Intelligent Technique Based Digital Differential Protection For Generator-Transformer Unit

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DECLARATION

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ABSTRACT

The requirement of digital differential protection has become more and more severe with the increasing capacity of Generator-Transformer unit and the development of power industry. An advanced principle, its application and perspective of differential protection are developed in this thesis.

Firstly, it is demonstrated in principle why the scalar product differential protection is more sensitive than the percentage differential protection. Then a best solution for the choice of two quantities ($\dot{I}_{max}$ and $\dot{I}_{\Sigma-1}$) of the product is achieved. The possible potential problems of the scalar product differential protection due to its sensitivity to phase angle are also put forward. A novel protection principle on ANN techniques is then proposed which breaks through the former ANN application bottleneck in relay.

Secondly, a new method to distinguish inrush state using multi-condition restraint criterion is presented. Incorporated with the introduction of breaker switching state and transformer voltage state, the transformer working state such as inrush, short circuit, fault-recovery inrush, sympathetic inrush, switching on unenergized fault transformer, and fault right after switching on unenergized transformer and so on can be differentiated by the multi-characteristics of inrush current. Moreover, there is no direct relation between the inrush restraint method and tripping time during switching on unenergized fault transformer. It is suggested that special over-excitation restraint function in the transformer differential protection is not necessary.

Thirdly, anti-CT saturation principles based on speed control, trap setting and deceleration are presented for preventing mis-tripping of differential protection. All these methods possess good performance in actual practice. The percentage restraint differential protection performance is analyzed both theoretically and practically when CT is saturated. Conventionally, mis-tripping is blocked during CT saturation. But in fact when external fault occurs, the calculated data are very easy to enter the action zone but will not stay too long because of continuous transient status of CT transient saturation. Accordingly, the transient process of digital algorithm and time staying in action area are also crucial to avoid the mis-tripping in addition to the percentage restraint characteristic.

At last, the sensitivity of the differential protection is discussed. It is pointed out clearly in this thesis that the differential protection sensitivity should be understood in a comprehensive way. Sensitivity is closely related to the principle, setting and realization of protection, which contribute to the direction to improve sensitivity. Object-Oriented software design method for protection brings forward a platform for digital protection research. Additionally, due to the protection configuration it is intended to emphasize main protection and simplify backup protection for generator and transformer unit.

Keyword: Digital Differential Protection, ANN application, Inrush current, CT Saturation, CT break

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Dear Authors,

This is to confirm that the following papers are invited ones of ICMLC2004. Due to the printing error, the invitation is not shown in the proceedings. I am sorry for that.

Wang Xizhao, Conference Co-Chair of ICMLC2004

Neural network based generator-transformer protection
Lu Yuping[1], L. L. Lai [2] and Tang Guoqing[1]
1. Southeast University, China
2. City University, London, UK

Medical diagnostic image data fusion based on wavelet transformation and self-organising features mapping neural networks
Q. P. Zhang[1], W. J. Tang[1], L. L. Lai[2], W. C. Sun[1] and K. P. Wong[3]
[1]Fudan University, China, [2]City University, London, United Kingdom
[3]Hong Kong Polytechnic University, China

Intelligent weather forecast
L. L. Lai[1], H. Braun[2], Q. P. Zhang[3], Q. Wu[3], Y. Ma[1], W. C. Sun[3], and L. Yang[4]
[1]City University, London, UK, [2]RebusIS, UK
[2]Fudan University, China, [3]Shanghai Meteorology Center, Shanghai, China

A structural representing and learning model based on biological neural mechanism
Wei Hui and Tang Hui-Xuan, Fudan University, China

A parallel evolutionary programming based optimal power flow algorithm and its implementation
C. H. Lo, C. Y. Chung, D. H. M. Nguyen, K. P. Wong
Computational Intelligence Applications Research Laboratory (CIARLab),
Department of Electrical Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong

LIST OF ABBREVIATIONS USED IN THE THESIS

I_d Differential Current

I_z Restraint Current

n_l Ratio of current transformer

I_n Neutral current of generator

I_T Terminal current of generator

I_n Terminal current of generator

$I_{J.bp.\max}$ Maximum unbalanced error current of relay

$\dot{I}_{J.cd}$ Unbalanced error current of relay

I_g Trans-point of curve of differential relay;

I_q Pick-up current of differential relay

K_s Slope of the differential relay curve(scalar product principle);

K_z Slope of the differential relay curve(ratio-proportional principle)

$\dot{I}_1$, $\dot{I}_2$, ... Currents of each side of transformer.

