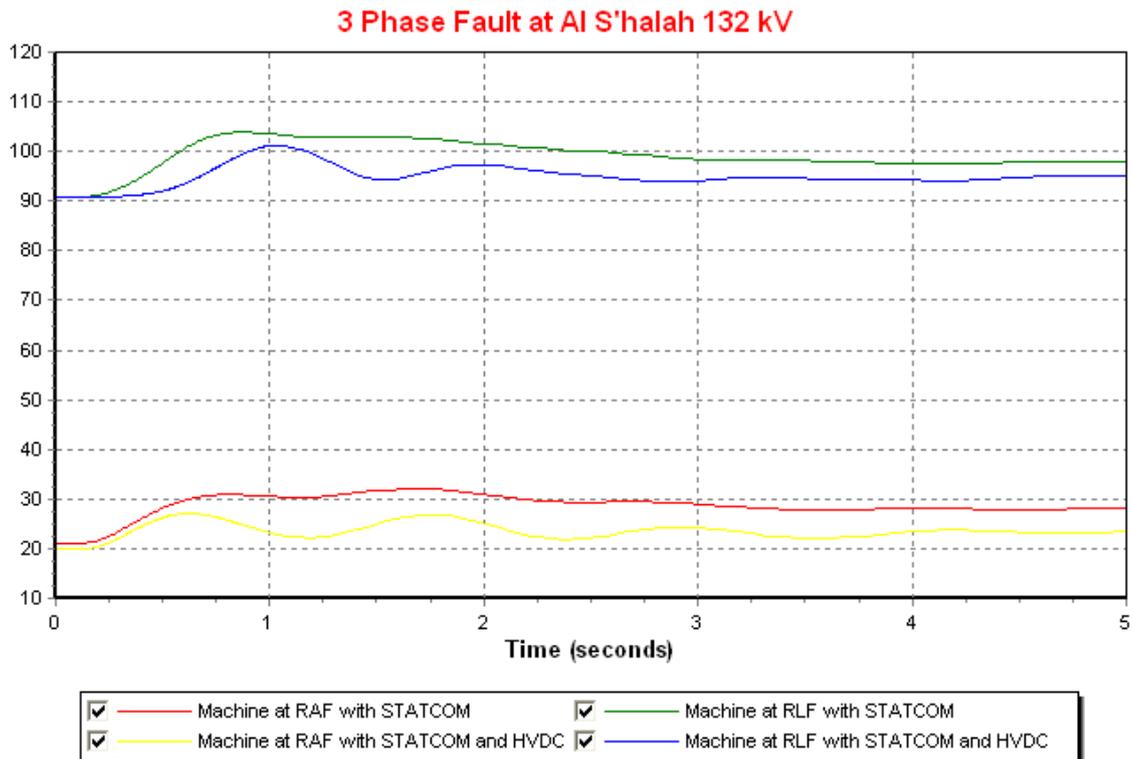
Figure 59: Machine rotor angles (degrees) following contingency-3

7.3.1 Concluding remarks

From Figures 57 to 59, it can be concluded that the system is transiently stable following contingencies -1, 2 and 3. Moreover, the machines rotor angles for the case with the STATCOM modelled alone are practically identical to the case with both the STATCOM and HVDC modelled. The starting angles before the fault and the final angles after the fault is cleared are almost the same. For both cases, there is a significant acceleration of the machines during the fault but the machines stay in synchronism and the oscillation is damped out after a few seconds. Therefore, the system is stable in both cases. A three phase fault at GCC busbar (assuming that is the end receiving power on the HVDC and normally open point in the ring) will be the worst contingency event for the HVDC and will likely cause a commutation failure [16].

7.4 Conclusions of the three case studies

Static and dynamic models of FACTS devices are developed using PSS®E, the professional verified power system analysis software. Time-domain simulations are performed for the developed dynamic models of STATCOM, capacitors banks and HVDC with different

control parameter settings. UPFC and GUPFC, SVCs, STATCOM, synchronized phasor measurements, and other technologies have been reviewed and assessed; in attempt to improve power system operation amid its overall potential.

Replacing the double circuit lines from Al S'halah to GCC 132 kV with two HVDC links will effectively control the flow of power in the area to avoid loop flows. In addition, the HVDC links will not require any more right of way than that of the already existing double transmission lines. Lastly the installation of the HVDC links will not have any negative impact on the reliability of the grid; instead it will improve the reliability of the grid by avoiding thermal overloads in the Western Ring. HVDC system can also modulate power transfer of the HVDC to damp power swings on the system [16]. HVDC although practically found feasible in long distance transmission lines, it is not limited to long lines applications. However it proved to be effective when integrated with STATCOM [16].

Chapter 8 provides analysis of smart distributed generations (DGs) in QPTS and their potential use.

Chapter 8: Potential Application of Smart Distributed Generation in QPS

8.1 Introduction

The applied research work done in this chapter is an essential part of thesis due to the creation of a mix of realistic distribution generation (DG) to cope with a seasonal peak load that occurs in the summer in QPS. The analysis of the annual load to refine the peak load days and hours, in the substations is a pure research effort of this thesis. The DG has included the battery storage, photovoltaic cells (PVs), in addition to other options such as demand side management (DSM). The applied research is investigated to the stage that made the implementation of this DG, an easy objective using a mini-scale renewable in the form of PVs integrated with battery energy storage system (BESS). The DG is designed to produce power in the range of 5 to 10 MVA with a suitable power factor during the peak hours. The topology of connecting the DG (BESS and PVs) is a practical design to distribute power of 7.2 MW at MV level and 315 kV at LV level. The findings of the research in this chapter are published in the thesis's papers [5], [7]. Refer to Table VIII at the end of this chapter which provides general overview of different DGs applications.

8.2 Problem Statement

Due to high and rapid growth in the electricity demand, QPS is facing a big challenge to meet the load requirement at the distribution level following the reliability criteria. There are reasonable number of 66/11 or 132/11 kV distribution substations in QPS with loading exceeded their firm N-1 capacities (25 or 40 MVA). There is a five years statement plan to upgrade these substations or divert some loads from them to newly committed/commissioned substations. However, due to long lead time in implementing the projects, this research has investigated the potential application of renewable energy storage system integrated with the distribution substations to help shaving and balancing the peak loads at that substations [7].

8.3 Daily Load Behaviour at Selected Substations During Summer

Distribution grid can actually operate in unbalanced loading conditions and subject to overload during peak hours. Qatar has the advantage that the peak hours occur mainly during the day time (peak time between 2:00pm – 3:00pm) and use of PVs would be an ideal choice. Out of firm (OOF) conditions at distribution substations may last for several hours and it is quite common in a rapidly growing distribution system like the one at Kahramaa. Dealing with such a condition is a big challenge for network planners [5], [7]. Figure 60, shows the load profile of five substations during the day of system load peak in 2011. As can be seen these substations remain OOF for many hours during the peak time and their load profiles make them good candidates for PV and energy storage application.
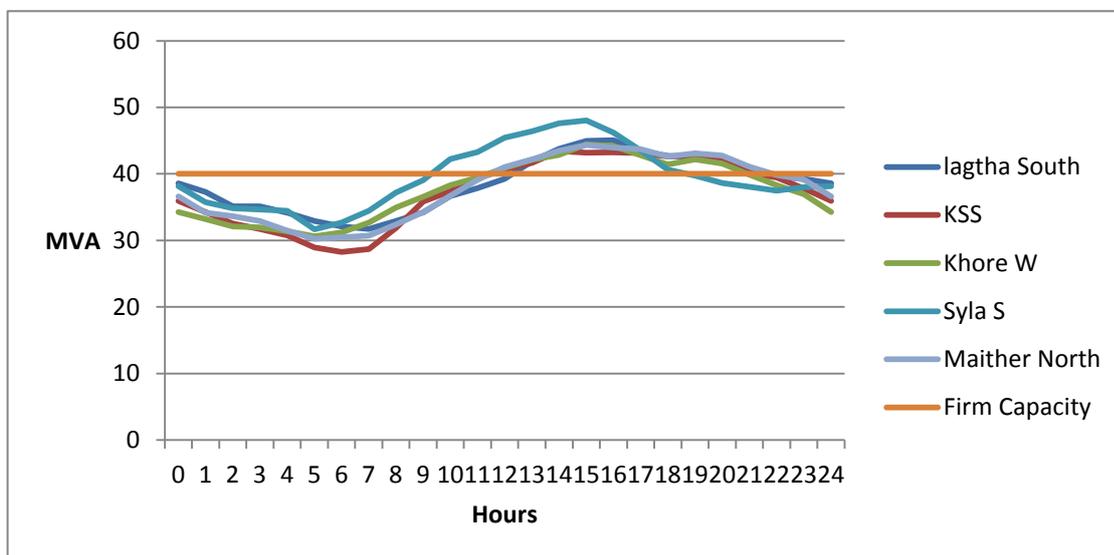
Figure 60: Load profile of some OOF substations during the day of 2011 system peak [7]

Figure 60, indicates that most of the substations were remained OOF for about 6-10 hours and the maximum loads were 4-8 MVA in excess of their firm capacities. The task is to select one substation for DG connection from these five OOF substations having similar loading condition. Also, the space availability and age of the substation equipment are key factors to be considered for selecting the candidate substation. Considering the above, Maither North substation seems to be a potential candidate for this project. The peak load recorded for this substation in summer 2011 was 44.5 MVA against a firm capacity of 40 MVA.

8.4 Planning and Operational Constraints within OOF Substation

Previewing the possibility of one of the incoming feeders/transformers being out of service, at Maither North substation the 11 kV bus-section is normally closed to feed this section without supply interruption (Figure 61). This switch allows for diverting the load corresponding to the transformer that is out-of-service to the transformer that is still operational [5]. During normal conditions (when none of the incoming devices is out-of-service), each of the two transformers distributes the power among the feeders that are connected to its busbar. The normal load flow in the substation is depicted in Figure 61.
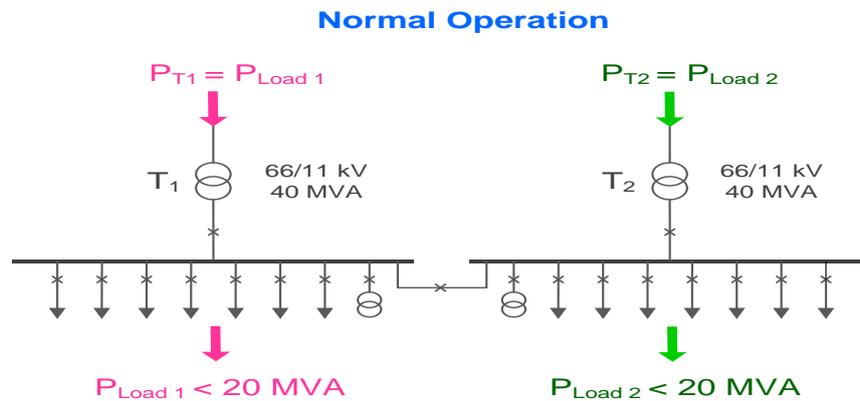
Figure 61: Operation of Maither North substation during normal conditions (without contingencies)

In this regard, no problem is observed since the capacity margin is still high (the peak power consumption is around 23 MVA per section). In N-1 criteria, each busbar shall not carry more than 20 MVA, or the total load in the feeder and the transformer, shall not exceed 40 MVA [5].

The problem arises when one of the transformers/cables (either T1 or T2) is out-of-service due to a contingency or any other programmed maintenance works. In that case, all the power is delivered by the only transformer that is still in service, as illustrated in Figure 62.

The next section will discuss how the actual load in the substation has violated the N-1 criteria during the peak period. As it can be observed in Figure 62, the loading of the whole busbar and the operating transformer could be exposed to power exceeding 40 MVA [7].
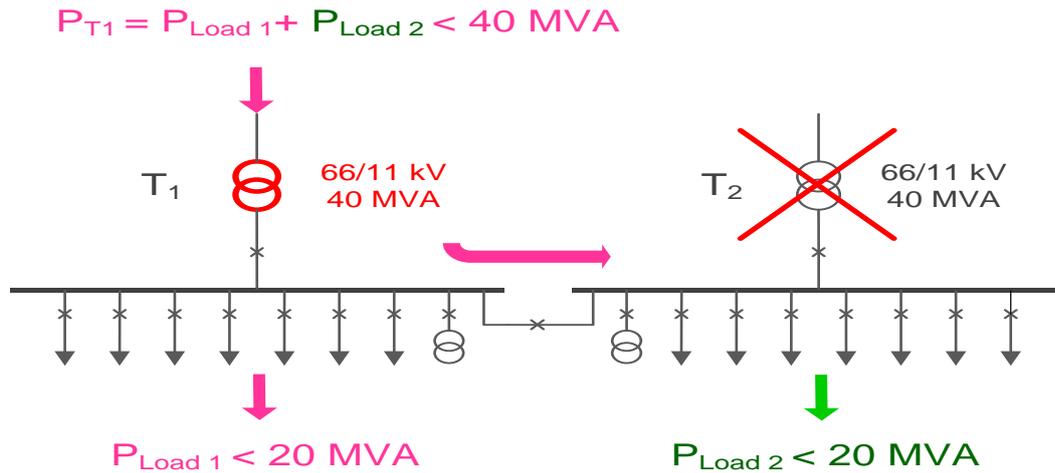
Figure 62: Operation of Maither North feeder-substation during a contingency [5]

If the power overload is integrated over time, during the worst summer peak load day the exceeded energy yields around 42 MWh [5]. Figure 63 (a), for example, constitutes a representative loading case of the substation under study during a full year. As it can be observed, the electricity consumption ratio between the summer and the winter months exceeds a ratio of three. In reality, the overload increases up to 45 MW and it is over 40 MVA (36 MW at 0.9 power factor) for around 6 hours per day during the summer months (from July to September 2011) as it is plotted in Figure 63 (b).

Another important constraint to take into account for the selection of the best solution is the available surface area and the building height limitation. Since the substation is located in a residential area, the height of the buildings is limited, perhaps to G+1 as the maximum limit. But, before introducing the solutions to avoid the OOF periods, the consequences of having overloaded substations will be roughly explained [5].

An overload condition arrives when the power delivered by a substation exceeds the nominal power, which is the power for which the substation (and the power system around) was originally designed and dimensioned. When a substation is overloaded it has not only an impact on the materials and devices of the substation, but also on the operation, the reliability and the stability of the distribution system. Next sub-sections further develop these points.
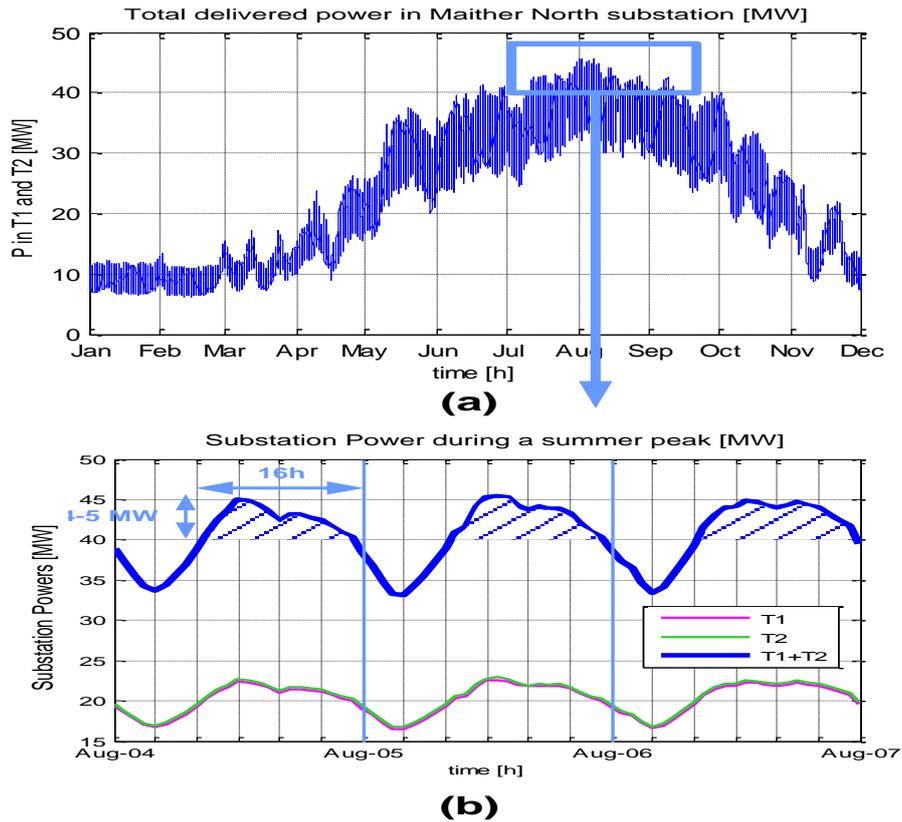
Figure 63: Maither North substation loading during 2011 [5]

8.4.1 Substation disconnection

The overloading of a substation may lead to a complete disconnection from the grid as a consequence of the tripping of protective devices. In that case, two different scenarios may be experienced:

Scenario I: The disconnection of the substation has a large impact on the rest of the distribution system compromising the stability of the system. The worst-case scenario would be a black-out of the zone. Figure 64, for example, shows a satellite image of one of the most widespread blackouts in history of US and Canada in 2003 after the southern Brazil blackout in 1999. It happened just before 16h10 of the 14th of August 2003 and it was mostly restored by 23h00 (but some areas did not get electricity until 2 days later). This blackout affected an estimated 10 million people in Ontario and 45 million people in eight US states [5].
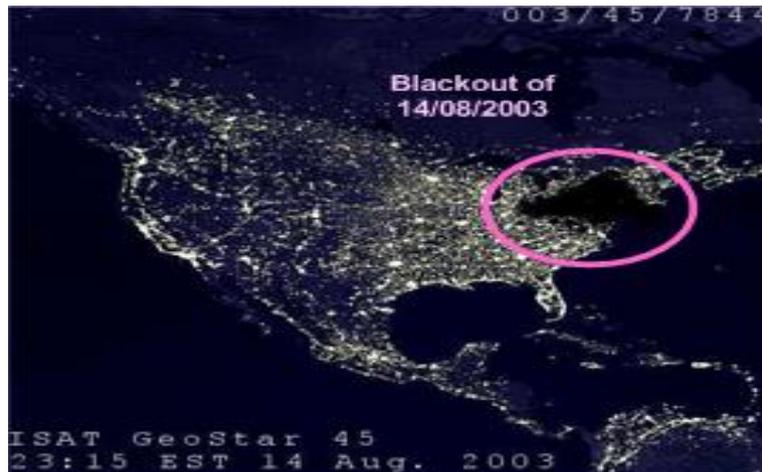
Figure 64: The US Northeast blackout of Aug 14, 2003 [5]

Scenario II: The disconnection of the substation does not have a large impact on the rest of the distribution system. In this case, the consumers connected downstream are affected but the grid-stability is not endangered [5].

In both of the above-mentioned scenarios customers would not be supplied for time periods that range from minutes to days. The loss of electricity supply would present the implications including damages and cost induced to industrial customers, loss of production, workers idling, and damages induced to sensitive equipment, data loss, need of installing back-up equipment. There are also damages induced to domestic customers. Also some TSOs/DSOs offer "curtailment programs" to large industrial customers. In these programs the TSO shall curtail the customer a certain number of hours per year getting, in exchange, a reduction in the electricity bill. For example, in Spain there are already 151 interruptibility contracts in force, which allowed REE, the Spanish TSO to curtail approximately 2122 MW (2012 data) [48]. This service is remunerated following the method described in [49]. Several studies have worked on assessing the costs induced by interruptions [45], [46], [47].

8.4.2 Poor power quality

Unplanned interruptions impact the power quality served to end-users. Power quality can be measured by different indicators. The number of minutes lost per year, for example, is a typical index used by network operators to measure and control their power quality levels [49]. Figure 65 depicts the minutes lost per year (excluding exceptional events) in every voltage levels in different European countries. In Qatar the system minutes lost (SML) in the transmission system is kept well below 10 minutes which constitutes an outstanding record comparing to the countries considered in Figure 65. This large difference can be explained due

to the older T&D assets of the countries considered in the figure. This means that the power quality in Qatar is very good and an upgrade of the existing assets is just justified by the need of reducing the OOF periods during N-1 conditions. The voltage level (EHV, HV, MV, LV) in Figure 65 relates to where the incidents occur [50].
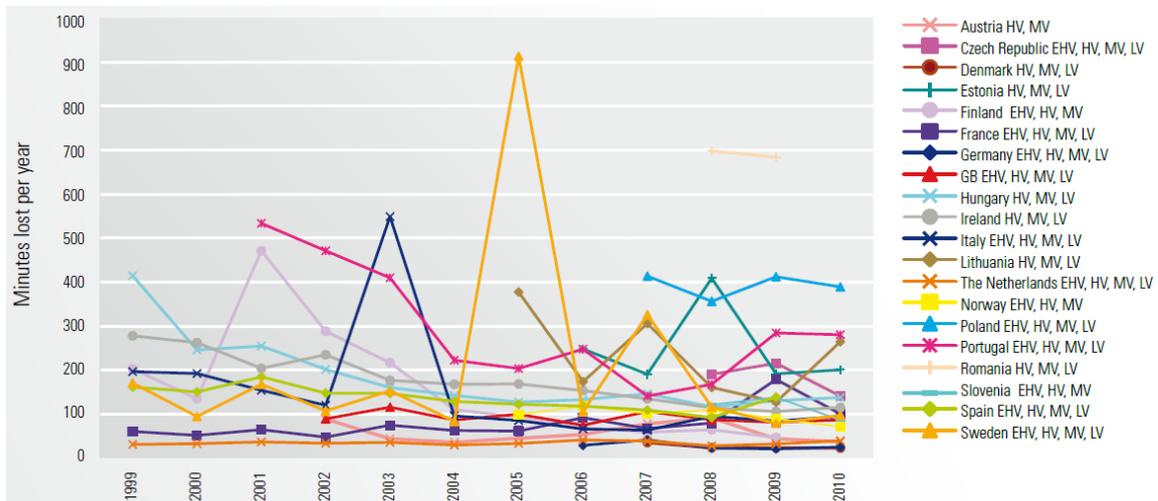
Figure 65: Unplanned long interruptions in Europe excluding exceptional events; minutes lost per year-1999-2010

8.4.3 Life-time reduction of materials due to overload conditions

Overload conditions, especially over-currents, that generate thermal stress, impact the life-time of the devices that compose the electrical substations. In [52] for example, the reliability reduction in electrical substations due to equipment overload is studied and in [53] a method is proposed for finding the optimal capacity of substation transformers considering the loss of capacity during its lifetime.

8.5 Energy Storage System (Battery Storage and PVs) Solution

Combination of renewable, online power electronics and advent of more efficient storage systems can give innovative solutions to similar challenges. Custom power electronic devices have capacities to be integrated with battery storage or superconducting magnet storage and such integrations can allow a voltage injection with varying angles. The successful application in power electronics is due to the evolution of silicon voltage source converter

(VSC) technology. The recent technology progress unveiled the advent of more techno-economic silicon carbide-SiC, which is expected to make some applications feasible for actual development that will serve the power utilities [4], [16]. Battery storage integrated with solar photo voltaic (PV) is one of the most beneficial approaches of providing solutions to existing network. Storage devices are capable of assisting in the distributed generation power which can be useful in implementing renewable energy to power systems and also facilitate the implementation of smart and micro grids. Such DC generation systems need to be combined with DC/AC conversion using a suitable means of power electronics commutations [5], [7].

This section describes a methodology of using energy storage system, including photo voltaic and battery storage, to provide energy during the peak hours of the day to avoid N-1 violation of reliability criteria. The methodology would be implemented at the selected substation described in this chapter, and the implementation process is also outlined in the paper [5], [7].

8.5.1 Photo voltaic - solar energy mapping of Qatar

Qatar is quite rich in terms of solar energy radiation since most of the year the weather is clear. The solar resource spatial distribution map for Qatar is developed by Sogreah under the consultancy services for National Food Security Program [43] with average DNI as shown in Figure 66.
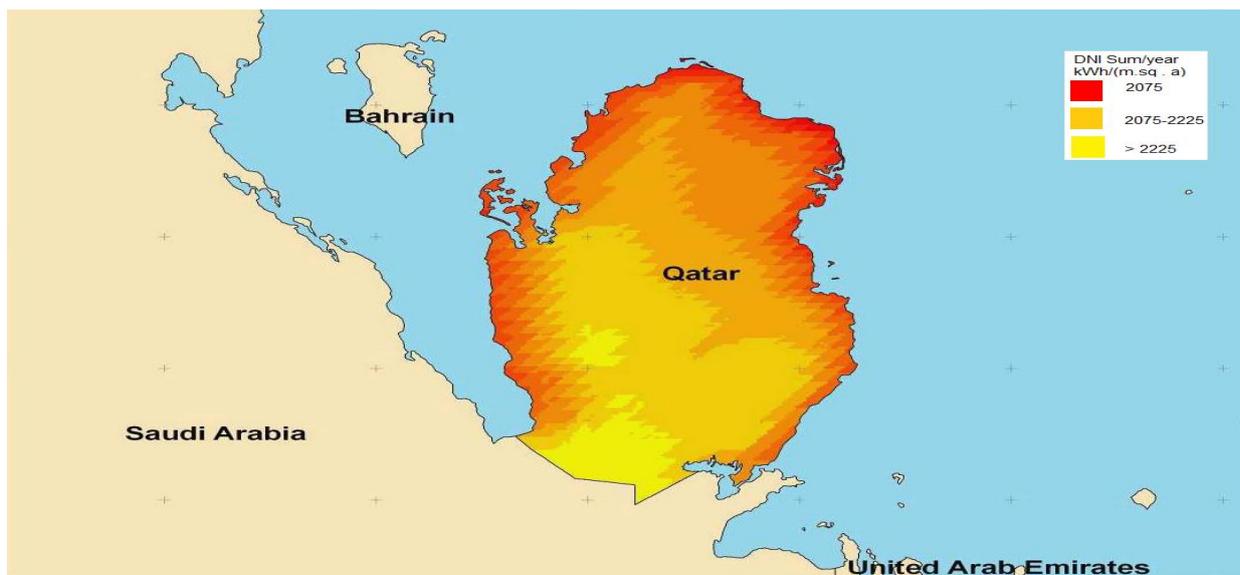
Figure 66: Solar resource spatial distribution in Qatar [7], [43]

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According to the DLR map the DNI conditions are quite good in Qatar since annual cumulative DNI would be 2075 kWh/(m².a) or higher in most places in Qatar [43]. This indicates that there is a huge potential of taping solar energy through PVs and other similar solar technologies for electrical energy generation. This project would be a stepping stone in entering to this field of energy conservation and getting experience with green field technologies through this pilot project on utility level in Qatar.

8.5.2 Land requirements for PV panels

The space at the roof of the substation and free area available within the fence could be utilized efficiently for PV panels' installation. Benchmarking with similar projects in other countries reveals that PV cells designed to produce 4 MW required an area of 45000 m² [7]. The land requirement is also studied for efficient solar panels commercially available in the market. It is found that a high efficiency commonly available panel of about $315W_p$ ($262W_{max}$) requires a dimension of 1.65×1.31 m^2. This implies that to have 1 MW of solar power, the solar panels area only would require at least 7000 m^2. Considering 40 % additional requirement for inter panels spaces and access corridors, the total area requirement comes around 9800 m^2/MW. Since, it is unlikely to have such a spare area available in an existing substation; it is intending to feed at least the substation auxiliary load (including the A/C load) from PVs under this project, not the customers load.