$I_{\max}$ Maximal current of each side of transformer

$k_{\max}$ Branch number of $I_{\max}$

$\dot{I}_{\Sigma-1}$ Sum of all currents of transformer but $I_{\max}$

W_{ij} Weight of first layer of ANN in differential protection

A_{jk} Weight of second layer of ANN in differential protection

η_2 Ratio of 2th harmonic current to fundamental

θ_{dz} Less current area (angle) in inrush current

λ Symmetry level of inrush current waveform;

$I_{2\omega}$, $I_{1\omega}$ Second harmonic and fundamental frequency component content;

$\eta_{2h.dz}$, $\eta_{2l.dz}$ High and low threshold settings of second harmonic restraint.

K_i Switcher state of the number i side of breaker;

jT Number j cycle;

Ue Rated voltage.

I_e Rated current

U/f Voltage over frequency

ε Less voltage threshold

U_{2dz} Negative sequence voltage

L_2 Load inductance

ψ Flux of transformer

i_{aL}, i_{bL}, i_{cL} Three-phase currents of the low-voltage side

i_{aH}, i_{bH}, i_{cH} Three-phase currents of the high-voltage side

I_{to} Current of t_o time;

$I_{f.\max}$ Maximum current;

ΔI_{to} Biased current of t_o time;

I_{t1} Current of t_1 time.

ΔI_{t2-t1} Differential current between the time t_1 and t_2.

K_{lm} Sensitivity of differential relay

N Branch number of generator.

a Branch number connected to differential relay.

$P(x)$ Approximate polynomial

k_1, k_2, Adjusting coefficients of every A/D channel

Chapter 1 Introduction

With the continuous development and progress of the electrical power industry, the unit capacity of a generator or transformer becomes larger. In China, the capacity of thermal electrical generators has reached 600MW, and the capacity of hydroelectricity generators grows to the extent of 750MW. The capacity of nuclear generator units will even exceed 1000 MW. When the cost of generators and transformers in the investment keeps increasing, on the other hand, the enhancement of network connection, the electric distance (connecting impedance) between the system and customers becomes shorter because of the improvement of network structure and. The capacity of a single unit only makes a smaller portion of the gross capacity of the system. It means that is to say, generator units become further away from customers. In overseas systems, disconnection of a generator (about 1000MW) will not cause much impact to the system and the reserve capacity in the system will fill up the gap of load quickly. The customers will hardly or even not be able to detect the disturbance. The domestic conventional idea is not to trip generators or transformers in order to ensure the security of the system except for emergency of them. However, with the development of modern electrical power system, these concepts are also changing and enriching. For protection, system safety and its cost are always a pair of contradictions that need to be balanced. As equipment cost increases, if a fault outside the protection region or in the device under protection is not handled in time or causes permanent damage to the device, the loss will be unimaginable. Especially in 2002, China are reforming power electrical industry. The independent management of power plants and transmission network is an inevitable trend. The economic and safe operation of power plants becomes an important factor. Thereby digital protection will be confronted with more rigorous requirement. Conventional protection theory, method, even idea will be changed fundamentally.

1.1 The development stages of digital protection

1.1.1 The simple realization stage

During 60's to 70's, computer technology was in its primal stage, and its application was not widespread. Digital protection was just in stage of theory and laboratory investigation. Research and reports in our country still represent the works of this stage.

At the beginning of 1965, P.G.McLaren of Cambridge University published a paper about realizing transmission line distance protection by sampling technique [1]. At the latter half of 1966, I.F.Morrison of University of New South Wales further researched theory questions about application of computer technology in relay protection, and gave a series of different algorithms [2]. All these works generally stayed in theory and laboratory investigation, but it also built a good foundation for the application of computer technology to relay protection. The real computer protection prototype did not come out until the end of 60's [3].

G.D.Rockeffeller of Westinghouse Electric Corporation started researching a practical equipment of digital protection in 1969 [4]. In 1972, they published the principles and field experiment report of the researching prototype. This is the famous project Proda-70 in the history of digital protection [5]. It helped us to understand AC sampling, gave a whole set of scheme in hardware and digital protection in software. Both this theory and scheme is hitherto the foundation of digital protection. It had basic elements of digital protection such as sampling, protection software, trip output, self-testing, etc.

After that, the R&D of digital protection accelerated remarkable. In 1972, G.K.Lagcock of Cambridge University finished his doctoral dissertation about constructing a distance protection using a computer under P.G.McLaren's direction. In 1977, M.A.Marin of the University of Bath used finite element spectrum analysis and realized distance protection on super high voltage long transmission line, and achieved a quick protection operation speed. In this period, major foreign companies began R&D of digital protection. For instance, at the beginning of the 1975, P.B.Allison and T.H.Lomas of GEC (Britain) applied computer to substation control and auto-reclosing, and achieved a very good result. In 1977, Japan also put forward digital protection into field operation [6].

1.1.2 The stage of digital protection realization and widespread deployment

In the 1980s, digital protection developed rapidly, and theoretical research carried on in depth.

1) Digital technology make advanced theory widely used.

One overriding concern about applications of conventional technology was that whether the technology could be realized by the industry at the time. An excellent theory that can't be comprehended is useless. In China, only 3% of technology inventions are utilized. Although there are many subjective and objective factors, in our country relatively lag in digital technology is also a major cause that results in much waste of manpower, material and financial resources.

Through the development of protection theory, we can find that in electromechanical relay period, primary concern of implementation method is whether it can be realized in electromechanical way. So current, voltage relays and their logical combination are generally used to improve the performance of protection. In the rectifier and transistor protection period, phase comparison and amplitude comparison principle was widely used. At the same time, suitable analytical method and theories were also developed. This made a solid foundation for the protection advancing to a higher stage. Analysis of these theories and methods shows the major research emphasis focus on how to reduce adverse impact which electrical power system brings to the protection through simple realizable approach. For instance, dead zone of impedance protection, directionality problem, overreach problem, transition resistance problem and so on. During integrated circuit protection period, using of some digital technology brought the methods and techniques of protection to a new step. But the speed and depth of theoretical development can't compare with the transistor period. The following emergence of digital protection is an epoch marking change in the protection history.

Digital protection is an entirely digitalized protection. It is formerly called microcomputer protection, but now it tends to be called digital protection. The term of digital protection can reflect the characteristic of the protection of this generation more exact since the naissance of digital protection, protection technology was divided into two parts the first part is the sensor, which turn analog signal or other signal required by general protection principle into digital signal that can be recognized by computer system (analog signal usually converted by A/D conversion). However, it doesn't need much theoretical research so sensor technology researchers have done it very well. Our mission is applying it to digital protection, and controlling electrical power system according to the computing results with protection hardware.

The second part is the theory of protection. Once the signals needed are digitalized, almost every theory can be realized by digital protection. This has been proved by the development of digital protection. All kinds of new theories and methods have been extensively used in digital protection. Now ANN theory has made remarkable progress in the application of protection. People need not consider reliability too much, and can concentrate on sensitiveness, selectivity, quick operation, safety and reliability of protection. So, the emergence of digital protection makes realization of protection principle quite simple. In fact, people have found that digital protections in different principle in protection have the same appearance, For example, they have similar hardware. Protection of different principles can be realized by similar or the same hardware, this indicates that the protection realization has become simpler.

2) The digital technology simplifies the realization of digital protection.

Because of the development of integration technology, IC has more and more functions and includes all kinds of categories. The emergence of many ASIC provides new approaches for conventional integration technology. For example, appliances such as telephone, mobile phone, and VCD player only have one major IC. This makes these equipments shrink in size, and raises the cost competition at the same time. Practice has shown that implementing multiplication, division, differential, integral and memory by hardware connections circuit is very complex. Even if some functions are implemented, sometimes the safety level of system will not be very high and the accuracy of system could not fulfill the theoretical demand easily. The implementing method by computer not only has a better safety and reliability, but also satisfies accuracy of theoretical analysis. Usage of high performance DSP greatly increases computing speed. The adoption of MCM package technology can further reduce the IC footprint. Along with the development of IC technology, modularization and standardization of protection hardware, the IC order volume will increase which makes the application of ASIC becomes possible. Therefore, digital technology is continuously simplifying the implementation of digital protection.

3) Digital technology greatly enhanced performance of protection.

The digital technology has some generally acknowledged feature, such as nonvolatile memory, convenient data access, powerful arithmetic and logical capability.