8.5.3 Election of battery storage system (BSS) type and capacity

BSS is probably the oldest method of grid energy storage system which was in place during the direct current electric power networks. With the advent of very efficient, high energy density, high power and long life batteries, the BSS is having many grid applications including power, frequency and voltage stabilisation. Sodium Sulphur and Vanadium Redox batteries are mainly used for grid energy storage. The BSS would require DC/AC (and vice versa) power conversion system (PCS) from the battery voltage to distribution voltage level (11 kV in this pilot case). Both BSS and PCS form a compact energy storage system (ESS). In order to avoid OOF condition in future, it is estimated that a BSS of 8 MW/48 MWH would be sufficient.

A Japanese manufacturer has proposed to use a containerized ESS of capacity 0.5 MWH with Lithium-Ion (LI) MHI batteries [7], however, this system which delivers ac power at 300 V, requires a lot of space and seems not suitable for Kahramaa application. Also, the LI

batteries seem more suitable for fast load smoothing rather than load feeding for long time. Sodium-Sulphur (NAS) batteries are relatively inexpensive, have high power, high energy density three times compared to conventional batteries and have fast response (2 milliseconds), while they occupy third space footprint [7]. Therefore, it is conceived that NAS batteries are best suited for the application and are recommended to be used for the project. There were some incidents of fire within certain NAS batteries installations that forced the manufacturer to exert many R&D efforts to improve the batteries design.

8.5.4 Land requirements and location for BSS and PCS

The typical installation area for NAS batteries is about W15mXD2.3mxH4.5m for 1 MW block (area of 34.5 m² for 1 MW and 138 m² for 4 MW (0.5 MW X 8 units) [7]. 34 MW of NAS battery system was installed for a wind and battery hybrid system in Japan in an area of 82mX33.5m comprising of 17 units of 2 MW each. However, we believe that instead of splitting the batteries into many units and housing them in separate buildings it is more economical to house all the units in one building considering the limitation of available space.

Figure 67, shows a tentative layout of BSS for an existing 4 MW unit which is housed in a 21mX40m building [7]. In order to install 8 MW of BSS a similar layout could be used in the second floor of the building, however, since the substations are in the residential area and there are limitations imposed on the maximum height of buildings. It is more suitable to have a single story building with an area of about 2x(21mX40m) and have PV panels installed on the roof of the building.
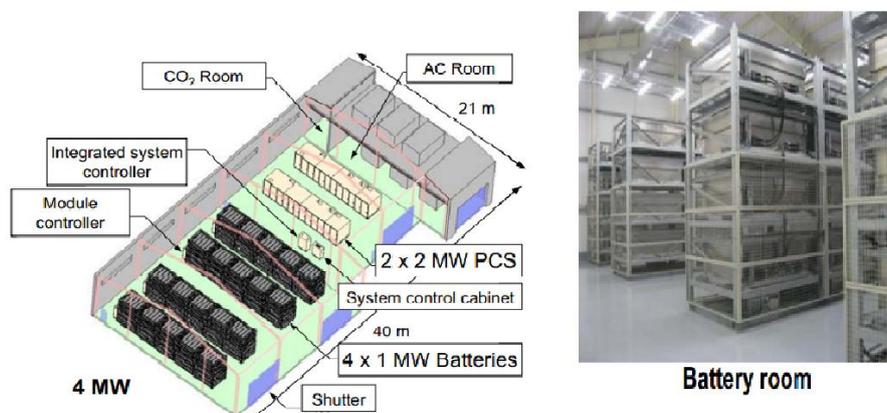
Figure 67: Layout of a typical 4 MW BSS [7]

8.5.5 Building layout for BSS and PVs

The layouts of the candidate substations were carefully reviewed for assessing the available area in the yard, at the roof and within the building for any required switchgear expansion. Considering the energy requirements, available land and substation's life, Maither North is selected for this PV and battery storage system project. The total area of the selected substation is about 6900 m^2 and the empty space available for solar panels and battery storage system is about 5000 m^2. The estimated power output by solar panels utilizing this area would be in the range of 250-350 kW, just about enough for the auxiliary supply of the substation. It is, therefore, recommended to install an 8 MW/48 MWh BSS for load levelling and a PV solar energy system to feed the auxiliary load of the substation during the day with an integrated control system. Figure 68, gives an overview of the available resources within the substation for energy conversion system. A conceptual layout of solar panels and BSS building is also shown in the figure. With this arrangement, it is expected to install at least 1000 solar panels with an expected output of about 262 kW (315 kWp) which is the required auxiliary load of the substation [7].

Figure 68: Conceptual layout of solar panels and BSS building in Maither North substation [7]

Maither North is a 66/11 kV, 40 MVA feeder transformer substation. Provision is available to add two bays at the existing 11kV switchgear which would be used to connect the BSS to the 11 kV busbar. The SLD of the substation is shown in Figure 69.
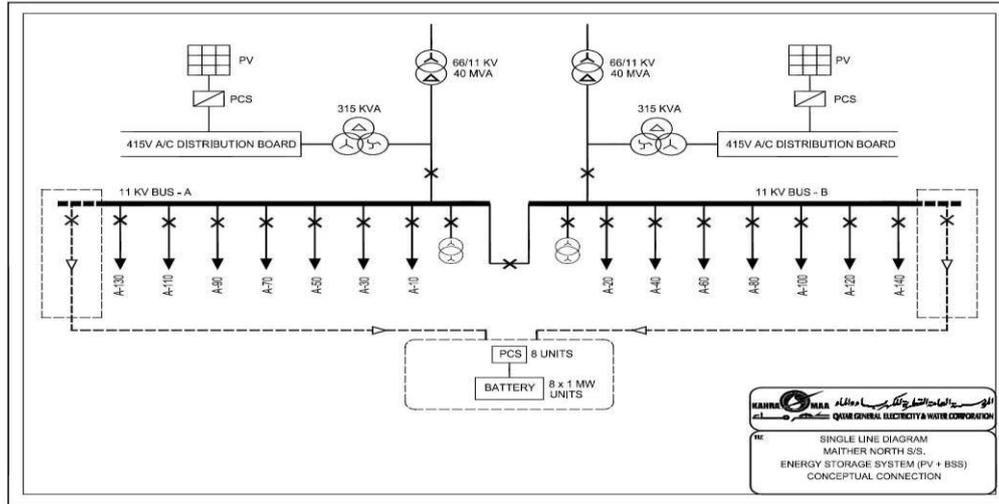
Figure 69: Single line diagram of the Maither North substation with conceptual connection of PV & BSS

At present the auxiliary supply for the substation is taken from the station auxiliary 11/0.415 kV 315 kVA transformers. It is recommended to connect the solar power output to the 415 V distribution board to feed the auxiliary load with suitable control.

8.6 Online Control of Energy Storage System

8.6.1 Online power conversion

Design of online UPS systems, integrated in an AC/DC converter, and providing real power filtering, power factor improvement and information about the AC input state is available in the market [44]. The output in, this technology can transmit high power from the battery system to the essential load, in a more efficient way compared to the available online UPS systems [44]. High rated power delivery will assist in fast and efficient evacuation from the high density batteries such as NAS.

8.6.2 Control methodology

Normally two kinds of control are available in the PCS, one is 'load following control' and the second is 'constant output power control'. In load following control the battery output follows the load profile and is adjusted to provide the additional power required for load levelling (in our case to avoid the OOF condition) as shown in Figure 70. In constant output control, a constant power of the battery is delivered during the peak hours irrespective of the load requirements as shown also in Figure 70. The constant output control may be useful from

overall system point of view when there are also some limitations on the generation side. However, in this case where there is a surplus generation available in the system, the load following control is more suitable considering battery life, longer discharging time window and is recommended for the project.
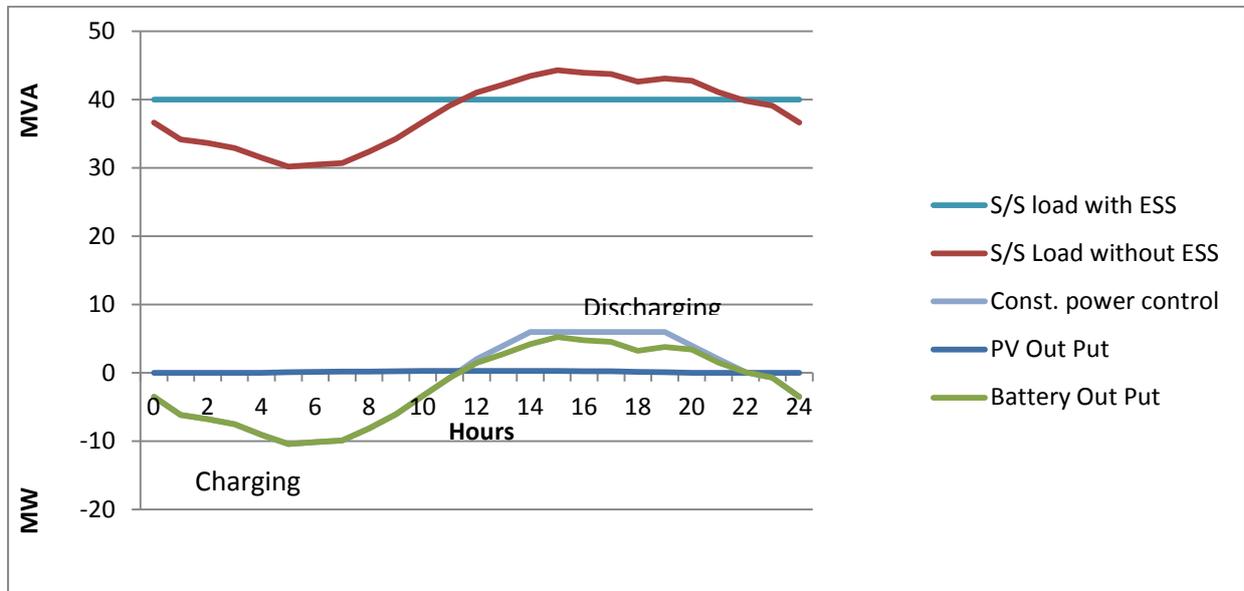
Figure 70: Battery output for load following and maximum output control philosophy [7]

Although the aspect of load levelling is considered only in this project, however other applications like voltage and frequency stabilization can also be included in the integrated control system to enhance the grid system performance when required [7].

8.6.3 Control of PV panels

There are different types of PVs controls researched and developed in different applications depending upon the scale of energy required. There are PV controllers based on satellite data acquisition, while there are PV inverters rating up to 12 MW for VAr and dynamic controls. Some manufacturers introduced a wireless PVs monitoring and control system solution for individual panels tracking, unlike most residential PV systems. Complete monitoring and control solutions for PVs are available in the market including asset management and solar tracking.

If the PV panels are attached with batteries then another sort of control is required to prevent batteries over-charging and also to prevent reverse current from the batteries to the

PVs during the night. The upcoming PV control will comply with statutory regulations for efficient and safe PV installation.

8.7 Implementation of Battery Storage System with Manufacturer Knowhow

Generally speaking, different types of solutions can be foreseen, while four types can be explained in this sub-section. As explained in sub-chapter, the obvious planning solution is to consider equipment up-rating.

8.7.1 To upgrade the power of the substation (Figure 71)

For upgrading the substation two different alternatives exist:

To replace the existing components by power-upgraded components:

This solution is rather expensive because the replacement of two transformers, two busbars, incoming switchgear and the undergrounded XLPE cables are required. Moreover, while the replacement is done the substation cannot supply power to the end-users and the replacement works may last for several months/years. Since the existing substation is placed inside a building, it is necessary to check that the required extra space (even if not very large) still fits in the building. Otherwise supplementary civil works shall be added to the budget. The upgraded transformer rating above 40 MVA would also conflict with Kahramaa standard and would increase fault level at 11 kV busbars and downstream distribution system.
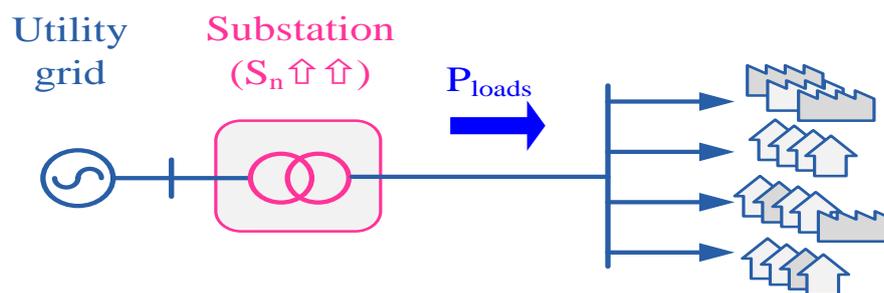
Figure 71: Possible solution to distribution substation overload: to update substation power [5]

8.7.2 To add two additional 40 MVA transformers and busbars

This solution is probably one of the most frequently implemented solutions because it enables an increase of the distribution grid capacity and does not require long shutdowns (can be done during winter months). Considering that the electricity consumption in Qatar is

increasing at astonishing rates, it can be an interesting choice. However, the delivery time is in the range of 3-3.5 years. Regarding the technology of the substation, two types of substations can be considered: gas-insulated switchgear (GIS) and air-insulated switchgear (AIS) [54]. The main difference between these two solutions is that, since gas presents a higher insulation capability than open air, the components of the substation can be installed at a less footprint and, as a result, GIS is much more compact (around 30%) than AIS. Moreover, GIS presents a higher reliability than AIS and the GIS is well adapted for highly populated areas where there is a lack of space. However, GIS is not yet available for medium voltage levels [54].

8.7.3 To install a distributed generation (DG) plant downstream the substation

DG can be of three different types (and its combinations), as illustrated in Figure 72:

i)   Thermal Energy Sources (TES).

ii)   Renewable Energy Sources (RES).

iii)   Battery Energy Storage System (BESS).

One advantages of these solutions compared to the upgrade of the substations is that, since the energy is locally generated, the transmission and distribution losses (and thus generation cost) are minimized.
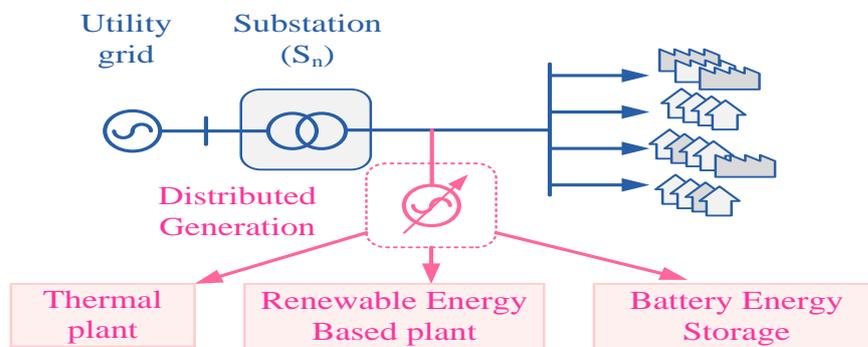
Figure 72: Possible solution to distribution substation overload: to add a DG plant downstream [5]

The main differences between RES, TES and BESS are that RES are:

RES is neither controllable nor predictable, while TES and BESS can be regulated to adapt to the load increase. In addition BESS has the capability of behaving as a regulated load. This means that BESS is very well suited for large RES integration cases where energy balance must be adjusted up or down at any time.

Another advantage offered by TES and BESS (especially BESS) is that they can be used to for intentional islanding of load plus DG clusters (micro grids). Intentional islanding enhances the autonomy of grid parts resulting in a higher stability and reliability of the main grid.

Additionally, TES and BESS can participate to ancillary services such as:

Primary/secondary frequency regulation.

Primary/secondary voltage regulation.

Black-Start capability

Comparing to TES, RES and BESS do not emit greenhouse gases (or at least little) so they are free of green taxes, while RES often requires large surface areas. For example, a 14.37 MW PV farm needs 28 acres land, which makes 1.26 MW/ha (1 acre=4 046.86 m2=0.4047 ha) [55]. And the largest onshore wind farm, Alta Wind Farm, which is located in California, has an installed capacity of 1020 MW over a 9000 acres land (3642.17 ha) [56], which is around 0.28 MW/ha. These large surfaces do not make RES well adapted for urban areas. Moreover, wind turbines shall be installed to a certain distance away from households due to their noise pollution. On the other hand, the efficiency of PV plants is still below 20 %, as it can be observed in Table VII:

Table VII: Module efficiencies and surface areas per cell material [55]

Cell material	Module efficiency	Surface area per kWp
Monocrystaline silicon	13-19 %	5-8 m^2
Polycrystalline silicon	11-15 %	7-9 m^2
Micromorphous tandem cell (a-Si/μc-Si)	8-10 %	10-12 m^2
Thin-film-copper-indium/gallium-sulphur/diselenide (GI/GS/Se)	10-12 %	8-10 m^2
Thin-film cadmium telluride (CdTe)	9-11 %	9-11 m^2
Amorphous silicon (a-Si)	5-8 %	13-20 m^2

8.7.4 To implement demand side management (DSM) techniques.

DSM works in controlling the consumption of loads as to:

Shave/reduce the peak load consumption, by increasing the temperature set-point of air conditioning systems or by reducing the lighting system intensity.

Shift the load profile. For example by scheduling warm-water heater or boiler at a different time (it is often programmed during night hours).

This method does not require the installation of high power equipment, but rather the deployment of a large measuring, communication and remote/distributed energy managing control system. DSM demonstrator projects are being implemented all over the world and the first conclusions from these studies start to come up [57].

8.7.5 Comparison between solutions

In order to offer a clear overview of the different solutions, Table VIII summarizes the most important characteristics by means of green, orange or red smiley, representing a good, average or bad adequacy in relation with the selected criteria. From this analysis the following conclusions can be extracted:

8.7.5.1 Solutions that shall be disregarded

There are a certain number of solutions that do not respond to the requirements of Maither North Overload. For example, actual GIS switchgear is only commercialized down to sub-transmission levels. For this reason, GIS solution could only be used in the high voltage side of the substation. A similar reasoning can be applied to combined cycle gas turbine (CCGT) plants since the existing CCGT power plants are in the order of hundreds of MWs. The integration of diesel generators shall be studied in future works. Finally, wind-based energy generation shall be pushed aside because wind turbines are not really well adapted for urban environments (noise, height, aeroplane landing, visual impact etc.)

8.7.5.2 Solutions that shall re-formulated

There are certain solutions that can be integrated in the substation but not to help for the main load-shifting functions, but for supplying the auxiliaries of the substation (control units, lighting, air-conditioning etc.). This is the case of PV panels, which can be installed on the roofs of the substation buildings or in the floor. If solar panels are installed in the 5000 m2 available area, 250-350 kW can be obtained [5], [7].

8.7.5.3 Potential solutions

The upgrade of the substation, the use of BESS devices (NaS) and the use of DSM techniques are finally found among potential solutions together with PVs. It is rather difficult to make a choice between these solutions because they all present advantages and disadvantages.

8.7.5.4 Upgrading the substation

The major advantage of upgrading the substation (adding a 1×40 MVA (firm) substation works in parallel with the existing substation) is that it is a very well-known technology. It does not take much space (a 2×40 MVA S/S only requires 2500m² in a single storey building or 1600m² if built in two stories). Its cost is in the range of 12.6-16.8 M€ (60-80 MQR).

The major disadvantage of updating the substation is that it does not offer any extra flexibility to participate in ancillary services (it has only on-load tap changers – OLTC) or to balance powers/ regulate voltage in case of a high penetration of rooftop PV in households. This last point can become very important (even critical) when PV penetration will reach higher levels. Moreover, since the electric power is produced in distant generation plants, there are power losses in the transmission path (2-3 % of the demand energy). In Qatar the transmission losses amount to 2% of the total demand, while the distribution losses are more compared to transmission losses. The delivery time of an additional substation is estimated to 3-3.5 years. This means that, during this time, the substation is in OOF conditions during N-1 operation, putting in danger the stability of the grid. Additionally, the substation needs to be partially shut down during some time (weeks to months) for the upgrade works and commissioning.

8.7.5.5 Using BESS devices

The major advantage of using a BESS device is in the flexibility that it offers. BESS can supply power during the summer peak but it can also absorb power in the case of an over-generation coming from a massive installation of PV panels during the rest of the year. Moreover BESS can participate to the different frequency/voltage regulation services and to the black-start of the system. Finally, BESS could also be used for creating autonomous micro grids (islands disconnected from the main grid). In comparison to a new substation, it is not necessary to install 40 MVA of BESS, as installation of 7-8 MVA of BESS (NaS) is sufficient

for relieving the summer peak. In terms of footprint, a 40 MVA substation and a 7-8 MVA (NaS) are pretty much equivalent (around 1200-1600 m2 on G+1) and they both fit in the available area of Maither North substation. The installation cost is also very much close but the operation is different in the long term, since the energy of the BESS is locally generated (near to the consumption zones), the transmission losses are avoided.

Another important advantage of BESS is that the delivery time is less than the delivery time of a 40 MVA substation (around half) and it does require the minimum shutdown of the substation. The major disadvantage of using BESS is that, since NaS batteries are based in sodium, some countries may ask for special permissions before their installation. However, the only manufacturer of this type of batteries in the world assures that there is no discharge of polluting gases and their noise level is very low. Another point to consider is that during winter months the battery would be under-used. It would be very interesting to combine the summer-peak load shifting function with other services to enhance the value of the battery. In any case, this is the same situation as for extra 40 MVA substations. It must be mentioned that, considering the limited space, the use of Li-Ion batteries would require too much space (only the batteries would need 1927 m²putting them one close to the other) and their cost is higher than NaS (in Li-Ion the cost varies very much from technology to technology and from provider to provider).

8.7.5.6 Using DSM

As for BESS, the major advantage of using DSM techniques is the flexibility that it can offer. DSM does not take any place (or very little) in the substation and the used devices are low-power apparatus that benefit from large-scale production and thus, have low prices. However, the deployment cost of DSM programs is still under study (the business models are manifold).The major disadvantage of DSM is the complexity needed to obtain the above-mentioned flexibility. Because, to obtain a high degree of flexibility, many users need to be aggregated and managed, and large communications and measuring infrastructures need to be deployed. Observing the large number of pilot projects running or planned, and the interest shown by different grid-stakeholders in this technology, it is considered as a very promising technology.

8.7.5.7 The BESS proposal

After this analysis it can be observed that the use of BESS, especially that of sodium-sulphur type, is in the short-list of potential solutions to be used for shifting the peak demand during the summer months in Qatar. Figure 73 shows a simplified representation of the solution proposed by a manufacturer.
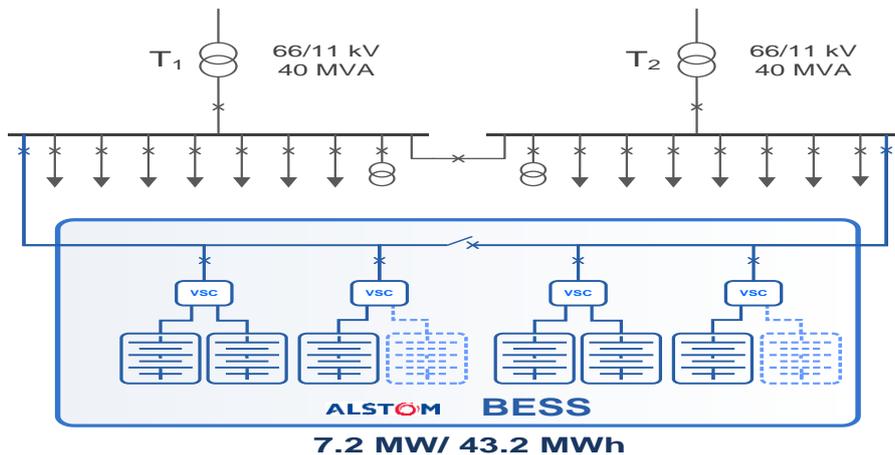
Figure 73: Simplified representation of the BESS solution proposed by a Manufacturer [5]

It consists of a 7.2 MW/43.2 MWh BESS. Since the solution is modular, the total power and energy capacity can be split between both busbars. This 3.6 MW/21.6 MWh can be connected to each of the busbars or the full capacity to the same busbar. This provides a higher flexibility. In this regard, two options can be considered:

- To relate some of the batteries to a particular busbar (as represented in Figure 73). The area of BESS solution is shown in Figure 74 compared the existing used area, the available area.

- To be able to connect any of the batteries to any of the busbars (Figure 75).

  This solution provides the highest flexibility but it is more expensive than the one before.

  The proposed solution requires a surface of 1066 MW (32.6 m×32.7 m), which lets plenty of space for the solar panels needed to supply the auxiliary circuits.
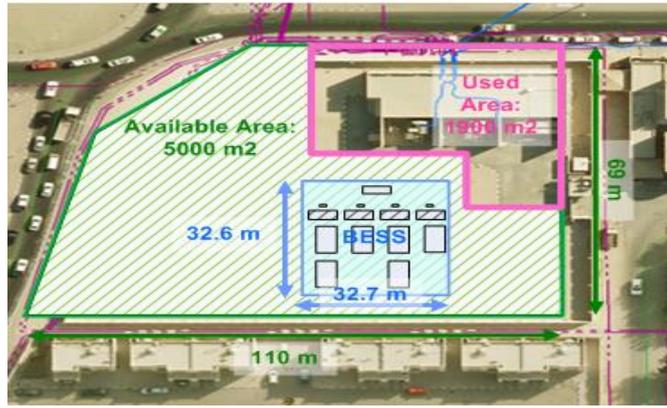
Figure 74: Aerial view of the BESS solution integrated in Maither North substation [5]

For a better understanding of the modularity of the solution, Figure 75 shows the simplified SLD of the BESS at the substation.
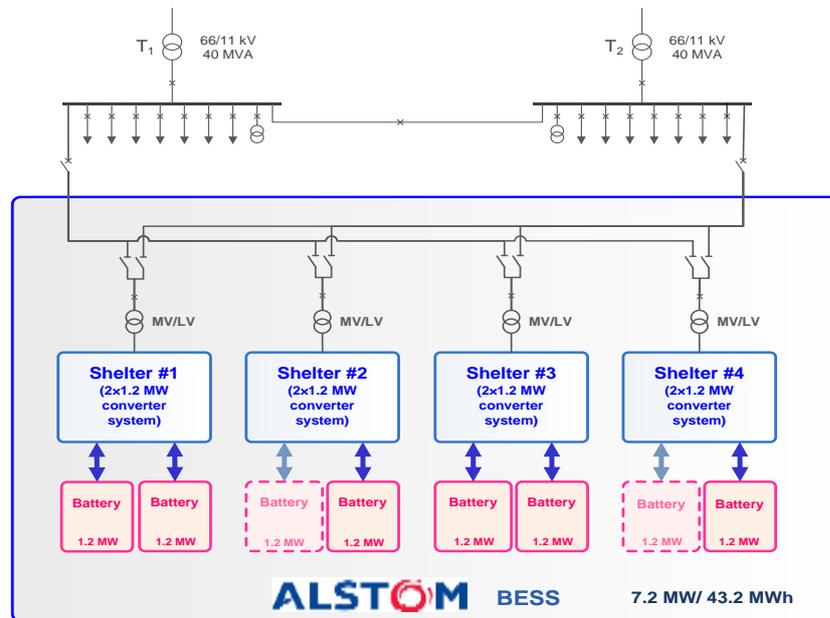
Figure 75: Simplified SLD of ESS [5]

8.7.6 General cost overview

A tentative cost analysis is described in this section. The market indicates that the NaS-BSS costs about $300/kWh on average [7]. The estimated energy requirement for this project is 48 MWh (8 MW output power) which makes the total tentative cost (EPC) for this project to be about $14.4M (52.5 MQR), i.e., about 6.6 MQR/MW. This is almost three times the cost incurred on a standard distribution (66/11 kV) substation per MVA. However, to avoid OOF condition, Kahramaa needs to build a new substation with 40 MVA capacity. Also, the ESS is a generation rather than a distribution system, which might support the justification for new

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investment. Moreover, this ESS is a new technology, usually characterized as more expensive; however utilities would like to embark in new smart applications on pilot cases.