Once the analog signals are digitalized and additional errors will not occur or be limited in a theoretical region and digital protection will not suffer the error alteration caused by hardware replacement. Therefore the digital technology will greatly improve accuracy and speed of protections. (For example, the protection time stage decreases to 0.3 second). Of course, new digital protection principles and methods continuously proposed are the major reason of protection performance increase.

4) Digital technology promotes safety and reliability of relay protection.

There are only two states of “1” and “0” in the digital technology, but not an indistinct middle state, which established a foundation for high reliability and safety of the digital technology.

In daily life, people know that video and audio information on DVD and VCD disc realizes will not deteriorate with the lapse of time. Satellite launch, missile guide and so on all benefit from high reliability and safety provided by the digital technology.

Relay protection can also be designed as digital protection with sufficient redundancy and high reliability. For example, the data integrity verifying methods of CRC widely used in communication can almost detect 100% incorrect data.

If higher data reliability is required, information returned and verification used in breaker operation of integrated automation technology can be adopted to ensure correct data transmission. With digital protection, sometimes, important data will be stored several times on different addresses to guarantee the data are correct and valid.

5) Digital technology simplified relay protection maintenance and made commissioning convenient.

The technique level of digital technology is complex and cutting-edge, but it brings us excellent performance, easy operation and friendly interface. The digital technology can complete many missions that are formerly done by human brainwork.

The usage of digital protection promotes operation, administration, maintenance, and commissioning of relay protection to a higher step. Besides fulfillment of protection function, the digital protection has its powerful self-check mechanism to detect almost every hidden danger of the protection equipment that may cause incorrect operation.

Friendly and fullproof style operation can greatly simplify maintenance, and can even avoid mistaken operation caused by negligence by checking setting and connections.

1.1.3 The developing trend of digital protection

The general developing trend of digital should be maintenance free and fullproof intelligent techniques, that is to say, flexible design, high performance index, easy operation and worriless maintenance.

1) The design is more and more flexible.

As we know, primary system design of power plants and substations are diversified. Primary systems of different voltage classes and equipment capacities are very different. Because differences of power system network structure, even primary system constructed by the same equipment is different. Of course, the understanding to the system of each designing institution is not completely the same, thereby identical power plant or substation may have different design. Therefore, if the main equipment protection is designed with architecture similar to early transmission line digital protection (Early transmission line digital protection generally assumes primary systems are same, and it is enough for the digital transmission line protection). It can not meet requirements of main equipment protections. Main digital main equipment protection designing and researching will produce 'invariable' protection to adapt variable primary systems according to this particularity. Digital protections will adapt to different primary systems automatically by an architecture whose I/O and function module can be defined and connected at will, all kinds of requirements can be fulfilled.

Now, overseas companies like ABB, domestic southeast university, and etc. have adopted this idea in digital main equipment protection design and R&D. Digital main equipment protection developing in recent years have also demonstrated that the idea have unlimited vitality in market.

2) The more advanced the principle is, the more perfect the performance is.

Digital protection could almost implement any new method and new principle tenable in theory, and provides a platform to boost relay protection performance. More than that, the emergence of digital protection fundamentally changes the way of digital protection development.

For a simple example, there are two kinds of protections in conventional protection, low voltage overcurrent protection and compound voltage overcurrent protection. And it is acknowledged that compound voltage overcurrent protection has a higher sensitivity than low voltage overcurrent protection, but for conventional protections, because it is difficult to implement the negative sequence voltage component of compound voltage overcurrent protection, the two kinds of protections have different cost and price. Thereby, there are cost performance differences in applications and configuration. But if implemented by digital protection, the hardware and software cost can be regarded as just the same. Now that compound voltage overcurrent protection surpasses low voltage overcurrent protection at performance, it is unnecessary to keep two kinds of protections. In theory, low voltage overcurrent protection could be deserted and substituted by compound voltage overcurrent protection. Thus protection configuration can be simplified, and sensitivity, safety, and reliability of protection can be also improved.

For further discussion, conventional protection consists of particular protection component units, so sharing information (e.g. current, voltage, and other analog signals) is almost impossible. While electrical power system is in a fault state, its behavior is quite complicated. In general, conventional protections choose one or several characteristic quantities from fault phenomena to distinguish fault property and category. They can't utilize and synthesize all fault characteristics and types. Furthermore, fault discrimination sensitivity and selectivity is somehow restricted. The emergence of digital protection could change the situation revolutionarily.

a) Information share

Once analog signals have been sampled to digital signals by digital protection, they are not restricted to be used in a certain protection component. Digital protection such as generator differential protection actually can make full use of all collected information to perform protection function. Theoretically, it only needs generator terminal current and neutral point current in differebtial relay. If generator voltages are normal when relay start up, it is better to verify the judgment of generator differential protection to avoid possible false judgment. Apparently, this information share does not cost more hardware.

b) Synthetic protection

Since that fault behavior is variable and the digital protection has the potential to convert all the behavior to digital quantities, relay protection researchers are absolutely capable to put forward protections that utilizing fault characteristics synthetically to improve both sensitivity and selectivity and to eliminate the dilemma between sensitivity and selectivity.

c) New methods and ideas

As to transmission line protection, because transmission line fault involves an extensive range (nearby systems), it's quite difficult to gather all the failure information. However, in power plants and substations, information is very concentrated. Information required by main equipment protection mostly focuses on plants and stations, and can be acquired easily. This brings up the possibility of researching protection issue in a new approach and new thinking. Now, there are already reports about applications of expert system, fuzzy control, and artificial neural network in relay protection, and remarkable effects have been achieved. But at present, these technical applications still mostly concentrate upon improving singular protection performance. As to applications of theory such as artificial neuronal network, it is entirely practicable in theory and more reasonable to take power plant or substation as a whole in protection construction.

In summary, digital protection brings bright future to relay protection staff.

3) Protection is free of maintenance.

First of all, we introduce the definition of “maintenance free”. The idea of maintenance free means that while equipment or device doesn't require maintenance, it is in good condition and doesn't need an overhaul. While its lifetime expires, the equipment should be discard as useless. That is to say, the equipment has very consummate self-checking and self-maintenance function. It is able to detect any equipment fault in time by examining itself and inform maintenance staff to request an overhaul 'initiatively'. Maintenance free can't guarantee that equipment will never fail, but it tells maintenance staffs what is the situation when a fault occurs.

Apparently, these feature required equipments must be intelligent and digital protection is no other than an intelligent protection system. Theoretically speaking, implementing 'maintenance free' is absolutely possible. As a matter of fact, besides protection function, now numerous digital protection devices have hardware and software self-checking at idle, and handle device fault that has a strong impact on safe operation in time. Consequently, digital protection safety and reliability greatly increased, but objectively speaking, such self-checking is still secondary. Sometimes it needs maintenance staffs’ participation yet to get a 'confirmed diagnosis'. It's yet far away from maintenance free target, but it is delightful to see digital protection increasingly developing to this direction.

Maintenance free is essentially different from 'repair free' concept of appliance adopted by some overseas enterprises in meanings. At household electrical appliances design and manufacture, to make full use of raw material and reduce the production cost, components with a certain lifetime are chosen. As an example, a TV set, suppose that its design lifetime is 5 years, then lifetime of its internal components is also 5 years. Thus, while the service life of TV set expires, for instance some fault occurs, even if the fault is very slight, it's unnecessary to repair. The best way is to replace it with a new generation TV set, because a repair might make the condition even worse. Apparently, difference between maintenance free and repair free are: a) the former has comprehensive self-checking, whereas the latter has not; b) the former requires components of high quality and with the ability of repair ability; c) the fault of latter is depended on human to judge which doesn't conform to maintenance free; d) the latter considers more in commerce (hope bad appliances turn into sales), and the former considers more in industry application. Of course, while the service time of the former has reached prescribed time-limit of standard, even if the equipment function normally, equipment replacement should be list in agendum to ensure equipment safety, and it's also in favor of technical development.

4) Artificial characteristic is introduced to protection equipment[41-47]

So-called 'artificial' characteristic is to wish that all behaviors of equipment (include operation, running, maintenance) could completely proceed according to users' custom and bent. That is to say, protection should act as how users want it to act and do what users want it to do. Relay protection job is a high tech and a risk management and control task. People working in this domain generally suffer from great stress. Electrical power system is a complex system inferior to social system. Its management, operation and maintenance are already quite complicated in normal state. When electrical power system needs safety control and emergency control, it is the very time that relay protection should work correctly. In addition, considering situation such as electrical power system operation affected by power swing, the operating behavior of relay protection is very difficult to predict. Any slight error in working may cause unthinkable consequence.