8.8 Concluding Remarks

Electrical energy storage using integrated batteries and PVs system, is rapidly evolving technology and is being accepted as a viable source and essential part of electricity delivery system. Its use in power as well as in energy oriented applications is quite promising in the modern power system of the future. This batteries and PVs system application, although small, satisfies part of Kahramaa long term objectives to utilize renewable energy as well as in the best use of energy conservation to minimize the total dependence on conventional fossil fuels. This article describes and discusses the differences between various solutions and technologies to alleviate the problems created by substations overload during N-1 conditions. The application is in line with Kahramaa strategic plans to comply with Qatar National Vision 2030 for renewable, including solar energy parallel to the energy conservation measures. The concept for this energy storage system shall be further studied for potential implementation. Table VIII below gives comparison between different distributed generations, and clarifies their merits and drawbacks.

Table VIII: Advantages and disadvantages of different DG solutions [5]

Solution	Cost	Footprint	Trans-mission Losses	Flexibility (incl. ancillary services)	Life time	Gas/ chemical emission	Efficiency	Shutdown S/S during works for installation	Maturity
Add GIS (HV) & (MV)	☺ 1×40 MVA (firm) GIS S/S would cost around **14-18.6 M€** GIS/AIS=1/0.9 (only materials, installation and maintenance [58]	☺ 10-25 % of a conventional AIS [57] **3200 MW/ha**	☹ Power needs to be delivered from generation centers	☹ Little flexibility OLTC	☺ >20 yrs (20 yrs supervision from original supplier [58])	☺ SF6 (depending on the technology)	☺ 88-92 %	☹ Weeks-months (winter)	☹ MV GIS substations not available yet but possible to combine HV GIS with MV to increase distribution efficiency [59]
Add AIS (MV) GIS (HV)	☺ 1×40 MVA (firm) GIS, AIS	☺ 2×40 MVA S/S is typically built	☹ Power needs to be	☹ Little flexibility	☺ >20 yrs	☺ SF6 (depending	☺ 88-92 %	☹ Weeks-months (winter)	☺

Solution	Cost	Footprint	Trans-mission Losses	Flexibility (incl. ancillary services)	Life time	Gas/ chemical emission	Efficiency	Shutdown S/S during works for installation	Maturity
	S/S costs around 60-80 MQR (**12.6-16.8 M€**)	in 50m×50m (2500 m²) **320 MW/ha**	delivered from generation centers	(OLTC)		on the technology)			
CCGT	☺ 1× 40 MVA plant costs around **22 M€** 550 €₂₀₀₆/kW@500 MW plant [60]	☹ Not enough place in urban area: 1.26MW PV/ha **8.3 MW/ha** [61]	☺ No transmission losses	☺ Yes but only in generation.	☺ >25 yrs	☺	☺ 55 % [60]	☹ Weeks-l months (winter)	☹ Small scale CCGT plants do not exist (diesel generators may be used instead).
PVs	☹ 1×40 MVA plant costs around **244 M€** 6100 €₂₀₀₆/kW@10 MW plant [62]	☹ Not enough place in urban area: **1.26 MW/ha**	☺ No transmission losses	☹ Intermittent generation	☺ >25 yrs	☺	☹ < 20% [55]	☹ Several months (winter)	☺ Work to do on efficiency
Wind	☺ 1× 40 MVA plant costs around **46 M€** 1150 €₂₀₀₆/kW@100 MW plant [62]	☹ Not possible to install a WT in urban area **0.28 MW/ha**	☺ No transmission losses	☹ Intermittent generation	☺ >20 yrs	☺	☺ 59 % @ MPP	☹ Several months (winter)	☺
ESS NaS	☺ 300-500 $₂₀₀₉/kWh=230-380 €/kWh [63] A 7.2 MW/43.2 MWh installation (all) would require around **12-16.4 M€** (only the batteries)	☺ 1.2 MW/ 7.2 MWh battery container with W9.4m×D2.3m×H4.8m A 7.2 MW/43.2 MWh installation (all) would require around **1066 m²**	☺ No transmission losses	☺ Specially energy oriented applications	☺ 2500-4500 cycles (around 15 years)	☺ Sodium installations need special environmental permissions	☺ 75-92 % [63]	☺ Minimum or no need of S/S shutdown	☺ Large experience by NGK (>300 MW installed)

Solution	Cost	Footprint	Trans-mission Losses	Flexibility (incl. ancillary services)	Life time	Gas/ chemical emission	Efficiency	Shutdown S/S during works for installation	Maturity
ESS Li-Ion	☺ 600-2500 $/kWh=456-1900 €/kWh [63] A 7.2 MW/43.2 MWh installation (all) would require around **19.7-82 M€** (only the batteries)	☺ 1 MW/ 0.5 MWh battery container with W7m×D3m×H3.3m A 7.2 MW/43.2 MWh installation would require >**1927 m²** (only the batteries)	☺ No transmission losses	☺	☺ 1000-10000 cycles (5-15 years)	☺	☺ 90-100 % [63]	☺ Minimum or no need of S/S shutdown	☺ Demonstrator projects promptly increasing (specially US [64])
DMS	☺ Depends on the number and type of end-users that must be aggregate and the type of functions to be deployed.	☺ Almost no footprint at the substation itself	☺ No transmission losses	☺ - Needs strong engagement of the end-customer - Complex aggregation and management	☺ No return of experience available yet	☺	☺	☺ No need of S/S shutdown	☺ Demonstrator projects [20], [57]

Chapter 9: Discussions, Conclusions, and Recommendations

9.1 The Discussions and Conclusions

This examination of literature, critical appraisal of existing conditions, compilation of discussion targeting the potential of online energy systems and online power electronics reveal the areas in which Qatar power transmission system (QPTS) can achieve the greatest benefit. The most relevant studies of QPTS have shown a substantial potential for the integration of FACTS devices, particularly the SVC (or STATCOM), TCSC and GUFPC, or HVDC and other power flow controllers. The case studies conducted showed how FACTS and HVDC devices can cope with the rising demand for Qatar power in recent and upcoming years. The studies explained the benefits of altering power system elements such as the capacity of cables, overhead lines, without a need for additional lines or substations in the mid-term.

The reconductoring of the overhead lines from Al S'halah – GCC-Umm Bab-Dukhan together with the installation of 100 MVA STATCOM device at Dukhan 132 kV bus was found to be the most feasible solution. The selected option has proved effective in solving the 132 kV power flow imbalance and the low voltage cases. Dynamic simulation analysis has shown that the STATCOM has improved the system's voltage profile in steady state and dynamic modes. The conventional capacitor banks have also similar performance to STATCOM, in steady state and dynamic analysis; however the STATCOM outperforms the capacitor in fast dynamic compensation. It is recommended that Kahramaa to install the STATCOM at Dukhan 132 kV bus (or at Dukhan-2) for the obvious benefits to QPTS discussed. The selection of 50MW/50MVAr is found to be the optimal allocation for GUPFC from different combination of active and reactive power ratings. The GUPFC can make a change on the way the utility controls the power flow in part of the network and this will pave the way for smart grid implementation in the QPTS.

When the HVDC is modelled in QPTS (with STATCOM and without STATCOM) the system has become transiently stable. However there is similarity in the machines rotor angles with the STATCOM modelled alone and with the case both the STATCOM and HVDC modelled. The machine angles for all states of the faults before and after clearance are almost the identical. The machines in QPTS stayed in synchronism and the oscillation is damped out

few seconds, post to the significant machines' acceleration during the fault. Therefore, the system is stable in both cases. The direct result is that two HVDC links will effectively control the power flow in the area and prevent the unwanted loop flows when they replaced the double circuit 132 kV lines in the case study. Further to this, HVDC links don't need any extension to the already existing right of way for the two transmission lines. Essential conclusion that the installation of the HVDC links has improved the reliability of the grid by avoiding thermal overloads in the area of study, while there is no negative impact on QPTS reliability.

A qualitative and quantitative comparison based on the particular case of DGs, has been performed (Table VIII) highlighting the advantages and disadvantages of each solution. The solution based on BESS is highlighted due to its remarkable flexibility, compared to other DG options such as PVs, winds, geothermal etc. The BESS can also assist with maintaining power quality in the network considering its effect in mitigating frequency, voltage and power factor variations. It is advisable Kahramaa to consider installing BESS in the mentioned substation to feed the extra load, together with PV panels to supply the substation auxiliary load. This is a green project that produces no polluted emissions; however environment permission is needed for use of Sodium batteries. Use of Li-Ion battery shall also be considered to huge improvement in its development and high output rating of new products. The pilot project can then be counted as part of Kahramaa fulfilment of Qatar National Vision 2030 and Qatar National Development Strategy 2011-2016.

9.2 The Recommendations

Generally speaking, the main recommendation of this evaluation of literature that the integration of flexible online power electronics controls is ideal for increasing the power flows of existing lines, balancing the flows and maintaining the voltages' profiles. The online controls serve to facilitate the need for additional online analysis, control, and security, while put more emphasis on wide-area and monitoring in QPTS.

It has been recommended to Kahramaa to carry out more techno-economic studies that would ultimately lead to the implementation of either FACTS or HVDC in QPTS. The operation performance of the STATCOM can be further enhanced with its compensation controlled via synchrophasors installed at various locations to work in a wide area monitoring and control (WAM, WAC) modes. The synchrophasor technology can benefit from the global positioning system (GPS) to provide synchronized time stamped measured signals to the

controllers. This technology has been found very useful in real utility application. As smart application it can be used in QPTS to control the FACTS compensation, influence the network power flows and the dynamic voltage. The GUPFC can receive measured data via PMUs and synchrophasor units dispersed at certain locations of QPTS, and synchrophasor technology can enhance decision making process of the system operators for increased power delivery up to dynamic limit of transmission lines.

9.3 The Contribution of this thesis

The power electronics data, analysis, and subsequent discussion and recommendations in this thesis, provide an extension of the evolving knowledge base as well as potentially beneficial information. The following points are the main contributions from this thesis:

- Applied research on realistic, existing power network of Qatar (QPS) is the key contribution in this thesis.
- Applying the new concept of 'online power electronics'-OPE driven by online FACTS controllers set based on phasor measurements. The OPE proved feasible in solving planning and operational challenges in combination with conventional techniques.
- Power electronics (FACTS and HVDC) modelling and analysis in a real utility transmission network (QPTS) is considered an applied research contribution.
- There are no HVDC/GUPFC devices implemented in Qatar or in the Gulf States in general. This will be a new idea in the region and innovation that will contribute towards the advancement of knowledge.
- Selection of the GUPFC among other FACTS devices as feasible for application in QPTS as a result of network modelling is an applied research contribution.
- Custom research solution applied to solve overload in distribution substations using custom power devices for energy conversion is an applied research contribution.
- The topology of connecting the distributed generation (BESS and PVs) is an applied research contribution design to distribute power of 7.2 MW at MV level and 315 kV at LV level.

9.4 The Recommendation for future work

After working exhaustively on QPTS challenges and problems, some open issues can be addressed in the coming future research. The following key technologies discussed in this thesis, however they need to be addressed further for feasible applications of the smart grid:-

- Online Analysis: better coordination of controls across the grid

- Wide-area monitoring and control: Phasor Measurement Units (PMU)

- Distributed Generation and Storage Devices

It is advisable to study more the application of wide area measurement and control with stamped signals from synchrophasors to have a better coordinated control. The use of FACTS is considered as one of the key technologies for the success of the upcoming smart grid implementation. From power electronic perspective, more emphasis shall be placed on FACTS devices and wide area control applications using synchrophasors. The transformation of protocols for controllers in transmission deeper analysis of the EMS system is needed for detailed configuration. This recommendation is still potentially ideal for implementation years later, and should be considered in greater detail across on-going analyses. Compatibility of OPE with DNP3 for FACTs shall be further researched and extended beyond HVAC to HVDC [3].

To complement the research in this thesis and for future research, it is recommended to conduct a comprehensive research and studies on the integration of alternative energy sources and its impact on the power quality and stability of the network. The upcoming research shall study the optimum location of online energy storage devices, which can provide the most effective stability and quality of the supply in the system. The study can be extended to include the smart metering infrastructure in power system networks and its implications. Micro grid is the theme of research and development in the foreseen horizon including distributed generation. This research can be followed by more investigations in the FACTS dynamic model in QPTS using the PSS®E software of other application. Fast transient response can be tested in QPTS including the FACTS using the relevant software. The mathematical explanation for the optimization of GUPFC allocation approach may be well researched against the known FACTS allocation techniques such as Genetic and Bee Algorithms.

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Appendix-A: - PSS®E Software used for Power System Analysis in the Study

The PSS®E software mentioned in the previous chapter, as stated, has been a common choice in academia and professional development alike. The PSS®E software [88] potential is so commonly used in the field. The earliest version initially developed by Power Technology Incorporation (PTI) of USA in 1976 (PTI is part of Siemens AG since 2005), the Power System Simulator for engineering program is currently one of the most comprehensive programs that harness available technology. According to the Siemens (2011) website, the program is "the premier software tool used by electrical transmission participants" world-wide. The probabilistic analyses and advanced dynamics modelling capabilities included in PSS®E provide transmission planning and operation engineers a broad range of methodologies for use in the design and operation of reliable networks. PSS®E is the standard Siemens offering for electrical transmission analysis that continues to be the technology of choice in an ever-growing market that exceeds 120 countries [88]. Meanwhile, despite its past rivalling with programs created with freely available developing tools by experts in academia in previous years, the program is asserted to have the most features, best performance, and highest potential for simulating power systems. PSS®E has primarily been designed to simulate, assess, and facilitate optimization of systems, the program integrates processes and features in the areas of power flow, network reduction, transfer limit analysis, dynamic simulation, optimal power flow, balanced fault analysis, unbalanced fault analysis, extended terms dynamic simulation, open access and pricing, reactive power sizing, probabilistic assessment, and more [88] . PSS®SINCAL [88] is another Siemens' software version has also been created to address power system simulation in areas other than electrical networks, such as water, heating, gas, and other areas, incorporating features which allow it to facilitate the demands of utility companies, municipal services, industry, or even consulting firms. With this, features include power flow, short circuit, harmonics, probability and reliability, dynamic simulation, protection, load forecast, cost assessments, and steady state and dynamic analyses for pipe network modules [6], [88]. Both programs offer a uniform GUI interface while providing sector processing, an open database, multiple modes of graphical display (i.e. schematic and topical), internet compatibility, GIS and SCADA interfaces with CIM standard. While the practical features of the program had been effectively mirrored by the program discussed by [33], the advanced technology and features of Siemens PSS®E continue to be used by the assumedly widest range of experts and professionals. Other results revealed similarities in

many areas with another program, concluding that the two programs were directly comparable overall, and supporting the concluding assertions of, that expert skills are more of a limiting factor than available technology in the field [33].

The research analysed the success of PSS®E in the power industry, reporting on the usefulness of the simulation and analysis features [89]. Pointing out that stability analysis, strategic planning for power systems and market deregulation affects the development of simulation techniques and network expansion, the researchers stated that the increasing size of networks and growing expenses further increase the value of simplifying any area [30]. Assessing the potential for an EnFuzion-based approach to computing in simulating large and complex networks in PSS®E, examining a 39-bus power system. EnFusion is basically using parallel computer to run simulations at the same time, especially idle computers, as this will make the simulation/analysis faster. Following multiple contingency analyses and an assessment of optimal power flow, it was determined that the applied method was one capable of increasing the speed of simulations and reducing elapsed time, while additional computer nodes proportionally facilitate these improvements [89]. Praising PSS®E's potential to conduct useful functions benefitting power system assessments through fault analyses, dynamic simulations, and power flow, the authors criticize the time and effort required for multiple case analyses involving any combination of expansive systems. The authors state "although a program can be manually split into several separate jobs which can be run simultaneously on multiple computers, the process was labour-intensive and susceptible to errors [89]. All of such means rapid increase in computing requirement for system operations, particularly in real-time dynamic security assessment. Distributed computing, a form of parallel computing is one of the direct results of the need to meet large-scale and complex computational demand common in many fields. It involves the integration, cooperation and management of network computers. The main goal of distributed computing system is to connect users and resources in a transparent, open and scalable way. Moreover, the internet allows simulation projects to be developed from a wider range of developers, improving the capacity to solve problems, and decreases the amount of time required for project completion. The EnFuzion software addresses these needs while it can be further applied to other areas, such as energy, engineering, telecommunications, three dimensional rendering, and more. The capacity of the technology facilitates ideal simulations through a high reliability, GUI, support of multiple platforms, efficient network use, a 'strong robustness,' and more. As this was applied to generate successful and desirable results in the research, future technology would similarly

benefit from addressing the aforementioned needs through these, similar, or improved approaches.

Researchers studied user defined excitation system models in PSS®E, citing the popularity of PSASP and BPA in the Chinese power industry, while a range of excitation system models used built with PSS®E [90]. The study validated the effectiveness of user-defined excitation system modelling, and demonstrated the potential of simulations ran through a single-machine infinite bus system [6], [90]. Later, other researchers would assess dynamic simulations in PSS®E, emphasizing computational curves, current decrement, and calculations [91]. The results of the analysis would show that the accuracy of the applied PSS®E BKDY simulation was desirably high, although the computational curve analysis proved to generate errors as a result of its conservative nature [91]. The potential for conservative nature to affect simulation and generate errors was stressed in the concluding discussion of the research, as was the general demand for dynamic analysis for short-circuits in the power system. It is very important to calculate the short-circuit current for selecting electrical equipment, configuring protective relaying, and automatic devices. The authors further explain that short-circuit current calculation which only requires network infrastructure details, considering steady state power flow while generating values for the periodic element of current, is a convenient calculation now available in the majority of power system simulation software [6], [91].

Figure 76 below depicts multiple aspects of power systems and simulation, while these areas can contribute to the path of research and development in the field [92]. A new research presented and assessed the capacity for a recently improved simulation program to emulate the electrodynamics of a modern power system. The program was planned to be integrated with an online security program monitoring power distribution in a large area of northern Mexico [92].
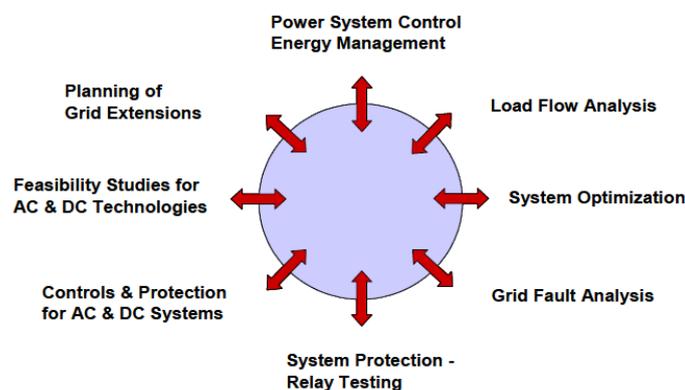
Figure 76: Areas in power system and simulation development [92]

Although this simulation program had first been created and developed to suit the needs of academic and research, the C++ and MATLAB based software was perfected using numerical libraries, differential and algebraic equations, and public licensure [6], [92]. While emphasizing transient stability analysis, the authors explained how even such a program, using common software development tools, could rival the PSS®E software potential so commonly used in the field.

Their results revealed similarities in many areas, concluding that the two programs were directly comparable overall, and supporting the concluding assertions of [33], that expert skills are more of a limiting factor than available technology in the field.

Appendix-B: - Research Dissemination Artefact and Plan

The Dissemination Artefact

This brief chapter provides a dissemination artefact and plan, considering both the literature and the research findings. The dissemination artefact plan provides a more dynamic and direct course of action for improving Qatar systems. This thereby summarizes the key findings of the results while applying them to an organized methodology for future research and development. This dissemination artefact and plan is designed as a formal call for action for progressive development and further research as it is presented in a way which is ideal for future publication.

It is therefore the intention of this chapter to outline all significant elements of research and findings in a communicable way, facilitating the expansion of the existing knowledge base as well as the continuation of developmental efforts and research. While development in power electronics and transmission is outlined by the combined findings clearly demonstrated the potential for improvements and progressive development for power systems in the near future. These findings and recommendations support the findings and recommendations generated from this research and analysis.

The primary aspect of recommendations for improving Qatar transmission systems is to integrate a flexible and comprehensive online system capable of wide-area control, monitoring, and generating (as well as storing). Meaningful data which can be used to assess output, potential faults and causes, and substation functions; meanwhile, this system should remain flexible for the integration of FACTS devices and smart power grids, particularly the increasing integration of power controllers and the expansion of the Qatar distribution system.

The research results will be communicated through publications at international conferences, seminars, professional journals, meetings etc. for calibre Institute such as US (IEEE), and UK (IET). The research findings will also be disseminated nationally through publication in related to electrical engineering and energy conversion (e.g., IEEE, IET). The research team also intends to establish a course on FACTS compensation controlled via synchrophasors with time synchronized data from wide area measurements and controls. The literature presented provides a foundation for a dissemination artefact and plan, while the

resources used for this analysis met specific inclusion criteria to be used and applied for the subsequent analysis and presentation of the dissemination artefact and plan.

The final key important element of recent case analysis and research of the integration of enhancing technology into the Qatar system was a cost analysis. Although this does not directly relate to the implementation of online controls, it shows a great deal of the general demand for resources, funding, and organisation for a substantial expansion or development initiative to the nation's power systems. The integration of online software beyond this point would be much less, although it could range greatly depending on both the functions of the software and the level of integration with improving developments (such as those outlined).

It is assumed that the improvement of technology recommended would facilitate adaptability and improving controls in the following years, while this shows that there is worthwhile potential for the (additional) integration of effective and efficient online controls. Closing the analysis, it is recommended that on-going research in the area examine the economics in greater detail, and investigate the nature of additional communications assisting the power controls (which could be integrated with a study of online controls).

HVDC Journal Paper Outlines

The paper discusses how to incorporate HVDC Power Transmission in QPTS. It started with the introduction, background, scope of research, and project approach. The paper contains, the general comparison of HVDC and HVAC Transmission, characterization of transmission needs, applying HVDC and AC Technologies to meet Qatar's System needs, Power Flow control with AC or DC. Operation performance of HVDC systems in the world was reviewed and compared with AC transmission systems for general criteria for evaluation and principal benefits of DC Transmission. The study comprised the optimal use of limited corridors by converting AC to DC giving an example of technical issues for converting double –circuit 230 kV to 188 kV DC (our lines/cables are 220 kV), converting single-circuit radical AC line to DC for increased reliability and DC transmission line and AC transmission lines on same row. The Modelling of HVDC part with links in AC Systems explained the techniques of how to model HVDC followed by modelling and analysing HVDC in Qatar transmission system. The relative cost of HVAC and HVDC transmission options is discussed taking into account the heavier line loading will increase losses, The break even distance between DC and

AC, variation in break-even distance with loading and contingencies and the value of lost transfer capacity.

The Dissemination of the Research project

To disseminate essential part of the research, it is intended to submit a power systems transaction paper. The paper is about modelling an HVDC/UPFC to control the flow of power (steady-state/transient) in Qatar transmission network, thereby avoiding loop flows. PSS®E software is used for the modelling and simulations of the HVDC and FACTS devices in the power network model.

There were communications with Editor of IEEE Transaction, to make sure that the paper meets the transaction criteria considering the fact that there are few HVDC/FACTS devices in the region in general, but not in Qatar and if this paper is implemented, it would be first in Qatar. The IEEE Transaction Editor response, that the paper is to prove to the editor and peer reviewers that what we are presenting the six key attributes of what an archival publication needs.

The Journal is the PES Transaction and the contact was done with IEEE PES Executive Office, at 445 Hoes Lane, Piscataway, NJ 08855-1331 USA, fax: +1 732 562 3881, e-mail: pes@ieee.org. The Editor was informed of the intention to submit a power systems transaction paper. The paper is about modelling an HVDC/UPFC to control the flow of power (steady-state/transient) in Qatar transmission network, thereby avoiding loop flows. It also includes using STATCOMS to improve the voltage profile of the network in dynamic/transient stability.

The Transaction Editor name is François Bouffard, Ph.D. and he is Assistant Professor and Member, GERAD at the Department of Electrical and Computer Engineering, McGill University, 3480 University Street, room 535 Montreal QC, Canada H3A 0E9 at the telephone +1 514 398 2761, email francois.bouffard@mcgill.ca and site, www.ece.mcgill.ca/~fbouff1.

The transaction Editor's responded to our request and has referred us to Section 8 of the IEEE PES Authors' Kit: http://www.ieee-pes.org/part-8-reviewer-and-editor-guidelines. The Editor's advice was that the job in the paper is to prove to the paper editor and reviewers that what you are presenting meets the six key attributes of what an archival publication needs. The requirements for a transaction paper includes: a new idea/innovation, something that will

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contribute towards the advancement of knowledge, something that has never been done before, etc. Next sub-section outlines the transaction paper to be published in the IEEE, PES.

There are no HVDC or UPFC in Qatar or in Qatar in general. So if this study is implemented, it will be first in the region and will satisfy the requirements of the PES Transactions. The next chapter presents the details of the case study carried and the results. The case study itself was described in more details in the Case Studies Chapter.

Introducing HVDC Transmission in Qatar Transmission System

The goal of this section is to develop an assessment of Qatar national electric utility system's need for electric transmission during the period 2013 to 2030 that could be met by HVDC transmission system. The assessment is to include both the technical and economical evaluation of HVDC transmission system in comparison with conventional AC transmission systems as well as with Flexible AC Transmission System (FACTS). The section looked at Qatar's electricity network challenges to supply new load interconnection requests at remote locations as well as to ensure the reliable operation of the existing network in light of the increasingly growth of load. The possible roles for HVDC transmission to solve these challenges are explored and then compared with AC transmission both technically and economically.

The load demand of Qatar's transmission system is increasing rapidly due to the country's expansive infrastructural developments. This expansion will continue in the next 17 years especially with the anticipated world cup football tournament in 2022 and Qatar National Vision 2030. The expansion will be challenging as it will increase QPTS load density. As the load density increases, the need to control the flow of power to avoid loop flows will become an inevitable. At the same time, the demand for power from remote and isolated locations far from the generating plants to feed the oil and gas companies' industrial loads will pose significant challenges to the network. Conventional AC transmission systems alone cannot solve these challenges. FACTS devices and HVDC should be incorporated in the network to help solve some of these challenges.

Scope of Research

The first task of this research is to look at Qatar's current and future transmission needs with the emphasis on the application of HVDC transmission system to solve these needs. Technical evaluation of the HVDC with traditional AC and FACTS devices will be analysed in this task. The second task of this research is to do an economical comparison of applying HVDC technology to Qatar's transmission network with the implementation of AC or FACTS devices. The third and last task of this research is to model and HVDC transmission in QPTS and analysed its performance.

Qatar Transmission Needs

This section identifies the future needs for new transmission facilities and re-enforcements to the current transmission network. Predicting the future needs of Qatar's transmission network, as in predicting any other country's transmission network, is complicated. However, unlike most utilities, Qatar's electricity utility is experiencing a rapid growth due to the extreme demand for electric power to feed the oil and gas industries in remote areas. Furthermore, the rapid infrastructural development in the urban areas is stretching the existing transmission network to its limits. The need to reliably and economically meet the increasing demand for generation from remote areas to supply the industrial demand and the load demand from the massive infrastructural expansion of the urban areas are two of the most complicated challenges face by Qatar's electricity utility company today. These challenges will become more complicated in the next 17 years.

For the near term, the increasing load demand in the urban areas can be met by the power plants that are located near urban load centres and by the re-enforcements of the existing urban network. Eventually, due to the massive urban expansion, the generating plants near the urban load centres will not have any reserve capacity left in them and all the near-load sites suitable for new generating plants will be all occupied. Similarly, there would be no available right of way for transmission re-enforcements. The nation's electric utility would be inevitably forced to use unconventional solution options such as the application of distributed generation, FACTS or HVDC to reliably feed the load would have to be implemented.

As the only electric utility company of an oil producing nation, the electric utility of Qatar supplies power to remote and isolated oil fields and other industrial facilities that are far

from the generating plants, where very little or no transmission infrastructure is available. Most of the transmission network of QPTS consisted of cables. As such, supplying power to remote and isolated loads can be very challenging because transmission cables cannot reliably transfer power for very long distances. In addition, it is difficult to control the flow of power to reliably supply remote and isolated loads. Since generating plants are far away from these loads, their dispatch pattern will have very little impact in avoiding loop flows.

Building new power plants near the remote and isolated loads centres could be very costly. As such, possible feasible solutions to supply remote and isolated loads that are far from the rest of the network are through the application of FACTS devices and HVDC transmission technology. For shorter distances, FACTS and HVDC transmission can transfer the same amount of power. However, for long distances, as in the case of remote and isolated loads in Qatar, the HVDC system can transfer up to twice as much as FACTS devices of similar operating voltage can do. The next section will explore the possible solutions of meeting Qatar's transmission needs with conventional AC network, FACTS and HVDC transmission.

Meeting Qatar Transmission Needs with HVDC and AC Transmission

This section starts by briefly comparing DC and AC transmission. Then it defines two functional needs of the Qatar transmission network that requires the enhancement of the transmission network. Lastly, it explores how DC and AC, with and without FACTS applications are likely to meet those needs.

Comparisons between AC and DC have been made since the infancy of the electricity industry. Over the years, HVDC has been proven to be economically competitive for long transmission lines in addition to being the technically feasible solution for mid-distance and long transmission cables. It is also the only practical way of interconnecting systems that have different frequencies, which is not a functional need of Qatar transmission system. This section will compare the application of HVDC and AC to the functional needs of Qatar transmission network. Two functional needs of Qatar transmission system that requires the transmission enhancements in the near future are the need to feed remotely isolated industrial loads and the need to reliably feed the growing load demand in the urban areas. Both requirements will challenge the transmission network to control the flow of power by optimally utilizing the existing transmission network in order to avoid loop flows.

Among the remotely isolated load areas in Qatar are ones that are virtually isolated by distance from the main grid such as the industrial loads at Dukhan and Umm Bab areas [1]. Unfortunately for such loads, there are no local generations to feed them. As such, they are fed by power plants that are far away. Sometimes, as in the case with Dukhan and Umm Bab loads, these loads are connected to the main grid through parallel transmission lines that have different distances [1]. As load grows in the area, there is the potential for one of the parallel transmission lines to be under-utilized relative to its thermal capacity while other is heavily loaded. Currently, this is the problem the 132 kV network at Dukhan and Umm Bab is facing. This parallel flow inequity, loop flow, is very difficult and costly to mitigate [14].

Especially in Qatar and in particular the 132 kV network at Dukhan and Umm Bab areas, where this problem cannot be solved through generation dispatch since the power plants are far from the loads. The choice between installing local generation and controlling the flow of power on the transmission lines has to be made. It is very costly to install new generating plants in remote and isolated areas since for the most part; they will be under-utilized. As such, installing local generation would not be the most feasible solution. Similarly, due to the length of the 132 kV transmission lines at Dukhan and Umm Bab [1], phase angle regulating transformer or line series compensators will not be effective in controlling the flow of power [14]. Furthermore, line series compensators are less flexible in controlling the flow of power.

On the other hand, FACTS devices or HVDC will be very effective to precisely control the flow of power on transmission lines to different desired values [63]. However, FACTS devices cannot match the range of power flow modulation possible with HVDC transmission, especially if power flow reversal is required [14]. Furthermore, unlike HVDC transmission, for long AC transmission lines, simply forcing active power flow on desired paths by using FACTS devices will increase losses in the system [14]. As such implementing an HVDC transmission would be better than FACTS devices to solve the loop flow problem at Dukhan and Umm Bab 132 kV network.

This research will look at integrating an HVDC line at the Dukhan and Umm Bab area to control the flow of power. The existing transmission line at Dukhan will be converted to an HVDC. This will avoid the need for a new right of way for the HVDC. Modelling and simulation of the HVDC will be done with Siemens Power Technologies (Siemens PTI) power systems analysis software, PSS®E. The modelling and the analysis of the HVDC will be presented in the later chapters.

Another type of remote and isolated industrial loads in Qatar are the physical islands of oil and gas fields that are located some distance from the main grid. These islands could produce their own local generation to feed their load. However, as their load increases and the need for reliability and power quality becomes a requirement, the islands will have to be interconnected to the main grid. An AC or DC cable interconnection to the main grid will provide better reliability, frequency control and voltage regulation than isolated operation. Furthermore, imported power is likely to be less expensive than local generation.

The load demand of an island and its distance from the main grid would determine whether AC or DC cable should be used. The larger the load demand of an island, the higher the voltage level of connection to the main grid would be. High voltage AC cables must be limited to short lengths to avoid excessive charging current from consuming the capacity for active power transfer. At the transmission voltage level, the submarine AC cable length is limited to about 70 km due to this problem. No FACTS devices can remedy this problem as of now. A possible solution would be underwater switching stations with submarine reactors, the cost of which makes an HVDC transmission more attractive.

In addition, the power quality and voltage support requirements at the load would increase the cost of the submarine AC cable, unless if local generation is available to provide the reactive power compensation needed at the load end. For higher load level and long distance from the main grid, HVDC transmission is the feasible option, technically. Furthermore, in the case where the primary intention of interconnecting the island to the main grid is for better reliability, better frequency control, and better voltage regulation, the HVDC transmission would be the feasible choice even for short distances. Power quality is equally as important as reliability for oil and gas industries because it impacts their production level. Unlike a submarine AC cable, an HVDC transmission will isolate the disturbances at the main grid from reaching the islands. Therefore, another potential place in Qatar to install an HVDC is at Halul Island, an oil and gas producing island which is about 100 km from the main transmission network of Qatar at Ras Laffan.

Lastly, the need to feed the growing load demand in the urban areas, another functional need of Qatar transmission system that requires transmission enhancement in the near future, is a very challenging task that cannot only be solved with conventional AC transmission. The demand for electricity in the city of Doha and surroundings will continue to grow rapidly even with the use of demand side management. The continue load growth in the urban areas coupled with the retirement of some of the power plants feeding these loads will eventually require

added generation. However, as the population grows in the city, new generation, large or small, will be impossible to site. As such the growing load demand must be met with increase in import capacity of the transmission network.

Since new right of way will become extremely difficult to obtain, the existing right of ways must be exploited. The ratings of the transmission cables might be upgraded and increased. Their operating voltages might also be increased in other to transfer more power; however, this might require more right of way than already existing. In cases where lines serving load centres are underutilized while other are over loaded, conventional techniques can be implemented to reroute the power flow in order to maximize the total import by using phase angle regulating transformers (PAR) or re-dispatching generation patterns since the power plans are not that far from the loads. Eventually, all of these conventional solutions might not suffice as load continues to grow. Furthermore, the transfer of AC power will be limited due to any one of the following reaching their limits: rotor angle stability constraints, steady state voltage constraints, or voltage stability constraints.

The use of FACTS devices and HVDC transmission will have to be implemented. Power would have to be imported from generating plants that are far away from the urban areas. As such, the amount of power that can be transported on a given transmission right of way, power density, would be important. For shorter transmission lines, the power density of FACTS devices is comparable to that of HVDC transmission. But eventually as new power plants are build farer from the city the power density of an HVDC transmission could be up to twice that of a three phase AC line with similar operating voltage. Furthermore, there would be very little power losses for the HVDC compared to the AC line.

In addition, an HVDC will be very attractive to load centres, since its inverters can provide the reactive power needed by the loads. This will be particularly important to load centres that lost generators due to retirement. If there was no local generation to begin with at these load centres, an HVDC would be superior to adding a local generation. The reason for this is because an HVDC transmission would require less space in addition to it would not increase the short circuit current as a generator would. It can in fact reduce the short circuit current levels. This will be particularly important to QPTS where the electricity network is currently experiencing high short circuit current levels. As mentioned earlier, as load grows in the urban areas, it is inevitable that certain AC lines will be under-utilized while other AC lines are overloaded. If the under-utilized AC lines are replaced by HVDC transmission, the effective increase in power transfer capability will be even greater than the difference between

the AC and the DC line ratings alone. The reasons for this are that the desired power will be forced to flow on the converted line that was previously underutilized and that the parallel AC lines that were overloaded would be better utilized.

Operational Performance of HVDC in the World

Deciding whether to use an HVDC or AC system should depend not only on the cost but also on the performance. Power quality and reliability of the system in commercial service should be the primary concerns of any transmission planning engineer. This section looks at the operational performance of an HVDC system by evaluating the commercial performance of the already installed HVDC systems. This information will help power system engineers in deciding whether to use an HVDC or AC system. In particular, this section will look at the energy availability of an HVDC system, the energy utilization of an HVDC system, the energy unavailability of an HVDC system, and the transient performance of an HVDC system.

The energy availability of an HVDC is the amount of energy that could be transmitted by an HVDC except due to limitation of transmission capacity following a planned or unplanned contingency. The energy availability of an HVDC is influenced by the availability spare equipments, stages of the construction which will affect the scheduled unavailability of power, system operational requirements such as low system demand which might economically allow the extension of outages beyond a minimum time, thus affecting the forced and scheduled unavailability. The average annual system availability of HVDC with thyristor valve system installed in the world is higher than 97 percent. This is an excellent performance. For the QPTS in particular, the available of energy is very important since the potential places in the system where an HVDC could be connected are the urban areas, and the remote and isolated places to supply power to oil and gas industries. Any service interruption at the remote and isolated places will result to a significant loss of revenue for oil and gas industries. Furthermore, once the energy is available again, it will take a lot of time for the production of gas and oil to reach their peak levels.

The average annual energy utilization of HVDC installed in the world is about 50 percent. Energy utilization is the amount of energy transmitted over an HVDC system based on its rating. It should be noted that individual HVDC system energy utilization varies from year to year depending on the demand and the availability of fuel such and wind and hydro resources. Based on these factors, it is safe to conclude that the potential energy utilization of HVDC in Qatar would be significantly more than 50 percent because the potential locations of

an HVDC in QPTS are in urban areas, where the demand for energy is very high and in remote and isolated areas to feed industrial loads, where the demand for energy is also very high and constant for the most part. Furthermore, the availability of unpredictable fuel such as wind and hydro would not be an issue in Qatar since all of the power plants in QPTS are gas or combined cycle.

Energy unavailability is the amount of energy that could not have been transmitted in the transmission system due to scheduled or forced outages. A scheduled outage is one that has been planned well in advance with a predetermined duration while a force outage is one that was not planned. A forced outage is defined by either a fault that is cleared by manual restoration or the failure of a power plant or equipment that would require repair or replacement. The average forced outages of an HVDC thyristor valve system is about 1.1 percent. The average total energy unavailability of an HVDC thyristor valve system is about 5.6 percent. In transient performance, an HVDC system performance is considered adequate if the transmitted power returns to the level of being transmitted prior to a fault that resulted to a voltage drop below 90 percent of the pre-fault voltage. In more than 98 percent of the times, the transient performances of the installed HVDC systems in the world are considered adequate. In conclusion, the installed HVDC systems in the world show an excellent performance and reliability.

Relative Cost of HVDC and HVAC Transmission Options

This section does an economic comparison between an HVDC and HVAC transmission in terms of the classical break-even distance. As stated earlier, the level of transmission loading in QPTS is expected to increase significantly in the near future. Even at present, during outages, some transmission lines/cables in QPTS are already loaded at more than 90 percent of their thermal ratings [1]. An HVDC will be cost competitive with HVAC if the transmission system can be loaded close to its thermal ratings. The reason for this is that heavier loading increases losses. Transmission losses increase as the square of loading. In addition, if HVAC loadings increase to their thermal limits, lower circuits will be used to transmit bulk power which further increase losses since the percent losses are higher at lower voltage levels. Furthermore, as line loadings increases, the reactive losses will also increase, thus necessitating the use of reactive power compensation. With HVDC transmission system, the entire line is available for active power flow, as such an HVDC with a similar rating with an HVAC; the HVDC will transfer more real power [23]. In addition, the line losses for HVDC are

significantly lower than that for comparable HVAC transmission. As such a significant consideration should be put into losses when comparing the costs of an HVDC with HVAC transmission.

The distance where the lower dc transmission cost pays for the higher dc terminal cost is called the break even distance. The break even distance is used for economic evaluation to determine whether to use an HVDC or an HVAC transmission system. However, losses are not typically included in the break even distance evaluation. When losses are included in the life expectancy of the transmission facilities, the break even distance will be lesser. This study assumes that QPTS facilities will be loaded at their maximum thermal ratings and that the ratio of the average loss to the peak loss of the year is 0.4, loss factor. The break even distance would be less if the loss factor is higher. Furthermore, the costs of HVDC converters are assumed to be $50/kW/terminal. From here on, the comparisons of the cost of an HVDC and HVAC will be based on these assumptions.

The possible voltage levels in QPTS where an HVDC could be installed are the 132 kV level and the 220 kV level. In comparing the cost of a double circuit 230 kV ac transmission line with a thermal rating of 1000 MW compared to the cost of a 281 kV dc bipole with similar thermal rating, the break even distance is 100 miles when the cost of reactive power compensation is not included and 90 miles when the cost of reactive power compensation is included. Reactive power compensation is needed to maintain a reasonable voltage level for long ac transmission lines at higher loadings. The cost comparison of a double circuit 230 kV ac transmission line with a 3-188 kV bipole, both of which have a thermal rating of 1000 MW, the break even distance without reactive power compensation is about 140 miles with that with reactive power compensation is about 125 miles.

The break even distance is significantly lesser for transmission cables than transmission lines because cables at higher voltage ratings as mentioned earlier needs a significant amount of reactive power compensation to be able to transfer power even for short distances. The break even distance for a double circuit 345 kV, 3 phase cable to ±400 kV cables, both of which have a thermal rating of 1000 MW is 28 miles. The break even distance for low voltage lines loaded to their thermal limit is lesser than that for high voltage lines loaded at their thermal limits because losses as a percentage of loading decreases as the voltage increases. This is particularly important for this study because the potential application for an HVDC in QPTS is at the 132 kV and 220 kV levels.

When lines are loaded near their thermal limits, the break even distance decreases as load increases as the square of line loading. However, it is important to note that when loadings are very low, the break even distance decreases as load decreases. This is due to the fact that as loading decreases, the converter cost declines while the line cost remains constant. In conclusion the cost of HVDC transmission becomes more competitive if the line is both underutilized and at maximum thermal loadings. The HVDC lines to be installed at Dukhan and Umm Bab area will be operating at its maximum thermal loadings.

Modelling and Analysis of HVDC

The HVDC system was modelled in PSS®E software together with a STATCOM as explained in the HVDC case study described in Chapter 6. After the verification of the HVDC model, the dynamic analysis followed PSS®E by subjecting the transmission system in the western region to various fault types. The conclusions derived from the case study (Chaper-3) have shown that QPTS dynamic performance has improved with HVDC and STATCOM and even with the STATCOM alone. There is considerable acceleration in the rotor angle of different machines, at the fault start, but the system remained stable. HVDC installation doesn't require new right of way as the existing right of way for the 132 kV overhead lines can be used.

Appendix-C: - Research Theory in Power Electronics Technologies

The following review of basic FACTS theory which explains the impact of power electronics in controlling the power system parameters. It is a summary of series of lectures conducted by Professor Arindam Ghosh, Department of Electrical Engineering, Indian Institute of Technology Kanpur, India [42].

Power Flow over Lossless Transmission Line

The transfer equation of lossless lumped parameter representation of the power transmission line is [42]:-

$$P_S + jQ_S = \widetilde{V_S}\widetilde{I_S^*} = \frac{V^2\sin\delta + jV^2(1-\cos\delta)}{X} \qquad (7)$$

Similarly

$$P_R - jQ_R = \widetilde{V_S^*}\widetilde{I_S} = \frac{V^2\sin\delta \pm jV^2(\cos\delta - 1)}{X} \qquad (8)$$

The real active power over the transmission line is:-

$$P_e = P_S = P_R = \frac{V^2\sin\delta}{X} \qquad (9)$$

The reactive (imaginary) power absorbed by the line:-

$$Q_1 = Q_s - Q_R = \frac{2V^2(1-\cos\delta)}{X} \qquad (10)$$

The power-angle curves and midpoint voltage sag are shown in the Figure 77.
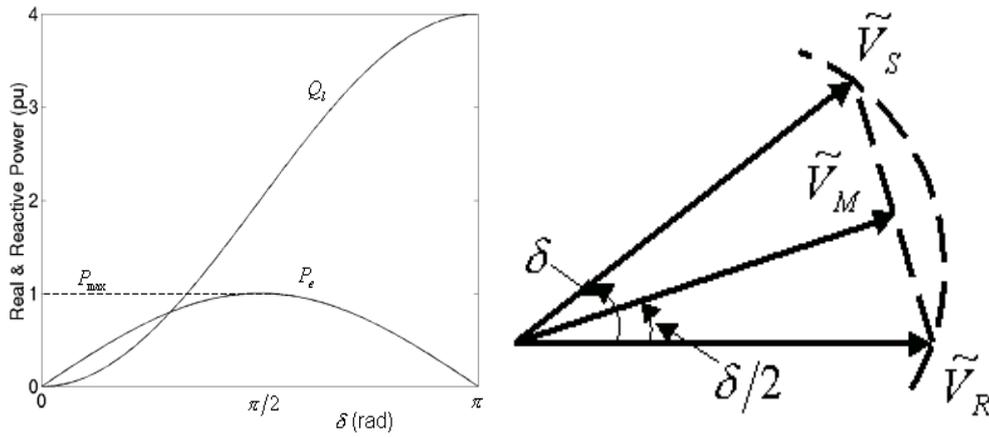
Figure 77: Power-angle curves and midpoint voltage sag [42]

It is assumed that $P_{max} = \dfrac{V^2}{X} = 1\ pu$

$$\widetilde{V_M} = V\cos\left(\frac{\delta}{2}\right) \angle \left(\frac{\delta}{2}\right) \qquad (11)$$

Voltage Stability

Voltage stability is the ability of the power system to recover from a disturbance fault incidence to the pre-fault nominal voltages of all system buses. In addition, the system shall also be able to maintain the nominal voltage at buses in the steady state (Figure 78). For stable power system, the bus voltages shall not drop continuously post to a load change or disturbance [42].
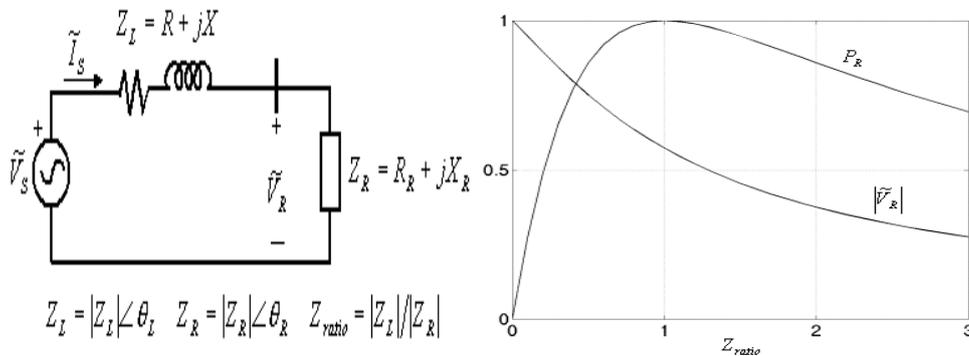
Figure 78: Transmission line model and voltage stability [42]

$$\widetilde{V_R} = \frac{1}{1 + Z_{ratio} \angle (\theta_L - \theta_R)} \, pu \, when \, \widetilde{V_S} = 1 \angle 0° \quad (12)$$

Voltage Stability

$$P_R = \frac{2Z_{ratio}^2 \{1 + cos(\theta_R - \theta_L)\}}{1 + Z_{ratio}^2 + Z_{ratio} cos(\theta_R - \theta_L)} \quad (13)$$

The transmission line impedance is constant and Zratio is inversely proportional to the load impedance (Figure 79). The maximum power transfer occurs when the load impedance is equal to the line impedance, which is called the surge impedance. The transmitted power decreases after this operation point and the voltage starts to decrease till a collapse point unless measures are taken [42].
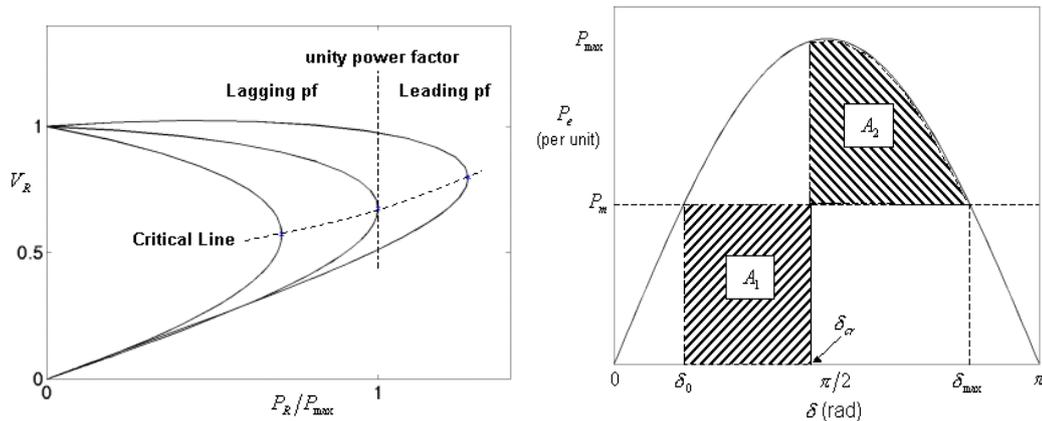
Figure 79: Angle stability and equal area stability (Pm = mechanical power, Pe = electrical power) [42]

As a result of power demand increase operation power systems are interconnected while machines are operated close to their stability limits [42]. In practical bulk power system a set of interconnected machines naturally oscillate against other groups of machines (Figure 80) in a frequency range of 0.1 Hz to 3 Hz. This natural phenomenon of oscillation of two groups of the system is called inter-area oscillation, which could be initiated by a small disturbance in any part of the system [42].

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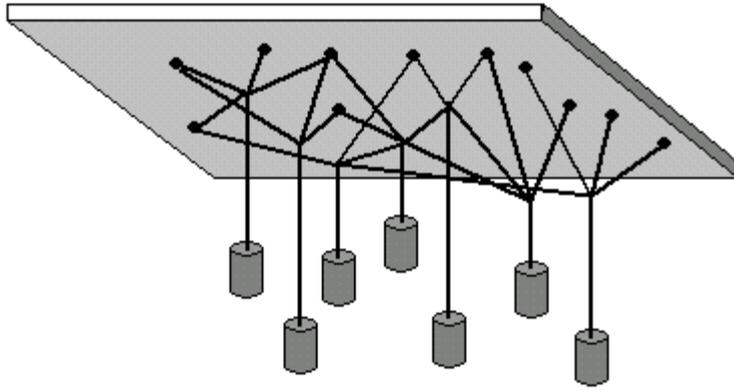
Figure 80: Multi-machine stability [42]

The lowest frequencies modes associate to system generators, while the higher frequencies are local modes oscillation between groups of generators. The small frequency modes are part of the power system dynamic stability and can be analysed through the linearization of the entire dynamic system model [42].

Power System Stabilizer (PSS)

An AVR main function is to regulate the generator terminal voltage and also to reduce the peak of the first swing following any disturbance. The main malfunction that, its high gain contributes to system negative damping resulting in the low frequency oscillations [42]. These oscillations are from the of kinetic energy interchange between generator rotors in the system [42]. A PSS can counteract these oscillations by providing positive damping to these small oscillations through negative feedback of the changes in rotor kinetic energy [42].

Sub-synchronous Resonance (SSR)
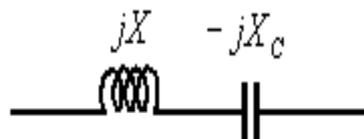
Figure 81: Line reactance and capacitor resonance [42]

SSR usually occurs in transmission lines systems compensated by series capacitors (Figure 81). For a radial series compensated transmission system, the natural un-damped frequency is given by [42]:-

$$f_n = f_0 \sqrt{\frac{X_C}{X}} \qquad (14)$$

Hence the complement frequency $= f_0 - f_n$, where f_0 being the nominal system frequency

SSR occurs when the complement frequency value becomes close to one of the torsional frequencies of the turbine-generator shaft system, especially the steam turbines [42]. A rotor induced small voltage oscillation can result in large sub-synchronous currents that can result in an oscillatory component of rotor torque with phase that enhances the rotor oscillations. The oscillation in the turbine shaft system can grow to damaging levels, if this torque overcomes the mechanical damping [42].

Shunt Compensation of Transmission Systems

Any FACTS or non-FACTS device that that is connected in parallel with a transmission line is called a shunt compensator. It is referred to as a compensator since it compensates for the reactive power in the ac system. It can improve the voltage profile, improve the power-angle characteristics, improve the stability margin provide damping to power oscillations (Figure 82).