The emergence of digital protection can relieve such stress. Current digital protection is already able to do as more as possible working formerly done by human, or help human to test and judge equipment characteristics. Actually digital protection can do more and better. Digital protection can fully utilize its intellectualized feature, take a further step at present condition to 'avoid' possible human mistakes, and makes digital protection staff can work in a favorable environment. A simple example is that an alarm about unreasonable settings is sent out when contradictory setting, irrational setting, setting exceeding confine and so on are found. For instance, the setting of 3Uo(zero-sequence voltage) based generator grounding protection is usually between 5-10V; generator overload protection setting should not be less than generator rated current, and setting parameter should not deviate too much from protection interior checking parameter, and Current setting and history setting disagree with each other, and so on. Hence, accidental setting mistakes can be avoided.

Of course, complete applications of 'artificial' to digital protection will take a long period, but if we consider 'artificial' characteristic as prerequisite for R&D digital protection, protection operator's stress can still be greatly relieved.

5) Multiple functions are integrated in one unit[48-91].

Digital protection can integrate fault data recording, RTU, data acquisition, system control, etc, and tremendously simplify secondary devices of power plants and substations. These functions require similar hardware, and could be implemented without much additional cost if these factors have been considered when designing digital protection.

6) Protection is interconnected intelligently.

Digital protection certainly is a member of electrical power system automation. Information sharing and network interconnection will be an inevitable trend.

Network development, especially popularization of Internet, on the one hand, makes information of digital protection share by different kinds of automatic system, such as SCADA, DCS (distributed control system), EMS, etc. On the other hand, protection manufacturer through Internet can connect digital protections, and distributed maintenance & administration of digital protection by manufactory becomes possible. By that time, running and operating of digital protection all over the country can be clearly obtained from Internet. Monitor and even control of protection units can be realized at any position around the world.

1.2 Development of digital differential protection [92-132]

Suppose protected equipment has n terminals and input current direction is the positive direction, while protected equipment has no internal fault (including normal running and external fault), then $\sum_{i=1}^{n}\dot{I}_i = 0$, i.e. the sum of input current must equal to the sum of output current.

When the protected equipment has an internal fault, the fault node becomes a new terminal, at that time $\sum_{i=1}^{n}\dot{I}_i = \dot{I}_d$, where I_d is short-circuit current of the faulted node.

In theory differential protection could be very sensitive, because its operating criteria can be written as $\left|\sum_{i=1}^{n}\dot{I}_i\right| > 0$, Although the equation $\sum_{i=1}^{n}\dot{I}_i = 0$ certainly exists, primary current requires flowing through a current transformer to protection unit. Due to the error of current transformers, $\sum_{i=1}^{n}\dot{I}_i / n_L = \dot{I}_{J.cd} \neq 0$ ($\dot{I}_{J.cd}$ means unbalanced current), the unbalanced current must be considered. So differential protection operating criteria should be rewritten as $\left|\sum_{i=1}^{n}\dot{I}_i / n_L\right| = \left|\dot{I}_{J.cd}\right| > I_{J.bp.\max}$ ($I_{J.bp.\max}$ is the maximum unbalanced current of differential protection).

Because the current signals from each side that differential protection senses have passed through several transferring stage, and the characteristic of these primary and secondary stages certainly will affect transferring, which will affect the performance of the differential protection. Primary system problems include transformer-magnetizing inrush current, over-excitation, and secondary system problem include CT saturation, CT secondary open-circuit, etc. At the same time, after signals introduced into a protection unit, they will also be affected by small CTs and performance of filters and data acquisition system. Finally, different digital filter algorithms have different impact on differential protection performance. Problems of every stage may cause differential protection to mal-operate. Therefore, the protection algorithm should adopt different countermeasures against the troubles from different stage to eliminate the adverse effects.

The following sections will discuss the performance and characteristic of different theories and methods, together with the current situation and development of both varios differential protection techniques.