Ideal Shunt Compensator
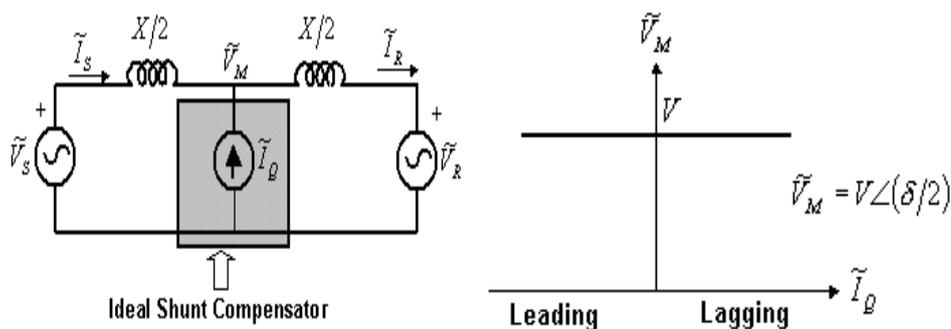
Figure 82: Shunt compensator at mid-point of lossless line and voltage current characteristics [42]

The ideal shunt compensator is represented by an ideal current source that supplies only reactive power and no real power and could be connected at the midpoint of a line (assumed lossless line with reactive impedance only).

Voltage Profile Improvement of Shunt Compensator

From the voltage-current characteristics shown in the Figure, the ideal shunt compensator has constant voltage at the midpoint for different values of injected current [42].

For $\widetilde{V_S} = V\angle\delta, \widetilde{V_R} = V, \widetilde{V_M} = V\angle\left(\frac{\delta}{2}\right)$ (15)

$\widetilde{I_s} = \frac{V\angle\delta - V\angle\left(\frac{\delta}{2}\right)}{jX/2}, \widetilde{I_R} = \frac{V\angle\left(\frac{\delta}{2}\right) - V}{jX/2}$ (16)

Since $\widetilde{I_Q} = \widetilde{I_R} - \widetilde{I_s}$

$\widetilde{I_Q} = -j\frac{4V}{X}\left\{1 - cos\left(\frac{\delta}{2}\right)\right\}\angle\left(\frac{\delta}{2}\right)$ (17)

Therefore the current shall be generated at phase quadrature with the midpoint shunt voltage, to inject only reactive power by the compensator. However both active and reactive Power compensation at midpoint improves the power flow over a line (Figure 83). The active power flowing through the line is:-

$P_e = \frac{2V^2}{X}sin\left(\frac{\delta}{2}\right)$ (18)

And the reactive power absorbed by the line is:-

$Q_l = \frac{8V^2}{X}\left[1 - cos\left(\frac{\delta}{2}\right)\right]$ (19)

And the reactive power generated by the shunt compensator is:-

$Q_Q = \frac{4V^2}{X}\left[1 - cos\left(\frac{\delta}{2}\right)\right]$ (20)
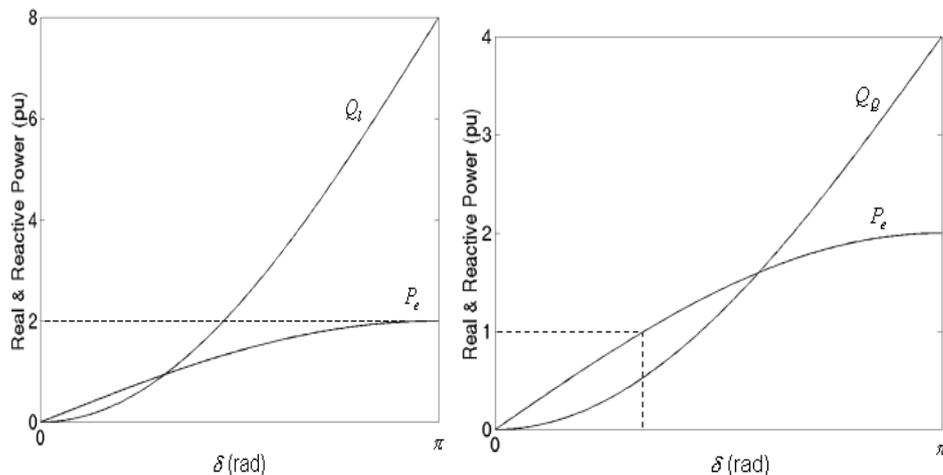
Figure 83: Power angle characteristics at 2 pu and active/reactive power & power angle at 1 pu [42]

Reactive Power Requirement

For a transfer of 1.0 per unit real power, the shunt compensator is required to inject a reactive power of about 0.54 per unit from, while for 2.0 per unit real power the compensator needs an injection of 4.0 per unit reactive power [42].

It is assumed that $\frac{V^2}{X} = 1\ pu$

For transfer of 1.0 PU, an active real power, the reactive power injection can be reduced by lowering the mid-point voltage (Figure 84) [42].
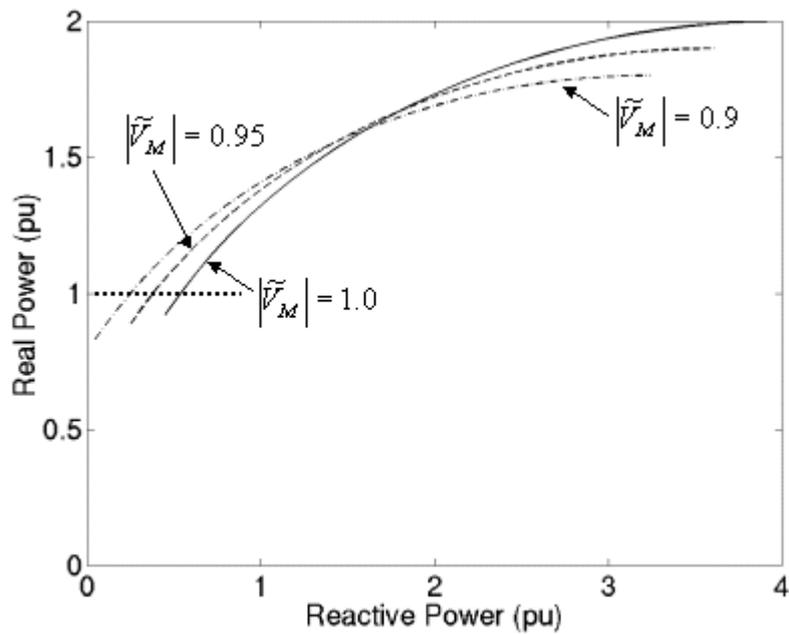
Figure 84: Real power vs. reactive power [42]

Improvement of Stability Margin
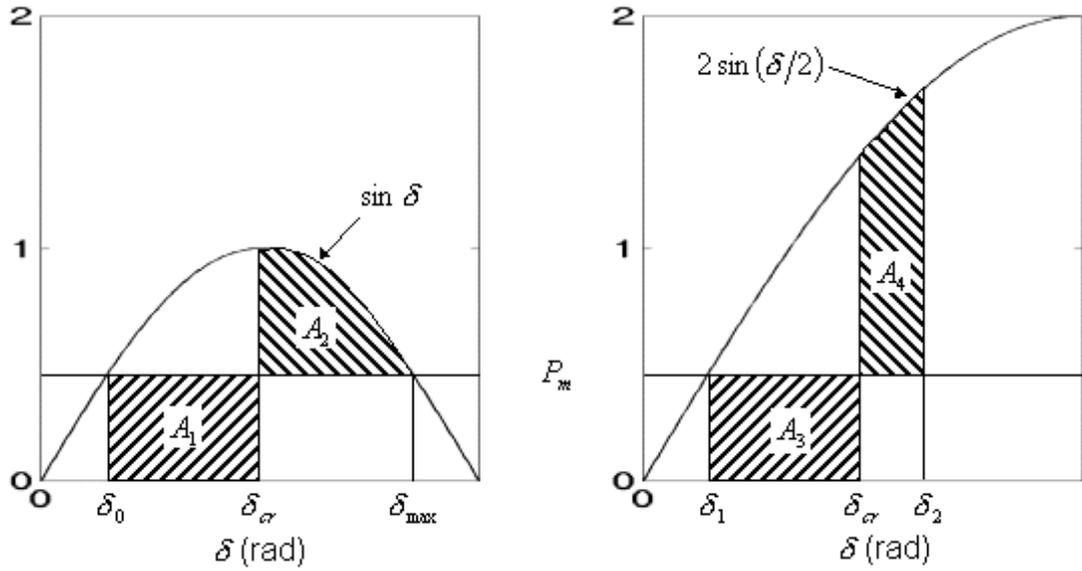
Figure 85: Power swing damping [42]

The power swing equation known by the mechanical, electrical power difference (Figure 85):-

$$\frac{2H}{\omega_s}\frac{d^2\delta}{dt^2} = P_m - P_e(\delta, |\widetilde{V_M}|) \quad (21)$$

Pm is the mechanical power input, whereas the electrical power Pe is defined as a function of the midpoint voltage magnitude and the load angle. The midpoint voltage and load angle can influence the transmitted power on transmission lines, for constant voltage values at both ends [42].

The swing equation can be linearized as:-

$$\frac{2H}{\omega_s}\frac{d^2\Delta\delta}{dt^2} + \frac{\partial P_e}{\partial |\widetilde{V_M}|}\Delta|\widetilde{V_M}| + \frac{\partial P_e}{\partial\delta}\Delta\delta = 0 \quad (22)$$

The midpoint voltage magnitude 'Vm' is regulated at constant value and therefore no increment

$$\Delta|\widetilde{V_M}| = 0$$

The linearized swing equation becomes:-

$$\frac{2H}{\omega_s}\frac{d^2\Delta\delta}{dt^2} + \frac{\partial P_e}{\partial\delta}\Delta\delta = 0 \quad (23)$$

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The roots locations of the swing equation are on the imaginary axis of the s-plane, implying that the load angle will have no damping and will oscillate with a constant frequency of [42]:-

$$\sqrt{\frac{\omega_s}{2H}\frac{\partial P_e}{\partial \delta}}$$

Constant oscillation in the linearized swing equation forms unstable system, and we can add a derivative of the load angle to it [42].

The midpoint voltage can be varied as follow and the linearized swing equation becomes [42]:-

:-

$$\frac{2H}{\omega_s}\frac{d^2\Delta\delta}{dt^2} + \frac{\partial P_e}{\partial |\widetilde{V_M}|}K_M\frac{d\Delta\delta}{dt} + \frac{\partial P_e}{\partial \delta}\Delta\delta = 0 \quad (24)$$

Which is an equation of a 2nd order system where

$$2H/\omega_s > 0 \quad ,\frac{\partial P_e}{\partial |\tilde{V}_M|} > 0 \quad ,\frac{\partial P_e}{\partial \delta} > 0$$

With a stable solution satisfied if

$$K_M > 0$$

For synchronisation of the shunt compensator injecting reactive power with the network, the angle of the voltage source has to be in phase with the midpoint voltage [42].

$$\tilde{V}_F = \frac{\tilde{V}_M}{|\tilde{V}_M|} \times |\tilde{V}_P| \quad (25)$$

The research proposes to regulate the midpoint voltage to 1.0 per unit using a PI controller of the form. System response to perturbation is shown in Figure 86 [42].

$$|\tilde{V}_F| = K_P(1 - |\tilde{V}_M|) + K_I \int (1 - |\tilde{V}_M|)dt \quad (26)$$
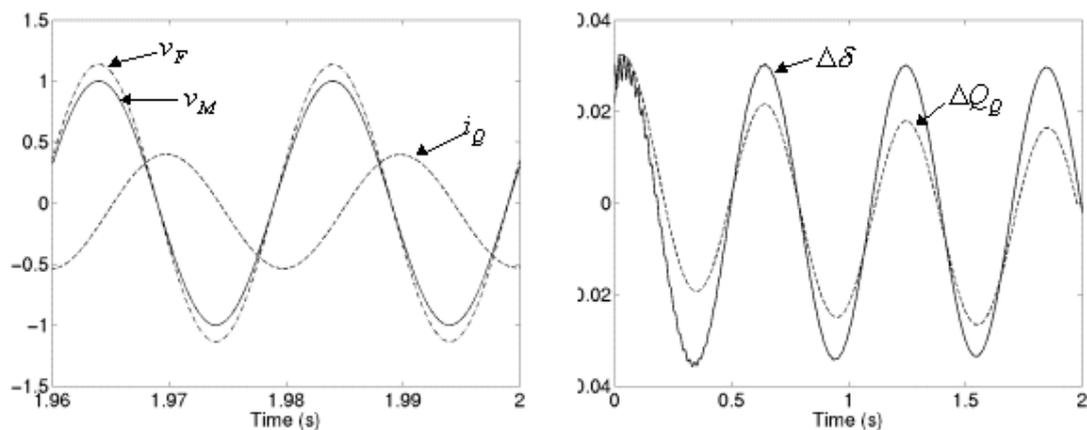
Figure 86: System response to a perturbation [42]

A term that is proportional to the deviation of machine speed in the feedback loop can be introduced to improve damping such that the control law is given by [42]:-

$$|\tilde{V}_F| = K_P\big(1 - |\tilde{V}_M|\big) + K_I \int \big(1 - |\tilde{V}_M|\big)\, dt + C_P \frac{d\Delta\delta}{dt} \quad (27)$$

The last term is the system damping to (Figure 87) [42].
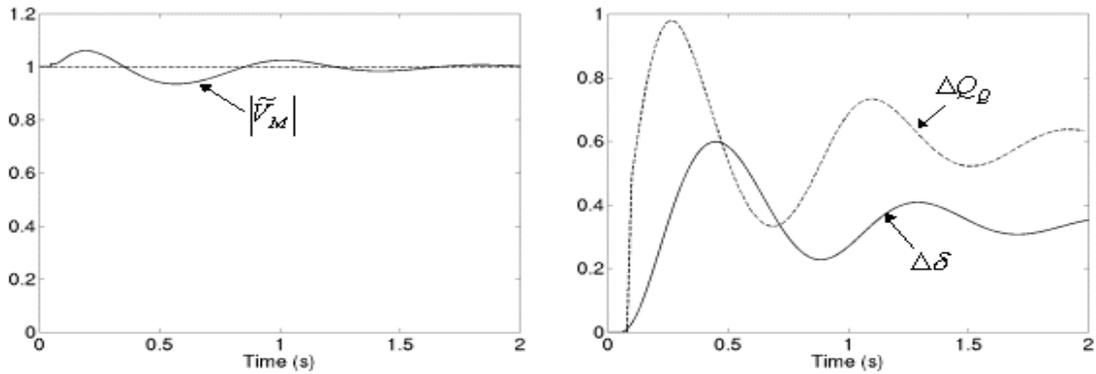
Figure 87: System response when the breaker opens inadvertently [42]

Real Shunt Compensators, SVC and STATCOM

The Static Compensator (STATCOM) produces a voltage, with a fundamental component in phase with the midpoint voltage. It comprises an inverter based synchronous voltage source (SVS) and a connecting step-up transformer to HV or EHV installations [42]. The oldest shunt compensator is the Static VAr Compensator (SVC), which acts as a variable reactance. For power transmission system without compensation (Figure 88) the system is represented by its Thevenin equivalent looking from the midpoint of the line. The variable reactive load is assumed connected at the midpoint [42].
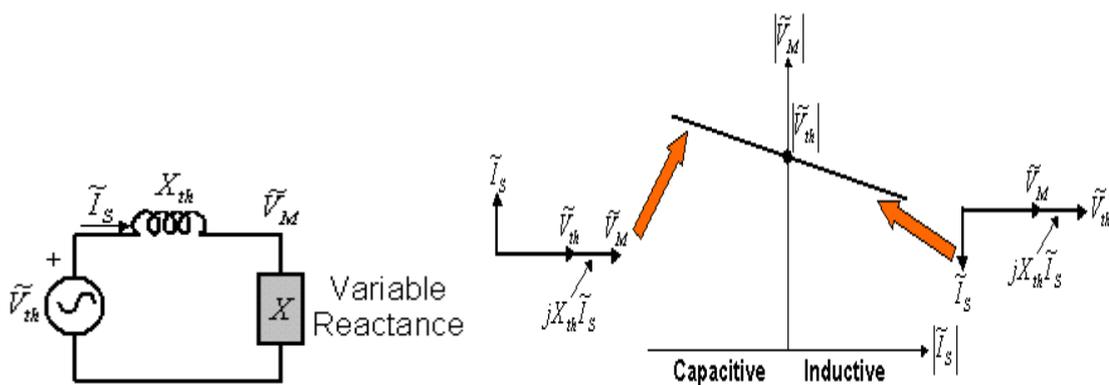
Figure 88: Voltage-current curve without compensation [42]

The capacitive load current raises the midpoint voltage linearly, while the inductive load current decreases it (Figure 89) [42].
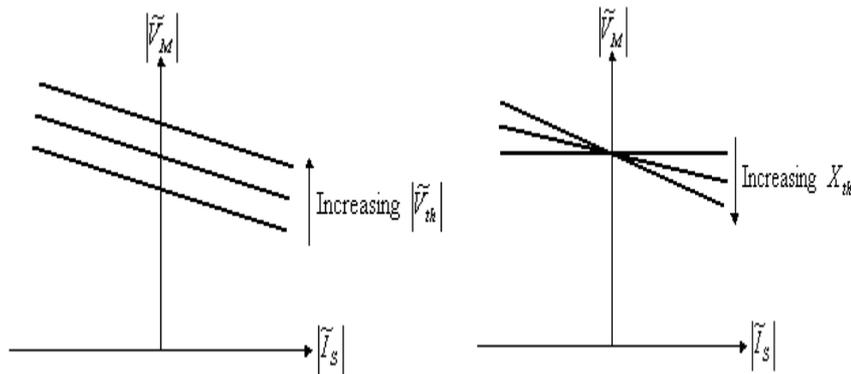
Figure 89: VI curve effects of increasing Vth (left) and Xth (right)-[42]

The SVC building blocks are made of fixed capacitor banks and a combination of one or more than one component of saturated Reactor, Thyristor Switched Capacitor (TSC), Thyristor Controlled Reactor (TCR), Thyristor Switched Reactor (TSR), and Thyristor Controlled Transformer [42].

Thyristor Switched Capacitor (TSC)

TSC capacitor is connected in series with two opposite pole thyristors. Current flows through the capacitor when the opposite poled thyristors are gated (Figure 90) [42].
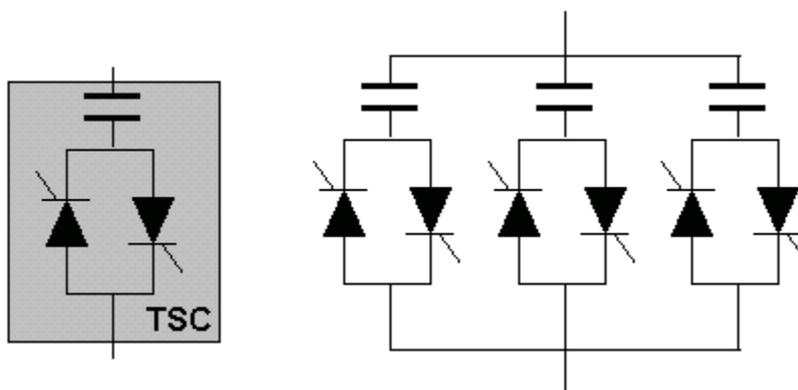
Figure 90: Components of TSC [42]

The effective reactance of the TSC pack can be changed by switching a TSC on or off. An n-pack TSC has effective reactance as [42].

$$X_{eq} = -j\,\frac{1}{k\omega C}\,, k = 0,1, K, n \quad (28)$$

Where k is the number of TSCs conducting

TSC suddenly blocks current or allows the current through it, in Transient-free Switching [42]. Therefore substantial transients occur if a TSC is switching while the current following through it is not zero. If a TSC is supplied by a voltage source V_S and has a capacitor voltage V_C and a current i_C through the capacitor, then as $i_C = C\,(dV_C/dt)$, the current is zero when $dV_C/dt = 0$, i.e., when the capacitor voltage reaches its peak [42]. Therefore for transient-free switching, the capacitor voltage shall be in its positive peak or negative peak during switching on or off. The device must be switched on at a particular instant of the voltage cycle. The capacitor voltage V_C is kept at the peak of the supply voltage when the switch is off indicating an open circuit (Figure 91) [42].
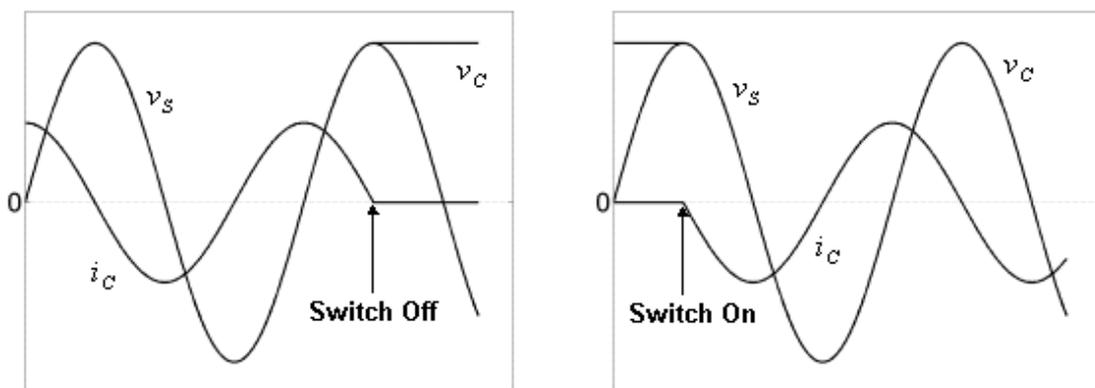
Figure 91: TSC - Transient-free switching [42]

Thyristor Switched Reactor (TCR)

Two opposite poled thyristors are connected in series to a reactor in a TCR. Each of these thyristors conducts in each half cycle of supply frequency (Figure 92) [42].
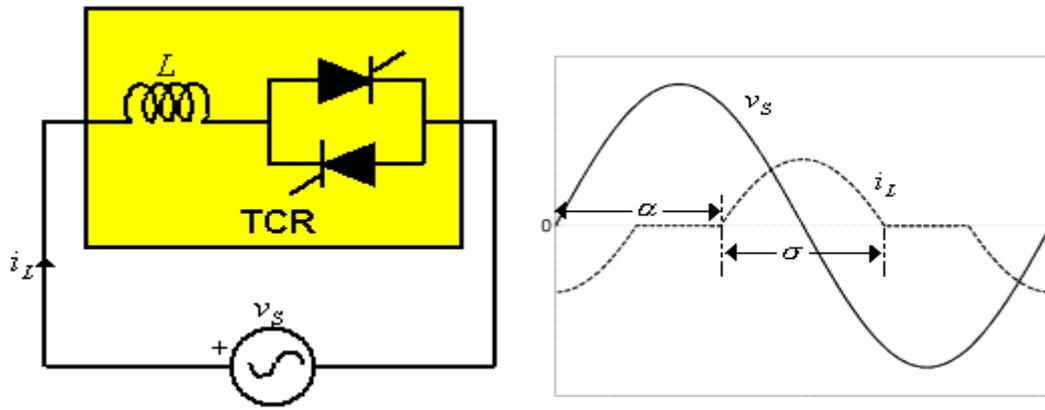
Figure 92: TCR model and VI relationship [42]

The gating signal to each thyristor is delayed by an angle 'α' from the zero crossing of the source voltage (α is the firing angle or conduction angle) [42]. The conduction angle must be in the range $90º \leq α \leq 180º$. For α= 90º, the current will have full conduction and will lag the voltage by 90º. For α= 180º, the current will be zero. (Figure93) [42].
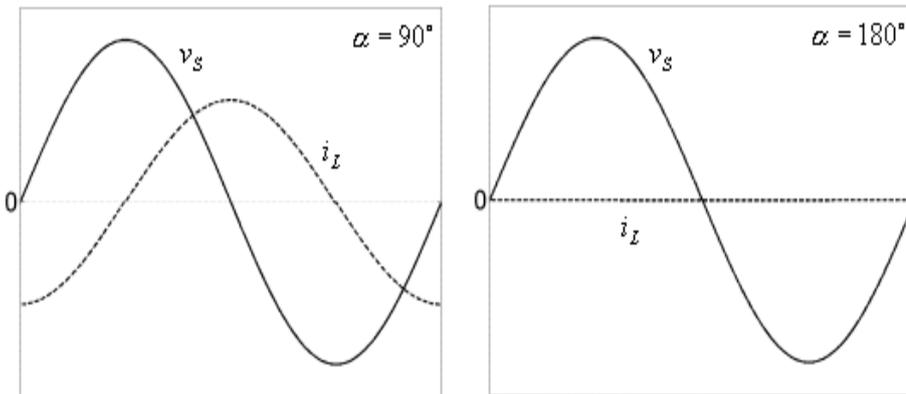
Figure 93: TCR - current relation with α= 90º and α= 180º [42]

The TCR fundamental reactance is given from the below equation [42]:-

$$i_L = \begin{cases} \frac{1}{L}\int_{α/ω}^{t} V_m \sin(ωλ)\, dλ = \frac{V_m}{ωL}(\cos α - \cos ωt) & \text{for } α \leq ωt < α \\ 0 & \text{for } α + σ \leq ωt < α + π \end{cases} \quad (29)$$

The fundamental current is derived from this equation as [42]:-

$$i_{Lf} = \frac{V_m}{πX_L}(σ - \sin σ)\sin(ωt - 90º) \quad (30)$$

Since the TCR fundamental current must lag the voltage by 90º, we have the fundamental frequency susceptance of the TCR as [42]:-

$$B_L(\sigma) = \frac{\breve{I}_{Lf}}{\widehat{V}_s} = \frac{\sigma - \sin\sigma}{\pi X_L} \quad (31)$$

The susceptance is zero for σ= 0º (α= 180º) and reciprocal of the chosen value of XL for σ= 180º (α= 90º) (Figure 94) [42].
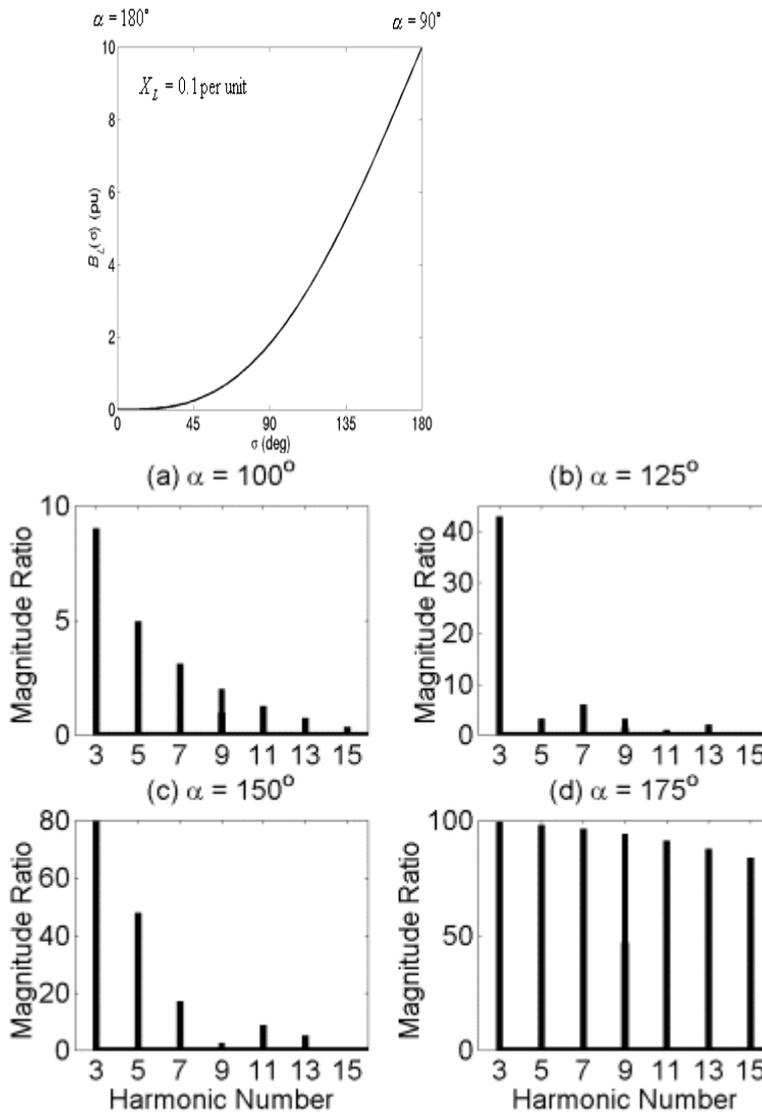
Figure 94: TCR – harmonics [42]

The TCR current will contain only the odd harmonics and doesn't contain dc or even harmonics. The peaks of the harmonic currents are given by [42]:-

$$I_{L-n} = \frac{4V_m}{\pi X_L}\left[\frac{\sin\{(n+1)\alpha\}}{2(n+1)} + \frac{\sin\{(n-1)\alpha\}}{(n-1)} - \cos\alpha\frac{\sin n\alpha}{n}\right], n = 3,5, K \qquad (32)$$

The normalized harmonic a spectrum for various values of α are shown in the next slide. As the firing angle increases, the magnitude of the harmonic currents increases. Both the peak and conduction period (σ/ω) decrease with increase in α resulting in a reduction of the peak of fundamental current and increase in harmonic contents [42].

Static VAr Compensator (SVC)
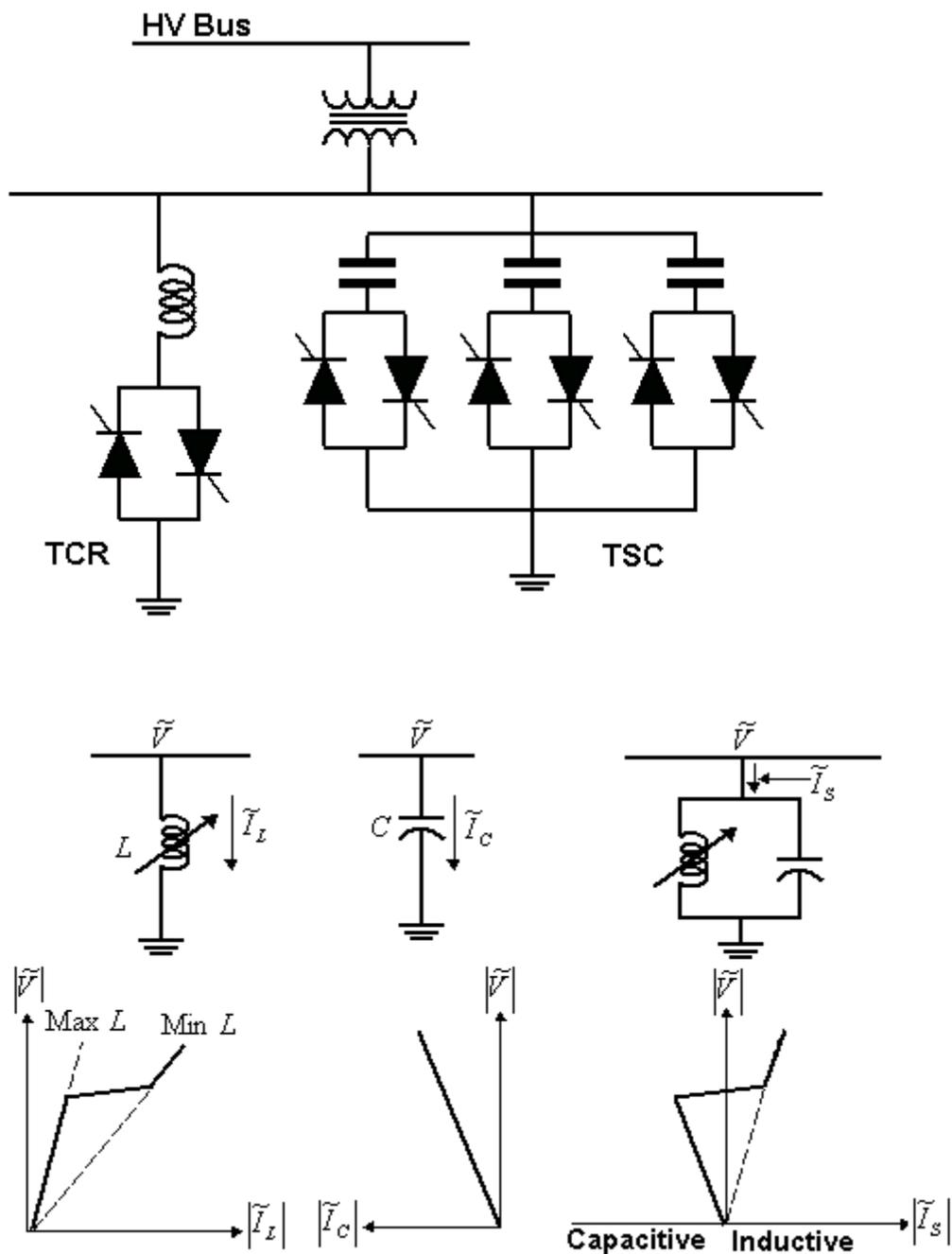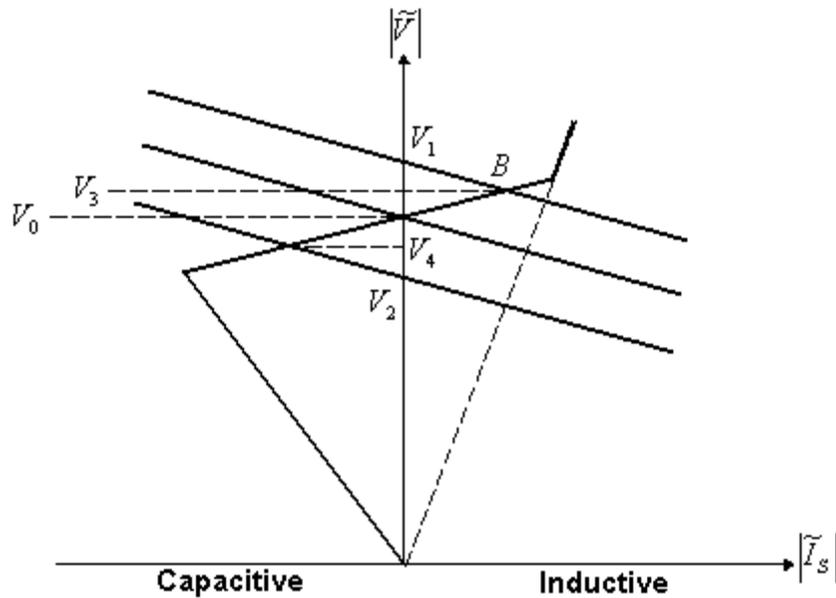
Figure 95: Typical SVC scheme and SVC VI characteristics [42]

When system voltage increases from an operating voltage V_0 (figure above), If the system to V_1, the SVC moves the operating back to voltage V_3 at point 'B' by absorbing the surplus inductive power. On the other operating side, the SVC maintains the voltage at V_4 in case of a decrease in the system voltage (Figure 95) [42].

Synchronous Voltage Source (SVS)

The figure below outlines the main scheme of the synchronous voltage source (SVS). The SVS transformer primaries provide a phase shift of 30º, 12-step output waveform and harmonic spectrum. Each of switches (S_1, S_2 ...S_6) is a two opposite poled thyristors conduct in each half cycle of supply frequency (Figure 96) [42].
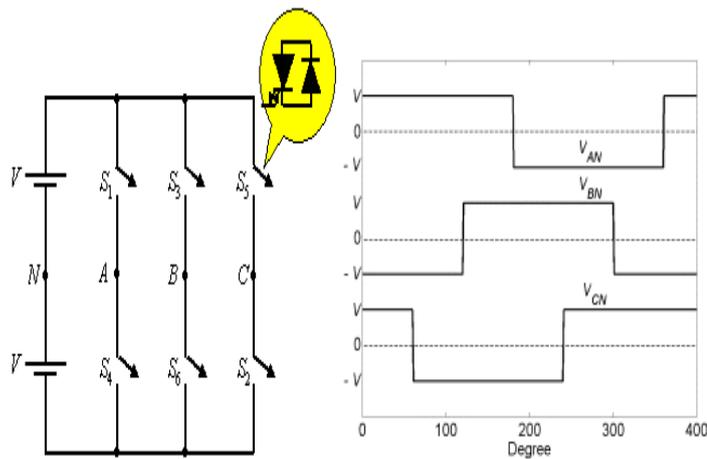
SVS - voltage waveforms
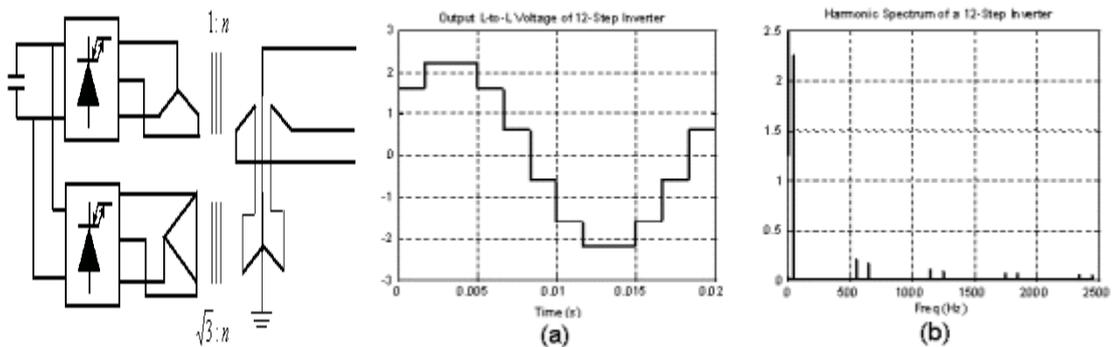
Figure 96: 12-Step SVS-output waveform and harmonic spectrum [42]

Similarly a 6n-step output voltage can be obtained by connecting n basic 6-step inverters and by providing phase shift through transformer connections [42]. Also a 24-step inverter (Figure 97) can be achieved by phase shifting each of the four 6-step inverters by 15º, while a phase shift of 7.5º between 8 basic inverter output will produce a 48- step output waveform. The firing pulses of the 6-step basic inverters must also be phase shifted by 15º or 7.5º to obtain 24 or 48-step output waveforms respectively. The lowest order harmonics in a 6n-step inverter is 6n $\pm$1 in the ac side and 6n in the dc side [42].
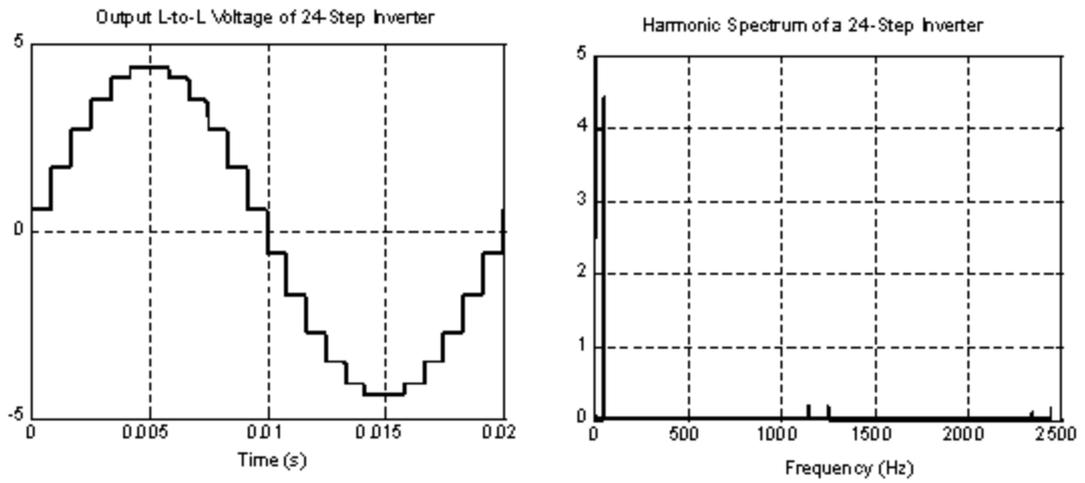
Figure 97: 24-Step output waveform and harmonic spectrum [42]

3- Level Inverter and 5- Level Inverter are shown in the Figure 98 below

	Switch Status			V_{AN}
S_{1a}	S_{1b}	S_{2a}	S_{2b}	
Off	Off	On	On	$-V$
Off	On	On	Off	0
On	On	Off	Off	$+V$

	Switch Status							V_{AN}
S_{1a}	S_{1b}	S_{1c}	S_{1d}	S_{2a}	S_{2b}	S_{2c}	S_{2d}	
On	On	On	On	Off	Off	Off	Off	$+V$
Off	On	On	On	On	Off	Off	Off	$+V/2$
Off	Off	On	On	On	On	Off	Off	0
Off	Off	Off	On	On	On	On	Off	$-V/2$
Off	Off	Off	Off	On	On	On	On	$-V$
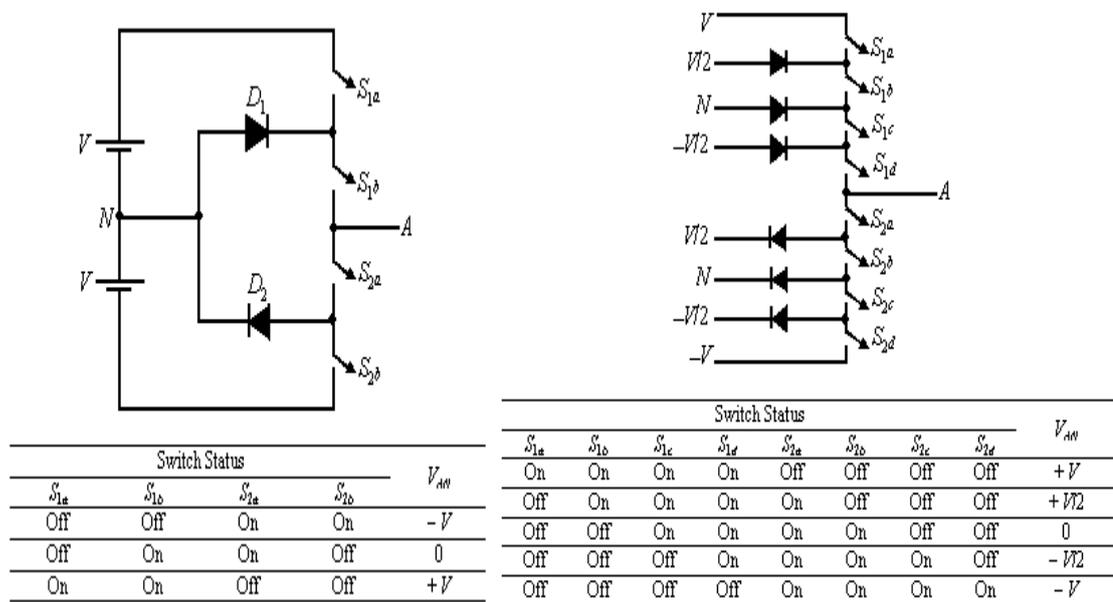
Figure 98: 3-Level inverter and 5-level inverter [42]

Static Compensator - STATCOM

A STATCOM is like an SVS that is supplied by a dc storage capacitor C_{dc} or batteries. The SVS is connected in shunt with the power ac system bus through a coupling transformer with certain leakage reactance [42].
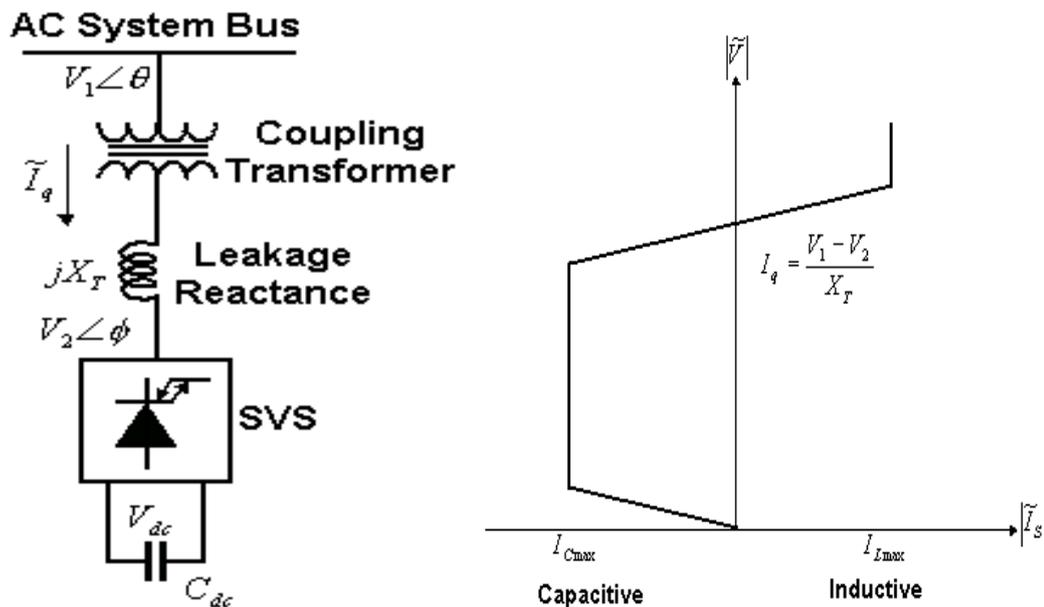
Figure 99: STATCOM - VAr generation and VI characteristics [42]

The reactive power absorbed or supplied by the STATCOM depends on the values of the phase angles (θ, ϕ) and voltages, at the bus and the SVC terminal. If $\angle\theta=\angle\phi$, and $V_1>V_2$, the purely reactive current I_q will flow from the ac network to the SVS and the converter will absorb the inductive power. If $\angle\theta$ is still equal to $\angle\phi$, and $V_2> V_1$ then the current will flow from the SVS to the ac system and the converter generates capacitive power for the ac system. In practice pure reactive injection or absorption may not be possible and is not desirable, since the converter will fall, the voltage across the capacitor falls due to the losses in the STATCOM outside the zero output region. The dc capacitor voltage can be regulated by replenishing the losses due to switching and in the coupling transformer circuit by absorbing power from the ac system. Therefore $\angle\phi$ must lag $\angle\theta$ by a small amount such that the dc capacitor voltage is held constant and hence the converter voltage [42].

In a multi-step converter, the fundamental component of the output voltage is determined by the magnitude of the dc capacitor voltage and the voltage magnitude V_2 can be increased or decreased vis-à-vis the magnitude of V_1 by charging or discharging

the dc capacitor through the control of the angle ɸ. The control loop will become slow, and pulse width modulation (PWM) can effectively be used in a multilevel converter to better the control response. In a sinusoidal PWM, the fundamental component of the output voltage magnitude can be changed by changing either the capacitor voltage or the modulation index [42]. Flying capacitor topology can be used, since the capacitor voltage imbalance problem poses restriction in diode-clamped topology [42].

Below table shows comparison between SVC and STATCOM:-

Table IX: Comparison between SVC and STATCOM [42]

SVC (TSC-TCR Type)	STATCOM
Controlled impedance	SVS
Maximum compensating current is proportional to system voltage.	Maximum compensating current is independent of system voltage.
Low losses at zero output.	Low losses at zero output.
Losses increase in stepped manner with capacitive output, smoothly with inductive output.	Losses increase smoothly with both capacitive and inductive outputs.
Maximum delay is one cycle	Maximum delay is negligible.
Harmonic filtering may be required.	No harmonic filtering required.

Appendix-D: - FACTS and Custom Power Devices Design Characteristics

The recent advancement in FACTS devices is attributed to the successful application of the evolutionary voltage source converter (VSC) technology. The upcoming silicon carbide (SiC) technology is more efficient and expected to supersede silicon technology and could further improve capabilities of FACTS devices by improving efficiency. For example silicon IGBT will be replaced by SiC IGBT. SiC is anticipated to have a better characteristic, less losses, broader band and higher voltage blocking. However it has been said SiC will revolutionize power electronics for a long time, without that much to show for it [16].The FACTS technology has been identified recently as one of key technologies needed for the successful implementation of emerging smart grid and micro grid. In power electronics the principles of electricity physical laws like Ohms, and the simplification methods Thevenin, Norton are still maintained [16]. The principles of physical laws are also maintained that we can't change current in the inductor instantaneously (L*di/dt) and we can't change voltage across the capacitor instantaneously (C*dv/dt). In the old saturable reactor compensator reactor/inductor banks are operated slightly in the saturation and can actually adjust the voltage changes, by the degree of saturation. Some FACTS devices such as SVC's use air core reactors [16]. Voltage Source Converter- VSC is known to have 96-98% efficiency depending on the technology used and can reach like 98% with modular multilevel converters. While the line commutated Current Source Converter- CSC is more efficient (99%). VSC is used more compared to CSC, as true CSC FACTS are not seen although SVC and TCSC are based on CSC technology [16]. While HVDC is mostly CSC however this trend has started to change in the last few years, with more orders (and an explosion in papers) on VSC HVDC [16].

Thyristors are PNPN latching naturally commutated devices means they depend on external circuits to make them start conducting currents. With the gate connected to the first N-type region, the PN junctions will be ready to conduct as soon as they are forward biased, but the NP will not be. By injecting a gate current into the N region, a sufficient number of charge carriers are injected to overcome that barrier [16]. Once the main current starts to follow into the device, it takes the place of the gate current to keep the device on. When the gate current latches the thyristor, it keeps itself on as long as the current flows and the PN- junction will stand in reverse till the current goes to zero. When the current starts to reverse the PN-junction will prevent the current from reversing. So the device is going to turn-off naturally like a diode

(naturally commutated). This is why the gate pulse to turn on a thyristor doesn't need to last for the entire time the devise needs to conduct. Turn on is normally done with gate current ~10 A, 20-40 V [16]. Thyristors can do only lagging power factor operation, but they can't interrupt current and still need external gate circuit to turn them off [16]. Thyristor can be used with a firing delay around zero (minimum firing delay), 3-5° in most cases for static switch it comes closer to zero. For firing delay angle α=0° or α=180° we have one half of the cycle, and most vary from α=0° or α=90°. Similar to IGBT, self-commutating devices like Gate Turn-Off Thyristor (GTO), Gate-Commutated Thyristor (GCT) will be able to interrupt current before natural current zero. With forced commutation, thyristor has an active circuit to force the current zero to make the thyristor off [16].

The Insulated Gate Bipolar Transistor IGBT is an extremely fast opening device with opening time in the range of 10's to 100's of nanoseconds. The IGBT is voltage based gating device and needs an appropriate voltage applied to its gate to turn it and keep it on. The voltage based gate pulse supplies a bias voltage, not a charge; with low power (drive circuit is usually 20 V DC). The IGBT would require the gate pulse to turn them on, to last for the entire time the devices need to conduct. In IGBT the current can be interrupted before it reaches the current zero [16].

Multilevel Converter

Multilevel inverter was first introduced for locomotive motors in Japan and Europe. Traction applications are switching to AC drives instead of DC drives, and needed to have an inverter that goes to higher voltages. In a multilevel converter we can vary the voltage magnitude directly by changing the conduction widths. The effective change in switch timing waits until the next time a level makes a switch transition. The output from multilevel inverter can take different multiple voltage values. 3-level inverter can generate 3-levels of voltages (+V, 0, -V). Multi-level converter will generally have relatively slower response compared to other converters and will not be suitable power applications that require fast response. This voltage topology is also a better way to increase the voltage rating with fewer switches connected in series. Since it needs extra diodes and capacitors, it will cost more than a bridge type converter. The losses are generally less, since even though the converter essentially switches as often, fewer switches are involved in each switching operation [4], [38] , [16].

Modular Multilevel Converter (Chain Link Converter)

The chain link converter is an extension of H-bridge connection and connected as 3-single chain of capacitors. In a chain link converter we can vary the voltage magnitude directly by changing the conduction. The effective change in switch timing waits until the next time a level makes a switch transition for one of the H-bridges. If there are more levels in the chain the converter will respond faster. This voltage topology is also a good way to increase the voltage rating with fewer switches connected in series. This will need more capacitors, raising the cost; however having simpler modules may mean the cost per module is lower. The problem here is that you need to make sure that you balance the voltage between the capacitors in each module. They usually add a slow control loop on the switching to maintain the balance on these capacitors; otherwise you end up with one capacitor having most of the voltage across and shrink on the other two. Before it was not usually suitable to connect between a dc source and supply mains because the energy is not drawn from a single source, however new HVDC systems are using this converter topology [16]. Each dc stage needs to draw energy from electrically separate sources. Some manufacturers use this design as it is cost-effective and has effective control to implement [4], [16], [38].

Pulse Width Modulation- PWM converter

The generated PWM control signal contains a carrier signal and modulating signal. We can vary the magnitude of the voltage by changing the modulation using PWM. The modulation ratio of the PWM scheme sets the magnitude of the ac side voltage (controls Q). The idea of any PWM is basically to take energy from the harmonics and put it in the frequency of switching. In some cases peak amplitude at the carrier frequency may be actually bigger than the fundamental component amplitude. However updates in the modulation ratio show at the next switch transition [4], [16]. The response can be improved by increasing switching frequency. However if switching frequency is increased the switching losses will also increase. If the switching frequency is already causes faster switch transitions than the rate of change of the modulation ratio, a faster control scheme is needed. PWM will tend to have the lowest efficiency (95-96%) with a significant operating cost. The drawback with VSC, it generates voltage harmonics that cannot be trapped using shunt filters and require series devices to round out the edges. PWM is one option to reduce voltage harmonics. Also PWM schemes are more complex if it is required to raise the system voltage rating by connecting the devices in series [4], [16], [21].

Direct and Indirect Controls

The modular multilevel converter is suitable for distribution applications; where unbalanced condition is common practice. Some manufacturers are targeting transmission with chain link converter as they found it more effective control-wise and cost effective to implement. Other manufacturers are using 3-ph bridge or multilevel converter; however this chain converter is better for unbalanced operation. PWM is a fast way of doing direct voltage control. The response time in direct control is as small as one cycle and can have a fast loop for varying reactive power [4], [16].

A direct voltage control scheme can be done by PWM converter, multilevel converter or modular multilevel converter (MMC). Direct voltage control scheme is the one where a command to vary the voltage magnitude on the output voltage directly changes the voltage. The two common ways are to change the modulation ratio in a PWM converter or change the conduction widths in a multilevel converter or in a chain link converter. In all these cases the average voltage is increased or decreased simply by changing timing of the switching, and we can say that |Vdc|=a*k*Vdc where 'a' is the modulation ratio [16].

Direct control is an option to independently control 3-quantities. We change the width of the square wave or we when we do PWM there is sensibility to cut notches to have a better sinusoidal fundamental waveform at ½ pulse switching frequency. With direct control there are two degrees of freedom in control: control Vac to control the reactive power Q and control Vdc to control the active power P. In direct control we can have a response time as small as one cycle (20 ms or 16.7 ms) and we can have a fast loop for varying reactive power, depending on PWM frequency or number of levels in a multilevel converter or chain link [16]. PWM is a fast way of doing direct voltage control [16].

The previous indirect voltage control is used for controlling the ac voltage (Vac) indirectly by controlling the dc bus voltage (Vdc) via charging and discharging the dc capacitor. In an indirect scheme, the ac voltage magnitude is proportional to the dc bus voltage. The switching scheme does not have the ability to directly scale the voltage magnitude, so |Vdc|=k*Vdc. Vdc is the same for all phases and it is very difficult to do phase balancing with indirect control 3-ph bridge. The ac side inductance also is a factor, since it affects the rate of change of a current, but the size of the dc capacitor is a chief factor [21].

In indirect control there will limits and control on the ac and dc voltages. The dc voltage is increased by transferring real power from the ac system ($\delta<90°$) to charge the capacitor and decreased by transferring energy out of the capacitor. The response of the ac voltage magnitude will depend on how quickly the capacitor voltage can increase or decrease. Indirect control is very slow and the time constant of changing the current through the inductance and the time constant of how fast we control the voltage across the capacitor are not going to change quickly. A larger capacitor will slow the response and smaller one will speed it at a cost of sacrificing waveform quality somewhat. The response is also limited by the fact that the phase angle δ can only change twice per cycle to initiate a change in the dc capacitor voltage [4], [16], [21].

The control loop will also influence the response time, but this will be fast compared to the response of the capacitor. These factors limit the response time bridge based STATCOM operating in indirect voltage control mode. The response time for indirect control is about 100 ms because of the capacitor (5/6 cycles on 50/60 Hz systems respectively).

Indirect control transfers power through the converter, while on average of several cycles the ac power (Pac) equals to zero. If voltage on the capacitor keeps going the capacitor insulation may fail. On the other hand when pulling energy out from the capacitor its voltage is going to be lower and lower. There will limit and control on the ac and dc voltages and there are couples of concerns while doing indirect control to keep the device within current limits and the big size of the dc capacitor. Indirect voltage control schemes are generally used for high MVA rated installations (balanced 3-ph) where GTO's are required. The switching losses from the devices are so high that it is more cost effective to build a 24 pulse or 48 pulse bridge (with relatively expensive transformer connections) than it is to tolerate the switching losses.

These installations also generally predate multilevel converters or create 48-pulse with multilevel (Westinghouse) [4]. Now this technology is obsolete and nobody uses this in new installations any more [4], [16]. As a critique and update, this technology is out dated, since there are existing converters using this, but it will not appear in new FACTS devices [16].

Mechanical Switches vs. Static Power Converter

Mechanically switched capacitors will be cheaper than a TSC; however mechanical switches sometimes pose operational restriction to some sensitive and fast varying loads. For arc furnaces or steel mills you will see significant voltage changes between 5 and 10 Hz,

whereas 11 Hz is the most irritating frequency for office buildings [4], [38], [21], [16]. Fast response is required and can't be attained with mechanical switches. This brings the cost difference with TSC down a bit. Drawbacks of mechanical switches can be summarized as follows:

- Slow as response time is a second or less

- Conventional circuit breakers actually interrupt the current at natural current zero and have no synchronization control on voltage to avoid closing on a peak capacitor voltage.

- They have wear and tear and associated operational and maintenance costs.

- They cannot be switched on constantly. So TSC is better, if it is required to switch the capacitor constantly (many times per day or more)

- In terms of control, electro-mechanical controls that might be associated with mechanical switches have inertia and take time to do control functions, while digital control is faster.

Any conventional circuit breaker actually interrupts the current at natural current zero and a capacitor stores a voltage peak across it (current phase angle in the capacitor is 90˚ out of phase with voltage). Mechanical switches connected to capacitor circuit normally have no synchronization control on voltage to avoid closing on a peak capacitor voltage. A mechanical switch when closed on a peak voltage on the capacitor, inrush current and transients will occur. These phenomena could be avoided with voltage measured on the other side of the thyristor and closes when the voltages match. The other trade-offs between mechanically switched capacitors and a TSC that the latter has inherited losses and integral cycle control. Static power converters can be used in these applications instead of mechanical switches for their merits and fast operation characteristics [4], [21], [16].

Static Transfer Switch- STS

STS can be used in essential distribution system to maintain the supply from two independent sources. Static power converters have merits and can be used instead of mechanical switches for applications that require fast operation characteristics. Dynamic Voltage Restorer- DVR (SC with stored energy supply) can respond to voltage dips in less than

a cycle or faster is useful in distribution systems [4]. STS has two thyristors connected back to back not fired continuously and turned on every half cycle. Since thyristors are not fired continuously and just turning on every half cycle we have to have some way of synchronizing the firing pulse. Once STS receives a trip signal, it will stop gating the thyristor and then naturally commutated off at natural current zero and the current will be interrupted. Advantage of STS is a circuit to synchronize with line current zero so we don't accidently interrupt the current when the alternate device is turning on. It is not required to synchronize the current because the current and voltage not necessarily going to be in phase with each other. Once STS receives a trip signal, it is going to wait for the natural current zero to interrupt the current. Thyristor implementation is less expensive. Static power converters have merits and can be used instead of mechanical switches for applications that require fast operation characteristics. Static Transfer Switch-STS can be used in essential distribution system to maintain the supply from two independent sources [4], [38], [21], [16].

Standards and Harmonics Filters

IEEE 519-1992 Standards used in US and Canada for harmonics, while IEC 61000-3/4/5 used in Europe. IEEE 519-1992, IEC 61000-3/4/5 Standards have different philosophies for harmonics mitigation and control. IEEE certain harmonics criteria (TDD and THD) have to be met by the load at the point of common coupling. IEEE 519-1992 regulates the load TDD and THD at the point of common coupling, while IEC standard controls the insertion of load into the power system by virtue of its contribution of the harmonic current to a certain threshold. THD is basically a measure of the harmonics relative to the present current, while TDD is measuring the current relative to the rated current. IEC standard regulates the load that produces the harmonics itself and basically if the content of harmonic current is worse than a certain threshold then the load can't be plugged into the power system

Passive filters are suitable for absorbing low order frequencies, while serious active filters work well in high order frequencies applications. Most of the 5th harmonics currents are going through the shunt filters and the series VSC filter can be used to clean around 7% of the 5th harmonics currents to the satisfaction of IEEE-519 or other standards. Series filter will isolate the harmonics sources from the system as it only passes nominal frequency current and can be viewed as a harmonic isolator. Active filters take less space but will probably cost more than passive filters. They can be tuned for a set of harmonics not just one harmonics and there

is a need for reactive compensation to have a capacitor. Active harmonics filters will help the situation while passive filters interact badly with the rest of the system [4].

12 pulse VSC configurations will still create significant 11th and 13th harmonic voltages, more than acceptable level. Even a 24 pulse configuration will exceed limits such as those from IEEE519. With sufficient design (48-pulse) the final output voltage can be made to approximate a sine wave closely enough so that no (or a very small amount) filtering is required. The 48-pulse configuration moves the dominant voltage harmonic frequencies to levels where a smaller series inductance will provide adequate filtering. The combined harmonic filter consists of both a shunt active filter and a series active filter. The series filter is connected between the main power system and the shunt filter and this combination can be viewed as part of UPQC functions. The effective impedance of an inductive circuit increases with the increase in frequency and the magnitude of the nth harmonic current reduces with increase in the value of 'n'. Therefore lower order voltage harmonics are of concern to any power system and since the power system is mostly inductive, the currents produced by higher order voltage harmonics get attenuated. This implies that the reduction in the current magnitude associated with lower order harmonics is not as significant as the reduction achieved for higher order harmonics. We must therefore try to eliminate the lower order voltage harmonics [4].

Shunt filters: Most loads producing voltage harmonics are going to produce current harmonics; however as a secondary effect of current harmonics few loads directly produce voltage harmonics. We can use a passive shunt filter to shunt current low frequency harmonics to ground. The shunt filter operates primarily on the low order harmonics and for frequencies above this passive high pass filter shall be used [4]. High pass filters will clean 80% of the higher frequency currents and the series filter will clean the rest. The other option is "shunt active filter" only designed to go up to 25th harmonics or lower. [16].

Shunt filters applications: We can add shunt 5th & 7th filters to cancel 5th & 7th harmonics which are the biggest components as 5th is more or less 1/5 of the total current. Actually in the best cases 90% of the 5th harmonics currents are going through the shunt filters. Although shunt filter is passive and limited to just the lower order harmonics it may have some capability to act also as a shunt compensator for load balancing or reactive compensation. However, this will create a trade-off, and may hurt harmonics filter performance. The notch single tuned shunt filters (e.g. 5th, 7th harmonics) are typically de-tuned slightly since the filter impedance at the resonant frequency is too low and the filter can

draw too much current from other sources in the power system at that harmonic frequency. Drawing these added harmonic currents causes two problems: the filter elements may exceed their current rating and the harmonics currents flowing through the power system impedance create a harmonic voltage drop. This can cause voltage harmonics at the harmonic frequency at the filter location, impacting all the loads present there [16].

The shunt filter is instead de-tuned to ensure that an acceptable level of harmonics enters the power system, rather than essentially none as would be the case with an ideal filter that was perfectly tuned. Another reason for detuning filter is that it will be difficult to get the exact values of L and C needed for tuning the filter. In addition, these values will change somewhat overtime especially the capacitance value. Larger filter installations might have taps on the inductor, allowing for some ability to fine tune the filter once it is installed [16].

Series filters: If there is a load that produces voltage distortions, then the cleaning options are a bit limited and can't just have a path to shunt these harmonics to ground. Instead this makes voltage drop and to keep them from spread, series inductors are used to filter the voltage harmonics. The VSC series filter will isolate the harmonics sources from the system as it only passes 50/60 Hz current and can be viewed as a harmonic isolator. It keeps the shunt filter from seeing the current harmonics present on the ac system. As a result, the shunt filter does not try to filter all those harmonics and its current ratings will be more consistent.

The series filter may clean up the remainder of low order harmonics, but it will also get the higher frequency harmonics. The series VSC filter can be used to clean around 7% of the 5th harmonics currents depending on how much it is needed to satisfy IEEE-519 Standard or other standards. Hence VSC series filter could be rated smaller and go for higher frequencies. To be able to filter higher harmonics, the series filter needs a higher switching frequency, so it will be limited in ability to do any other series voltage waveform compensation, although it could do some by circulating power. In realistic converter, this will be quite limited [16].

The exception is that some loads have VSC at the front end and those are fairly low. Active series filter can be used to attenuate current harmonics by inserting a series voltage proportional to the line current and can inject currents 180° out of phase with load currents. Most people trying to install series filters are using three single-phase H-bridges instead of 3-phase bridge as it is difficult to filter the 3-ph independently with 3-phase bridge. Active filters take less space and will probably cost more than passive filters. They can be tuned for a set of harmonics not just one harmonics and anyway you need reactive compensation to have a

capacitor. Putting active harmonics filters will help the situation because passive filters interact badly with the rest of the system.

In power electronics, transformers connection wye/delta, wye/wye has phase shift of 30° and will get amount of harmonics cancellation that makes the filter cheaper. Transformer connection with 30° phase shift can be used with 12-pulse converter while, transformer connection with 15° phase shift can be used with 24-pulse converter and 7.5° phase shift is used with 48-pulse converter. In general 12-pulse configuration isn't enough and even in 24-pulse configuration you have to zoom in upper course of current to see any distortion. Beyond 12-pulse the simple transformer connection wye/delta, wye/wye can't be chosen and the tertiary configuration wye/ wye-delta is needed. The current is good in 48-pulse but the 7.5° phase shift needs complicated transformer configuration that costs higher [16].

Static VAr Compensator- SVC

Static VAr Compensators- SVC comprised of TCR and capacitors normally connected in delta and has half cycle response for 6-pulse configuration and faster response for 12-pulse. The time constant, Td, for the transfer function in SVC is typically 2.5 ms to 5 ms and is 20 times faster than a MSC, but it costs 10-15 times more [16] , [21]. On the average, the TCR-TSC low losses at zero will increase in steps with increasing VAr capacitor output reaching about 1.0% at rated output [16], [21].

The conventional TCR in SVC produces current harmonics and is not able to operate in PWM, since PWM operation requires self-commutating devices. By varying the firing delay angle (α) on thyristor we can change the fundamental RMS current at the expense of producing a lot of harmonic distortion in the current. At firing delay angle (α=0) there will virtually be no harmonics and only the fundamental current will dominate. Harmonic filters are installed in parallel to SVC to shunt the current harmonics to ground, while firing delay angle (α) can be chosen to control a little. In practice the TCR and capacitors will be connected in Δ, and no filtering will be needed for triple harmonics (3, 6, 9, etc.). Harmonics filtering will be needed for 5, 7, 11, 13, 17, 19 harmonics etc. This could be accomplished with notch filters for 5th harmonics, 7th harmonics and high pass filter for the rest [16], [21].

The notch filters for 5th, 7th harmonics will have capacitive contribution to the SVC circuit when operating at the nominal frequency (50 or 60 Hz) and thus will contribute to the required capacitor value on the system as far as the SVC is on. Also 12-pulse configuration can be used to reduce the harmonics produced due to varying the thyristor firing delay angle and will eliminate the 5th and 7th harmonics. In some cases, the triple-n harmonics content are not identical in each phase and their normal cancellation will not take place through the conventional delta connection. This will lead to the generally unneeded operation mode that requires the installation of the third harmonic filters [16], [21].

The overall efficiency of a SVC could be improved if the capacitor banks could all be switched out of the circuit however, but normally not all of the capacitors could be switched off when providing inductive reactive power or even zero reactive power unless the SVC is off entirely. The TCR will need to cancel all of the capacitance first. This will result in a much larger current through the TCR, increasing conduction losses in the thyristor and resistive losses in the inductor and some resistive losses in the capacitors. Also the system will lose ability to filter the harmonics since part of the capacitance will come from the harmonic filters, and they can't be switched out if the TCR is operating. If only one capacitor bank could be switched out, then the TCR current would be reduced by $\frac{1}{3}$ and it would be reduced by $\frac{2}{3}$ if two capacitor banks could be switched out. TCR can only absorb reactive power, making it necessary to switch the capacitors with a net VAr surplus [16], [21]. Thyristors are not able to turn themselves off and interrupt the current. If the thyristors are replaced with IGBT's or GTO's then PWM use is possible, however the circuit topology would probably need to change too to more fully to utilize the IGBT or GTO [16]. PWM produces voltage harmonics with a TSC and in VSC, however PWM would not produce voltage harmonics if used in a TCR type connection since PWM is done in a current source, not a voltage source [16]. In any case, the voltage harmonics cannot be shunt to ground using the parallel filters and require devices such as transformers to smooth out the transition [16]. Harmonic study or harmonic frequency scans shall be done when it is required to install SVC [16], [21].

With unbalanced system voltages the compensating currents in each phase would become different. SVC is good for load balancing since it is possible to control the three compensating admittances individually by adjusting the delay angle of the TCRs for each phase so as to make the three compensating currents identical. It is assuming delay angles for the 3-TCRs to be different to compensate for different phases. The function of this compensator is to make the load balanced and looks like a real power unity power factor load

(resistive) when the line currents drawn by the load are in phase with the line voltages [16], [21].

Normally not all of the capacitors could be switched off when providing inductive reactive power or even zero reactive power unless the SVC is off entirely. The TCR will need to cancel all of the capacitance first. This will result in a much larger current through the TCR, increasing conduction losses in the thyristor and resistive losses in the inductor and some resistive losses in the capacitors. Also the system will lose ability to filter the harmonics since part of the capacitance will come from the harmonic filters, and they can't be switched out if the TCR is operating. If only one capacitor bank could be switched out, then the TCR current would be reduced by ⅓ and it would be reduced by ⅔ if two capacitor banks could be switched out. TCR can only absorb reactive power, making it necessary to switch the capacitors with a net VAr surplus [21], [16]. Thyristors are not able to turn themselves off and interrupt the current. If the thyristors are replaced with IGBT's or GTO's OR PWM use is possible. However PWM also produces voltage harmonics and in a conventional TCR based SVC, the voltage harmonics cannot be shunt to ground using the parallel filters and require devices such as transformers to smooth out the transition. Harmonics Study or harmonics frequency scan shall be done when it is required to install SVC [16], [21].

SVC normally connected in delta and has half cycle response for 6-pulse configuration and faster response for 12-pulse. The time constant Td for the transfer function in SVC is typically 2.5 ms to 5 ms and is 20 times faster than MSC, but it costs 10-15 times more. On the average, the TCR- TSC low losses at zero will increase in steps with increasing VAr capacitor output reaching about 1.0% at rated output [16], [21].

Static Compensator- STATCOM

The Static compensator – STATCOM is a FACTS device based on high power voltage source converters (VSC). The STATCOM, employing will produce the required VAr (Q) for power systems in a linear relationship with voltage, unlike a conventional SVC which has a voltage squared relationship. By varying the capacitor voltage source-VS, in STATCOM by changing the modulation using PWM, one can vary the magnitude of the voltage. The STATCOM produces voltage harmonics and there will be smaller current distortion, moved to higher frequencies than is the case with a SVC. The current distortion could be cleaned up with shunt filters, but the voltage harmonics pose more of a problem and they can induce current

harmonics from many loads, which can cause them to misoperate [16]. They require series filtering to clean voltage harmonics up. One option is to use series inductance; however a lot of inductance is needed to filter the lower frequency harmonics. The compensator will have additional reactive load to compensate from this inductance. PWM operation allows the VSC in the STATCOM to push the harmonic energy up to frequencies where a smaller ac side inductance produces acceptable filtering. However PWM schemes are more complicated if devices need to be connected in series to raise the voltage rating. Also transformer inductance will act as a low-pass filter and will round the edges of PWM and smooth the transitions out (harmonics) at the expense of adding more losses to the transformer, if the transformer needs a higher leakage. For IGBT's, it would be more effective if a VSC STATCOM were built instead of SVC, since there would be significant voltage transients trying to turn off the current through an inductor prior to a natural current zero. STATCOM with chain link converter or with multi-level converter will generally have response slower than PWM, but it will work for some power system needs that don't require fast response. The losses are generally lower than for PWM, since even though the converter essentially switches as often, fewer switches and lower voltages are involved in each switching operation [16], [21].

The STATCOM converter has no internal energy storage and requires the net instantaneous power at the ac and dc terminals of the VSC always be equal. The STATCOM will generally draw balanced sinusoidal currents in quadrature with the system voltages, but the dc capacitor will experience no charging current because no real power is exchanged with the ac system. It is not that much cost and saving to have one capacitor verses three phases and for unbalanced condition. It is better to avoid 3-phase bridge, so as not to exceed the capacitor current rating. There is also inherited voltage sharing problem with 3-phase bridges. In general, the STATCOM will draw a negative sequence fundamental component as well as a positive sequence third harmonic current component. The third voltage harmonics generated in the STATCOM output is unwanted [16], [21]. This is mainly true with slow PWM that resulted from GTOs. Development in a new transmission STATCOM installation will most likely involve modular multilevel converters, which will go back to the idea of individual converters on each phase leg [16]. The STATCOM operation under unbalanced conditions is different from that of the SVC, but both have similar consequences. For such operation the alternating power component at twice the fundamental frequency will appear at the ac terminal of the STATCOM converter. This will be matched by an alternating second harmonics charging current in the dc terminal, producing in turn an associated alternating voltage component of the same frequency across the capacitor shunting the dc terminals [16], [21].

The STATCOM is more expensive and has more losses (even if PWM is not used) and we have to trade that off. In the past real power application PWM is not used as much because of the penalty in losses, until very recently new STATCOMs used PWM, but the very newest designs are instead using many levels (possibly hundreds) [16]. For higher frequencies, the chief delay will be in calculating the new set points; however in general PWM could respond in 2-3 msec. The attainable response and the closed voltage regulation loop of the STATCOM are significantly small. The time constant for the transfer function of the STATCOM is typically 200 μs to 350 μs [21]. The combination of a STATCOM with mechanically switched capacitors-MSC may provide a good and economical solution for many applications. This is because the STATCOM would be able to provide capacitive VAr output immediately upon demand and the additional capacitive output would be delayed by the MSC operation [16], [21].

First generation STATCOMs required a 48-pulse structure to reduce voltage harmonic distortion to acceptable levels, while the second generation STATCOMs used slow PWM or multilevel converters [2] , [3] , [21]. Modern STATCOMs take that a step further by increasing the number of converter levels or increasing the PWM switching frequency. These improvements in performance reduce voltage harmonics, which decreases the need for series filtering to clean them up. One option is to use series inductance; however a lot of inductance is needed to filter the lower frequency harmonics. The compensator will have additional reactive load to compensate from this inductance. The use of multilevel converters also reduces the voltage stress on the power electronic devices and serves to improve efficiency [2], [4], [16], [21].

Other miscellaneous aspects of the STATCOM include its capacity to be integrated with superconducting magnet storage or battery storage, as these integrations can allow a voltage injection with varying angle, while the operation of the approach amid unbalanced conditions has similar potential consequences as the static VAr compensation [2] , [3] , [16].

Series capacitors- Thyristor Controlled Series Capacitor- TCSC

Basic series compensation can be improved through the use of a thyristor controlled series capacitor, as thyristor control can serve to provide fast dynamic response without generating harmonics and requiring harmonic filters. This technology is possible through the

installation of a reactor with a thyristor in parallel with a fixed capacitor, thereby being installed in lieu of conventional switches. Meanwhile, the thyristor controlled series capacitor is integrated within the system in series with a transmission line devoid of coupling across phases [2], [16]. Static Synchronous Series Compensator- SSSC with VSC can also be used to inject voltage to compensate for magnitude change and phase due to a fault in one phase or compensate for magnitude change in three phases. Also a SSSC or TCSC can be used ideally to limit the fault currents in transmission lines by using a power converter that looks like a large inductor when the fault occurs [16], [21], although nobody has implemented it. The chief drawback for conventional SC is the potential sub-synchronous resonance. When designing a series capacitor in a system, it can be put with hydro generation and avoid steam turbines as they may have multiple resonant frequencies below 50/60 Hz. However exciting resonance frequencies above the nominal frequency will help damping oscillations on the transmission lines above 50/60 Hz. Other drawback is the impact on system protection due to protection bypass for out of system faults which leave compensation out of system during recovery from disturbance when is needed most. Series capacitor compensation suits longer overhead lines, but is not practical for use in short overhead lines [16], [21].

TCSC is connected in series with a transmission line with no coupling between phases, while SVC is shunt connected (wye or delta). Harmonic currents (3, 5, 7, 9, 11 etc.) are produced by the TCR in the TCSC, during partial conduction (when σ is at angle other than 0˚ or 180˚). No element is connected in Wye/delta to circulate the triple-n harmonics and the harmonics currents need a circuit to close the conduction path. In TCSC, the easiest path is through the capacitor (circulating current). As a result, only a small percentage of the harmonic current spread into the transmission system, so harmonic current filters are not needed. The capacitor impedance is divided by the harmonics order 'n' as $(1/n)X$. It will look smaller and smaller impedance to harmonics and current harmonics mostly go for the capacitor in TCSC. This is why the TCSC doesn't need harmonics filtering for currents [16].

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Therefore in most cases, filtering or harmonic cancellation through a 12-pulse connection is unnecessary in TCSC. While harmonic filters are not required, harmonic currents are produced by this design in partial conductance, and the impedance of the capacitor is inversely proportional to the order of harmonics. The reduced impedance and tendency from the current harmonics to travel along the easiest path results in only a minimal portion of the harmonic currents being distributed through the transmission system (the reason why filters are not required). The harmonic currents travelling through the capacitor generate voltage harmonics at the frequency through the capacitor, as the impedance to the voltage increases due to the proportional rise with the order of the harmonics [3] , [16]. Ultimately, the voltage harmonics are reduced along the line inductance [4], [16], [20].

The harmonic currents flowing through the capacitor create a voltage harmonics at that frequency across the capacitor (and the TCSC). The largest harmonics voltage will occur at whatever frequencies have the largest current harmonics from the TCR. These would be viewed as harmonic voltage sources connected in series with the line, rather than current sources. While the harmonics order 'n' times inductor impedance (n. X) will make the impedance to the voltage harmonics bigger. Therefore voltage harmonics will get dropped across the line inductance and usually cause a little bit less for power system, but it is an issue with GTO control series capacitor [16], [21]. It will also result in little harmonics distortion (especially since the fundamental component is large). Again, filtering or harmonic cancellation through a 12-pulse connection is unnecessary. The TCSC is normally connected on each phase as a three independent converters. If one wants to connect the TCSC in wye, delta 12-pulse and so on, one would need to interface the TCSC through a transformer. 12-pulse configuration reduces the harmonics produced due to varying the thyristor delay firing and is sufficient for series compensation- TCSC. Controlled series compensation- TCSC can be applied effectively to damp power oscillations. To damp sub-synchronous resonance a resistor can be put in the thyristor circuit what is known as NGH-SSR. This can create fundamental 50/60 Hz resonance and designed so that the lower set range of firing angle looks like an inductor and above that the system works as a net capacitor [16], [21].

Convertible Static Compensator (CSC) – IPFC

One of the used FACTS devices is the convertible static compensator (CSC). CSC was installed before by the New York Power Authority (NYPA), including (IPFC) as a pilot [16]. The CSC-project shall increase power transfer capability and maximize the use of the existing

transmission network. Within the general conceptual framework of the CSC, multi-converter FACTS device, the Interline Power Flow Controller (IPFC), is among many possible configurations.

Generalized/Unified power flow controller- GUPFC/UPFC

One of the potential configuration of CSC and a variation of phase shift transformer is UPFC (Unified Power Flow Controller) which is arguably the most comprehensive CSC FACTS device that is capable of providing active and reactive control, as well as adaptive voltage magnitude control and phase angle regulation. The UPFC is a successful application of the evolutionary voltage source converter (VSC) technology for shunt compensation and series compensation. Till recently only, two UPFCs were used around the world one in USA and one in South Korea. The UPFC has dual function using two VSCs, one shunt VSC similar to STATCOM and one series VSC for series compensation similar to SSSC. UPFC can do more than a phase shifting transformer with two degrees of freedom that can meet multiple control objectives by adding the series injected voltage with appropriate amplitude and phase angle to the sending end terminal voltage.

A UPFC can inject zero power or produce no voltage or produce voltage 90° offset from the current, like SSSC. The UPFC can act as a capacitor and put power into the system or as an inductor and pull power off the system. When the power is non-zero the shunt converter has to be putting this much power back into the system and is circulated through the dc bus [16], [21]. Change in the injected voltage can increase or decrease the real power transfer and changing the angle of the injected voltage will also affect the real power flow. Voltage change coupled with angle change may reverse the direction of the real power flow. The injected voltage can be at any angle with respect to the line current and the UPFC can be used to control power flow through an electrical transmission line connecting various generators and loads at sending and receiving ends [16], [21]. In most cases it is normally required to maintain a constant level of real power flow with the angles variation. The UPFC can also maintain a constant flow through the line no matter what phase angle difference between the two ends of the line. When a constant current is maintained with voltages magnitudes, it is basically just implies that the angle difference between the two ends will vary, but the magnitudes won't vary [16], [21].

UPFC can be used to control the current flow over a branch interconnecting two systems that are normally out of synchronism. It will do this by injecting the appropriate series voltage with an appropriate magnitude and angle until it reaches its limits. It will also probably need very high current ratings on the shunt converter to support the circulating power for the 180° condition. So it will either need a very high rating, or it will need to be tripped, however UPFC is not recommended for such application, unless the systems are kept close to synchronization unless that UPFC has a very high voltage rating for the series injection converter. Otherwise the angle across the line could get larger than the UPFC could compensate, requiring the line to be tripped [16], [21].

The approximate voltage ratings for UPFC shall be determined from different factors. With SSSC we can inject voltage 90° out of phase relative to the current (+/- jX), while UPFC has a greater angle margin including a full circle of magnitude-angle spectrum. UPFC inserted voltage phasor has controllable magnitude from zero to maximum value and angle from 0° to 360°. In general, and for a practical system, UPFC can provide fast reactive shunt compensation with a total control range of 320 MVAr (-160 MVAr to +160 MVAr) and control power flow in the 138 kV high capacity transmission lines, forcing the transmitted power, under contingency condition, up to 950 MVA. Normally UPFC equipment comprises two identical GTO thyristor-based converters, each rated +/- 160 MVA [21].

The converter side voltage is of the main transformer is 37 kV phase to phase (for both shunt and series transformers). The shunt-connected transformer has a 138 kV delta-connected primary, and series transformer has three separate primary winding each rated at 16% of the phase voltage. If utility can afford it can maximize the benefits of installing two identical main shunt transformers and single main series transformers have to be provided with configuration that can provide a shunt compensation with a total control range of +/- 320 MVAr [16], [21].

HVDC

Two lines commutated current source converters:

Consider the topology of basic six-pulse bridge converter, based on line commutated, current source converter with stiff voltage source is on the ac side using GTOs (turn off

thyristors) and stiff current source is on the dc side. The six-pulse current source converter is connected to dc side through a smoothing reactor big enough to remove ripples from the current. We consider this as 1-pole connected to the +ve side of the dc voltage and with ground connection to –ve side of the dc voltage [16], [21].

The current source converter–CSC, topology uses thyristor control rectifier and associated with series dc inductor. The CSC is 99% efficient compared to VSC efficiency 96%-98%. The second six-pulse current source converter will be connected the same way. The second HVDC line will have similar converter topology as described and connected to the first HVDC line. The two current source converters are connected to the ac source via 3- winding wye/wye-delta transformer with certain transformer inductances Xc. This will form 12-pulse bridge and because of Δ/Δ/y transformer 5th and 7th harmonics will cancel and so 11th and 13th will make the harmonics. So we have high pass filters for 11th and 13th harmonics at the transformer primary side. The two lines will be connected point to point with earthing system on the middle to have a clamp on the voltage on this earthing point [16].

Two voltage source inverters: The topology is everything almost similar to above configuration except 3-ph, six-pulse bridge inverter, based on, voltage source converter is used instead of the current source converter. Again assume that the centre point of the dc system is grounded as described above. In both cases A & B the two conductors will be installed on one tower. The voltage source converter–VSC, topology uses DC bus system (capacitor) and associated ac/dc- dc/ac conversion. The VSC has efficiency in the range of 96%-98%.With VSC we are able to reverse the polarity of the current, but the voltage is always fixed. On the other side dc/ac the current polarity does not change and we can reverse the voltage polarity as the thyristor will be facing one-way. The parallel capacitor on the DC side will contribute to the fault current and may produce harmonics.

In both cases this is the rectifier (ac/dc) configuration on the end of the first ac system, while on the other ac system there will be an inverter (dc/ac) topology with the same converter structure described above.

For system response for a fault at the midpoint of the positive pole of the transmission line, for fault on the +ve pole of the transmission line will have a return path to the grounded centre point of the dc system. The current does not reverse and there will be no feed to the earth fault from the negative pole. They actually have controls on these that they measure this

current and then they put offset on the firing delay to keep this current zero. The converter will have very fast, direct control over the firing delay angle α. The converter at the far end of the line cannot feed the fault as it cannot conduct current in the reverse direction. The dc voltage is controlled by firing delay angle as Vdc= Vdo* cosα, where Vdo=3√2/π|Vll| and α is the firing delay angle. If α=0° then Vdc=3√2/π|Vll|= 1.35 |Vll| (the dc voltage will be 35% greater than the ac system line to line voltage). So the dc current is indirectly controlled by changing the firing delay angle α and if we stop sending gating the devices on, they will not stop carrying current. So during earth fault the dc voltage shall be zero to stop the earth current from flowing, i.e. Vdc=0 and this happens when cosα=0 (means α=90°). In normal operation we want to keep α small and the general objective is to keep the primary angle in the neighbourhood of α=15-20° to have a working power factor cosα= 0.97-0.94 respectively. If we set the firing delay angle > 90° we will get a negative number and so we can make the fault on the sending end converter negative and start positive current or fault current. The problem that the devices require time before it can see the forward voltage across it and will forward voltage when the angle passes 180° and hence the devices will shoot away and fail on conducting and tend to recover extinction angle 180° max of conduction. If the firing delay angle gets too big (α=180°) there will be what is called commutation failure and the fault current will fall and rise again [16].

Previously a couple of Henries inductor is installed to control this current and limit the current rise. This dc reactor is very expensive and in the newer system they put a reactor of less than a Henry (H) to cut the cost and try to compensate by changing the converter control. Actually the cost of this inductor is more than all the engineering cost including the design.

Additional protection equipment needed (AC or DC):

The common problem for protection is the ac side. The issue is that the current will not fall to zero immediately on the ac side inductance and there shall be some protection equipment on the ac side. Also the inductance on the ac side limits the transition, so whenever there is a switch from device to another you see commutation overlap in the dc fault current. The RMS ac current equivalent to the dc current Idc will be equal to Irms= Idc √6/π and if the transformer sees all harmonics the true RMS current will Irms= Idc √2/√3 with assumed transformer reactance in the range 12-20%.

The first requirement needed is a suitable circuit breaker at both ac sides of the lines. The circuit breakers shall be attached with suitable protection and tripping control schemes

with associated telecommunication and tele-protection from the fault measurement on the dc. The circuit breaker can also be equipped with suitable over-current and earth fault protective relays.

Control measures

All systems around the world they have one voltage relative to the ground and then another voltage relative to the ground. They don't use the whole return ground. They actually have controls on these that they measure this current and then they put offset on the firing delay to keep this current zero. The reason to keep it zero, if you start to put current through the earth and a path between them you will find a lot of people upset with you because of a lot of interference with electronics. If there is a pipe (water or gas) that follow the same corridor, this current will follow on their pipe conductor and will speed up the corrosion of the pipe line unless other measure is taken.

Suppose we have two systems that are normally out of synchronism. At present there are several HVDC connections linking them, but no ac connections. If the systems are slightly off frequency from each other, the phase angle across this line will vary continuously with the potential for large, uncontrolled power flows, so the HVDC connection is used to decouple the two systems. Would it possible to install AC line between these two systems with a UPFC installed to control the power flows instead of putting a HVDC connection? How would this need to be rated (i.e. what angles can achieve, what approximate voltage ratings, etc.) if it were installed. Assume that the equivalent voltage at each end of the line is 1.0PU and you want to maintain a constant current through the line no matter what the phase angle difference between the two ends of the line does. It is possible to install AC line between these two systems with a Unified Power Flow Controller –UPFC installed to control the power flow instead of putting a HVDC connection.

Application of Power Electronics in Fuel Cells Distribution Energy Systems

Fuel cells can supply energy from the stored primary chemical sources to produce a distribution system of 400V L-L [16]. The system requires a static dc/ac converter to connect them to the distribution network. Criterion has to be defined to choose the inverter taking into account the difference of voltage values between a typical fuel cell (200V, 10 A) and the available industrial network voltage, 400V. The total number of parallel fuel cell stacks depends on the distribution load current flowing and the output current of each fuel cell stacks.

The classical solution for this kind of conversion is a boost converter plus PWM voltage source converter-VSC [16].

Different converter topologies such as a bridge voltage source converter, a multilevel voltage source converter, a current source converter can be used. The most common will be alternative energy generation whether if VSC to connect the fuel cell or even cases of wind generation are going to produce voltage harmonics and they have to meet the Standards [16]. Alternatively, the inserted series voltage is added to the voltage at the point of common coupling such that the device can provide a buffer to eliminate any voltage dip, sag or flicker [4].

Using the Voltage Source Converter- VSC Topology, the alternative energy is considered as a voltage source and shall be connected in series with an inductor. The value of this inductor depends on the permissible dc current ripple and on the pulsation frequency of the PWM. A switch with two semiconductors a diode plus an IGBT are used on a 3-ph, bridge configuration. The capacitor is normally connected in parallel with additional series connected diode and IGBT, for bi-directional blocking. The three PWM voltage sources represent the three-phase distribution network together with the output filter capacitors [16]. VSC converter may need more switches and an IGBT compared to CSC for current blocking in the reverse direction. If this is going to be connected to build distribution system then three- single phase bridges is better than 3-ph bridge as distribution system will always be unbalanced. Centre grounded point will provide voltage clamp at the grounded middle point between the two voltage sources or fuel cell stacks (+/- Vdc) [16].

Using Current Source Converter- CSC Topology, PWM -CSC based on IGBT can be used. A matrix converter is also studied for this connection with CSC [16]. The topology can have switch with two semiconductors, an IGBT used on a 3-ph-bridge configuration. Bi-directional blocking switch is needed and the switches have to be able to block negative and positive voltages. The PWM current source inverter is connected, in series with an inductor, to the three phase distribution network. CSC type of converter has more conduction losses than the other topologies, depending on input current. The PWM CSC has some advantage, as it commutates less and has less commutation losses than VSC. The switching power losses in the PWM, CSC is smaller than those in a boost plus PWM, VSC. The power circuit for CSC is simpler and has no intermediate electric energy storage [16]. For higher power application GTO thyristors can be used, however for distribution system applications, the preferred device usually is the IGBT as it can carry fairly large current and has a fast switching characteristics

and low losses. There is an N-type diode that inherent in the IGBT package or added to GTO and GCT, but is not needed in CSC [12]. It is not recommend reversing the current either under transient operation or due to current ripple driven by the converter and additional series diode and IGBT are needed for blocking. For balanced load, though the load currents are balanced and do not contain any triple harmonics, the neutral current may not always be zero in the steady state. The initial excursion neutral current is due to the inverter circuit in forcing the currents through the inductive load. However, the transient dies down very fast and the neutral currents settle around zero. There will be a high frequency ripple in the neutral current due to switching action, but the average current has the desired value of zero. For zero sequence unbalanced load, there will be a significant neutral current; in addition, the high frequency switching ripples are also present in the neutral current. It can be connected with anti-parallel diode. The chain link convertor is suitable for distribution, and this may however be strength for photovoltaic or fuel cell applications [4].

Appendix-E: - Optimization of Power Losses

This Appendix derives the optimization of power losses formulae in transmission network. The research work in this Appendix is an individual research effort of the Writer of this doctoral thesis, with the help of other references in the field. The research topic is 'Determination of Power Network Losses Using Decoupled Techniques'.

Optimization Technique:-

Transmission losses are given by:-

$$P1 = \sum_{n=1}^{K} Pn - Pd \qquad (33)$$

Where

K = number of plants

Pn = output power of the n-th plant

Pd = total demand of the system

For a specified operating conditions Pd is constant and for any change in active generation, there is a corresponding change in transmission losses, so to discuss this relation the following quadratic formula connecting P1 and Pn may be suggested:

$$P1 = \sum_{m=1}^{K} \sum_{n=1}^{K} Pm \; Bmn \; Pn \quad \text{(transmission loss formula)} \qquad (34)$$

Bmn are the B-coefficients (1/MW) and must be determined. The incremental transmission loss (I T L) can be obtained by differentiating the equation.

For any plant n

$$\partial P1 / \partial Pn = 2 \sum_{m=1}^{K} Pm \, Pmn \qquad (35)$$

For minimum transmission losses

$$\partial P1/\partial Pn = 0 \ \text{ or } \sum_{m=1}^{K} Pm\,Pmn = 0 \qquad (36)$$

Hence an optimum set of plant outputs can be determined by solving the equation. The technique used is to equate this equation to a parameter λ

$$\sum_{m=1}^{K} Pm\,Pmn = \lambda$$

After that reasonable incremental values of λ are taken and the corresponding plant loading P1, P2, PK are determined using the elimination technique discussed in Chapter 2. For each set of plant loadings, the constraining the relation should be less or equal to some tolerance. If this equation is not satisfied, then a new value of λ is taken. Once this equation is satisfied, then the corresponding P1, P2, PK are the optimum plant outputs.

To follow this optimization technique, then it is necessary to determine the B-coefficients.

Determination of the B-Coefficients:

Differentiating the equation with respect to Pn one obtains:-

$$\partial/\partial Pn\,(\partial P1/\partial Pn) = \partial^2\,P1/\partial Pn^2 = 2\,Bnn \qquad (37)$$

And differentiating the equation again with respect to Pm gives:-

$$\partial/\partial Pm\,(\partial P1/\partial Pn) = \partial^2\,P1/\partial Pm\partial Pn = 2\,Bmn \quad (38)$$

Thus if the second derivatives of the system transmission, losses with respect to plant outputs can be found, the B-coefficients can be determined.

The left hand side I T L the equation can be written as:-

$$\partial P1/\partial Pn = \sum_{j=1}^{N} \partial P1/\partial\,\theta j \ . \ \ \partial\theta j/\partial Pn$$

θj = phase angle at bus j

N = Number of buses in the system.

The term $\partial\theta j / \partial Pn$ stays constant for any change in plant outputs or load levels around the operating condition. This term can be referred to by a set of constants Ajn. The I T L for any plant 'n' can then be rewritten as:-

$$\partial P1/\partial Pn = \sum_{j=1}^{N} \partial P1/\partial \theta j \ . \ Ajn \qquad (39)$$

Differentiating equation with respect to Pn and Pm, the following two equations would be obtained for the B-coefficient constants:-

$$Bnn = 1/2 \sum_{i=1}^{N} \sum_{j=1}^{N} \partial^2 P1/\partial \theta i \partial\theta j. \ Ain \ . Ajn \quad (40)$$

And

$$Bmn = 1/2 \sum_{i=1}^{N} \sum_{j=1}^{N} \partial^2 P1/\partial \theta i\partial\theta j. \ Aim \ . Ajn \quad (41)$$

Expression For $\partial2 P1/\partial\theta i\partial\theta j$:-

The transmission loss P1 can be expressed in terms of voltage magnitudes and phase angles as:-

$$P1 = 2 \sum_{n=1}^{N} Vn^2 \ Gnn \ - \ \sum_{n=1}^{N} \sum_{K=1}^{N} Vn \ Vk \ Gnk \ \cos \ (\theta k - \theta n) \quad (42)$$

Gnk = conductance between buses n and k

If the bus voltages are assumed constants then the first derivative of P1 with respect to θj is:-

$$\partial P1/\partial\theta j = 2 \sum_{K=1}^{N} Vj \ Vk \ Gjk \ \sin \ (\theta k - \theta j) \quad (43)$$

Differentiating equation (12), first with respect to θj and second with respect to θi, the following generalized equations would be obtained:-

For $\quad i \neq j$

$$\partial^2 P1/\partial\theta j^2 = 2 \sum_{K=1}^{N} Vj \ Vk \ Gjk \ \cos(\theta j - \theta k) \ - \ 2Vj^2 \ Gjj \quad (44)$$

For i = j

$$\partial^2 P1/\partial\theta i\partial\theta j = -2 \ Vi \ Vj \ Gij \cos(\theta i - \theta j) \quad (45)$$

Calculation of the A-Constants: -

The term Ajn represents a change in phase angle θj for a change in plant Pn with all other plants remaining constants. The steps followed to determine Ajn are as follows:-

A base case load flow must be carried out to determine the power at the slack bus and also the voltage magnitude and angle at each bus.

The total demand power is increased by 5% and the total demand power plus losses is supplied by any plant taken as slack bus. The changes in phase angles θj for all buses are determined. This determines the first column of the A-constants matrix.

Then another plant is taken as slack to supply the same demand as stated in step (2) plus the new losses. This step determines the second column in the A-constants matrix.

The process is repeated for every plant in the system. Therefore if an N-bus system contains G plants, the order of the A-constant matrix is N x G.

Derivation of the equations:-

Expanding equation (2) assuming that we have 3-generators in the system:

$P1 = P1^2 B11 + P2^2 B22 + P3^2 B33 + 2P1\ P2\ B12 + 2P1\ P3\ B13 + 2P2\ P3\ B23$

Differentiating P1 with respect to P3

$$\partial P1/\partial P3 = 2P3\ B33 + 2P1\ B13 + 2P2\ B23 = 2\sum_{m=1}^{3} PmBm3$$

Differentiating $\partial P1/\partial P3$ again with respect to $\partial P3$:-

$$\partial/\partial P3.\ (\partial P1/\partial P3) = \partial^2 P1 / \partial P3^2 = 2B33$$

Generalizing for any generator n, the previous equation follows as:-

$$\partial^2 P1/\partial Pn^2 = 2Bnn$$

Similarly $\partial/\partial Pm\ (\partial P1/\partial Pn) = 2Bmn$

Derivation of the equations:-

Expanding equation, assuming a 3-bus system

$\partial P1/\partial P1 = \partial P1/\partial\theta1.\ A11 + \partial P1/\partial\theta2.A21 + \partial P1/\partial\theta3.\ A31$

$\partial Pl/\partial P = \partial P1/\partial\theta1.\ A12 + \partial P1/\partial\theta2.A22 + \partial P1/\partial\theta3.\ A32$

Then

$\partial^2 P1/\partial P1^2 = \partial/\partial P1[\partial P1/\partial\theta1.\ A11 + \partial P1/\partial\theta2.A21 + \partial P1/\partial\theta3.\ A31]$

Thus

$\partial^2 P1/\partial P1^2 = A11\ [\partial^2 P1/\partial\theta1^2.\ \partial\theta1/\partial P1 + \partial^2 P1/\partial\theta2.\partial\theta1.\ \partial\theta2/\theta P1 +$

$\partial^2\ P1/\partial\theta3.\ \partial\theta\ .\ \partial\theta3/\partial P1] + A21\ [\partial^2\ P1/\partial\theta1.\partial\theta2.\ \partial\theta1/\partial P1 +$

$\partial^2 P1/\theta2^2\ .\partial\theta2/\partial P1 + \partial^2 P1/\partial\theta3.\partial\theta2.\ \partial\theta3/\partial P1] +$

$A31\ [\partial^2 P1/\partial\theta1.\partial\theta3.\partial\theta1/\partial P1 + \partial^2\ P1/\partial\theta2.\partial\theta3.\ \partial\theta2/\partial P1 +$

$\partial^2\ P1/\partial\theta3^2\ .\ \partial\theta3/\partial P1]$

Substituting for the partial derivatives of phase angles with respect to plant outputs, by Ajn yields:-

$\partial^2 P1/\partial P1^2 = A11^2\ .\partial^2 P1/\partial\theta1^2 + A21^2.\ \partial^2 P1/\partial\theta2^2 + A31^2.\partial^2\ P1/\partial\theta3^2 +$

$2A11.\ A21.\partial^2\ P1/\partial\theta1.\partial\theta3 + 2A11.\ A31.\ \partial^2\ P1/\partial\theta1.\partial\theta3 + 2A21.\ A31$

$\partial^2\ P1/\partial\theta2.\ \partial\theta3$

Generalizing for n-generator in the system:-

$$\partial^2 P1/\partial P^2 n = \sum_{i=1}^{n}\ \sum_{j=1}^{n}\ \partial^2 P1/\partial\theta_i.\partial\theta_j.\ Ain.\ Ajn$$

Other equation follows in the same way:-
Derivation of the equations:-

Expanding equation for a 3-bus system:-

$$P1 = 2V1^2. G11 + 2V2^2. G22 + 2V3^2 .G33 - V1^2 G11 - V2^2 G22 - V3^2, G33 - 2V1.V2. G12. \cos(\theta1 - \theta2) - 2V1.V3. G13. \cos(\theta1 - \theta3) - 2V2. V3. G23 \cos(\theta2 - \theta3)$$

Differentiating P1 with respect to θ1 twice, one obtains:-

$$\partial^2 P1/\partial\theta1^2 = 2V1. V2. G12 \cos(\theta1 - \theta2) + 2V1 .V3 . G13. \cos(\theta1 - \theta3)$$

$$= 2\sum_{k=1}^{3} V1. Vk. G1K. \cos(\theta1 - \theta k) - 2V1^2.G11$$

Generalizing for N-bus system:-

$$\partial^2 P1/\partial Qj^2 = 2\sum_{k=1}^{N} Vj\; Vk. GjK. \cos(\theta j - \theta k) - 2Vj^2.Gjj$$

Results:-

A simple 3-bus system was discussed.

The optimum loss of this system was determined following the optimization technique steps. The A-constants were calculated manually with this aid of the load flow results obtained for the system. These constants can be calculated using the computer as a part of the optimization program. The A-constants are calculated only once at the beginning of the program since they are independent of load increments around the operating conditions.

The following steps represent the procedure followed to obtain optimized losses of the 3-bus system. A base load flow of the system was carried out and the results obtained are shown in Table X.

Table X: Base load flow result. Losses = 0.045 pu

Bus No.	Voltage	Angle	PG	PL
1	1	0	0.545446	0
2	1	- 0.009044	0.5	0
3	0.898367	- 0.08220	-	1

The total load demand was then increased by 5% and the load flow results obtained are shown in Table XI.

Table XI: Load flow result for 5% increment in total demand. Losses = 0.04818

Bus No.	Voltage	Angle	PG	PL
1	1	0	0.59818	0
2	1	+0.007376	0.5	0
3	0.898367	- 0.088558	0	1.05

With the same load in step (2), bus (2) was then taken as slack, the load flow results are presented in Table XII.

Table XII: Load flow result for 5% increment in total demand (bus 2 is slack). Losses = 0.04841

Bus No.	Voltage	Angle	PG	PL
1	1	- 0.002831	0.545446	0
2	1	+0.009042	0.552962	0
3	0.898367	-0.089714	0	1.05

Note: - all values are in pu based on 300 MVA

The A-constants were obtained using the results in the steps. As defined before the A-constants are given by:-

$$A_{jn} = \partial\theta_j / \partial P_n \approx \Delta\theta_j / \Delta P_n$$

From the load flow data in the tables.

$$A11 = 0$$

$$A21 = \frac{0.007376 - 0.009044}{0.59818 - 0.545446} = -0.0316304$$

$$A31 = \frac{-0.088558 + 0.0822}{0.59818 - 0.545446} = -0.1205673$$

From Tables (1) and (3)

$$A12 = \frac{0.002831 - 0}{0.552962 - 0.5} = -0.0534534$$

$$A22 = 0$$

$$A32 = \frac{-0.089714 + 0.0822}{0.552962 - 0.5} = -0.141873$$

The B-coefficients using the computer were found to be:-

$$B11 = 0.0309 \quad , \quad B12 = 0.0243$$

$$B21 = 0.0243 \quad , \quad B22 = 0.0358$$

Computer result for minimum losses was found as presented in Table XIII:-

Table XIII: Optimum condition for the system. Optimum losses = 0.015 PU

Bus No	Base Pg	Optimum
1	0.545	0.545
2	0.500	0.470

$$\lambda = 0.06$$

Since the load increment in the steps is small, the voltage magnitude for the load bus (3) is assumed constant. The voltage can also be maintained constant at generator buses (1) and (2) by varying the exciter. Hence the assumption made in deriving the A-constant formula is satisfied.

Appendix-F: - Authors' Publications- Doctoral Research Published Papers

The following nine papers were published by the PhD Authors in different international conferences held in USA, Europe, Asia and the Middle East during the course of this research work from 2007 to 2012. Eight papers from the mentioned nine below are used as references in this study except one which is in the study focus as it is related to measuring human exposure to magnetic fields.

Paper I:

Elsayed H, Cham E, Al Jaidah Y, Al Najjar A. (2013) 'Towards Smart Power Grid in Qatar: Application of STATCOM and Composite Conductors'. The paper was presented and published in the 4th Arab Union of Electricity General Conference, held in Doha, Qatar, between 7-9 January 2013.

Paper II:

Elsayed H, Borya M, Al Jaidah Y, Amoussouga E, Al-Marri S, Al Najjar A. (2013) 'Battery Storage and PVs Energy Conversion System to meet Summer Peak in Qatar: A reasoned choice among potential Smartgrid solutions'. The paper was presented and published in The 4th Arab Union of Electricity General Conference, Doha, Qatar, 7-9 January 2013.

Paper III:

Elsayed H, Abu Eida S, Chaudhry S, Al-Mahmoud A. (2012) 'Dynamic Control of Voltage and Power Flow in Qatar Transmission System'. The paper was presented and published in Session A1, Paper A103, Cigre GCC Power 2012 Conference & Exhibition_ Oman 12th – 14rd November 2012.

*The paper has been selected as one of the best three applied research papers in the conference.

Paper IV:

Elsayed, H.I.; Johnson, B.K.; Lai, L.L. (2012), 'Online Systems Potential Applications in Intelligent Power Grids'. The paper was presented and published in PES IEEE General Meeting, San Diego, California, USA, 22-26 July 2012.

Paper V:

H.I. Elsayed, S.R. Chaudhry, A.-A.A. Al-Mahmoud (2012), 'PV, Battery Storage and Energy Conversion System for Meeting Peak Load in a Substation'. The paper was presented and published in CIRED and IET 2012 Workshop_ Integration of Renewables into the Distribution Grid Lisbon, Portugal, 29-30 May 2012, www.cired2012-workshop.org. IEEE Xplore Digital Library E-ISBN: 978-1--84919-628-4, Digital Object Identifier: 10.1049/cp.2012.0758.

Paper VI:

K. El Lithy, S. Al-Suwaidi, H. Elsayed, 'Measuring Human Exposure to Magnetic Fields near EHV 400 KV GIS Substation and Power Lines in the State of Qatar'. The paper was presented and published in 2011 North American Power Symposium, Boston, Massachusetts, USA, August 4-6, 2011.

Paper VII:

El-Sayed, H.I. ; Chan, K. ; Al-Jomali, A.A. ; Johnson, B.K. ; Lai, L.L. (2010), 'Operation Enhancement by Power Flow Controller - An Investigation in the Qatar Transmission System'. The paper was presented and published in The IEEE 2010 Power and Energy General Meeting, Minneapolis, Minnesota, USA, 25-29 July 2010.

Paper VIII:

H.I. El Sayed, B.K. Johnson, L.L. Lai, N. Tse (2009), 'Investigation into the advancement of FACTS and their implementation impact in a Utility'. The paper was presented and published in The 8th IET International Conference on Advances in Power System Control, Operation and Management, APSCOM2009. Kowloon Shangri La Hotel, Hong Kong, 08-11 November 2009.

Paper XIX:

Elsayed, H., Sasono, P., and Lai, L. (2007), 'Risk Assessment and Mitigations of Electronic/Cyber Intrusions into SCADA, DCS and LAN Systems of a Utility'. The paper was presented and published in 3rd GCC CIGRE International Conference and Exhibition (GCC Power 07), Dubai, UAE, 05-07 Nov. 2007.