1.2.1 Transformer differential protection

For transformer protection, each terminal is theoretically not a physical node. So the unbalanced current is also affected by the transformer exciting branch circuit. For instance, exciting current increases caused by over excitation, and inrush current caused by switching on an unloaded transformer are difficult puzzling problems to be understood. At present, puzzles met by researchers mostly related to magnetizing inrush, CT saturation and over excitation. The more severe situation is that these problems might take place simultaneously, which makes the problems more difficult. For example, if magnetizing inrush and CT saturation occurs simultaneously, then dead angle will disappear. This brings difficulty to differential protection based on dead angle restraint. Another example is that an internal fault drives CT into saturation. In this case, the differential current will have ample second harmonic, and may cause differential protection based on second harmonic restraint component to mal-operate. To deal with these problems, both foreign and domestic researchers put forward many solutions such as research about magnetizing inrush current waveform characteristics and adding voltage signal for fault judgment. Other ways include some signal analysis methods, protection principle criteria improvement. Magnetizing inrush current characteristic criterion extensively applied in China is DC component, dead angle, second harmonic or even harmonic, but these methods more or less have some problems. For example, DC component restraint sometimes lacks DC component of one phase when magnetizing inrush of three phases occurs. Furthermore, differential protection based on DC component 'quick' saturation will certainly delay operation during internal faults conditions. For dead angle restraint, dead angle during primary magnetizing inrush may disappear at secondary side of instrument transformers.

Whereas presently applied transformer differential protection principle can be divided into two categories, namely applied conventional methods and some intelligent theory, for example, ANN, fuzzy principle, wavelet principle, etc. These principles will be discussed separately in following paragraphs.

(1) Conventional methods

Second harmonic restraint [7] makes use of the characteristic of the even harmonic content, in particular the second harmonic, is usually high in the magnetizing inrush current. Therefore if the second harmonic of differential current is figured out and its amplitude is comparatively high, differential protection will distinguish whether or not magnetizing inrush current happens. Second harmonic restraint is simple and clear, and it has been applied to conventional protection. The implementation of this restraint method with microcomputer is easier than with that of other conventional protection. Thereby, current foreign and domestic practical computer transformer protections in service adopted this restraint method in general. However, transformer protection with second harmonic restraint has its limitation. When transformer terminals connected to long transmission line or static compensation capacitance, the internal fault transient current may also cause considerable second harmonic. Thereby, the growth of system and the increase of operating modes make the second harmonic not a distinct characteristic of inrush current. In the case of severe internal faults, large transformers may resonate and produce considerable second harmonic that will delay protection operation. The method utilizing second harmonic current to identify inrush current has successful application and rich practice. In addition, at present foreign and domestic practical operating computer transformer protection mostly adopted this restraint, so it is relatively well developed.

Dead angle restraint distinguishes internal faults and magnetizing inrush by the voltage waveform characteristic when magnetizing inrush takes place (inrush waveform has obvious characteristic of deal angle) [8]. Our country takes the lead in putting forward dead angle restraint and makes prototype. Its analogous protection units have already applied in field. Compared with second harmonic restraint, dead angle restraint has the following advantages: utilizing the obvious waveform characteristic of inrush current, which can make it clearly distinguish internal faults and magnetizing inrush; usually adopting individual phase inrush discrimination method and will immediately trip transformer internal faults; having some ability of anti-overexcitation. However, the implementation of dead angle restraint with microcomputer has two difficulties: One is correct measuring of dead angle, and anther is dead angle waveform distortion caused by CT.

(2) Neural network method

The key problem that the ANN application to transformer protection is to solve is identification of inrush current too. Many home and abroad scholars have launched researching in this domain. Paper [9] utilized transformer two sides current, two sides negative sequence current, one phase instantaneous current value, harmonic contents of differential currents and primary side current dead angle to synthetically identify transformer internal faults, external faults, magnetizing inrush, over excitation and so on. Its neural network samples use both real sample and training sample. This method is able to correctly identify different states of the transformer and has a response time less than 10ms. Paper [10] puts forward a neural network inrush current detection method, and uses neural network to restore primary current when CT is saturated. This method can rapidly identify inrush current and reconstruct primary current after CT has been saturated. Papers [11, 12] use sampling value as characteristic input of neural network and use real experimental data as sample data. In test, this method can effectively distinguish transformer inrush current and internal short-circuit faults and paper [11] has implemented the method with DSP hardware.

The key issue of neural network applications to transformer differential protection is the sample selection. Due to difference of transformer models and core manufacture, samples are not representative. Trained neural network can only be used for trained transformer, and its applicability to all transformers cannot be guaranteed. Thereby practical ANN applications need a further study. Paper [29] puts forward a completely new technology about ANN theory application in relay protection, ANN technology based on protection principle[30]. The technology incorporates relay protection theory, which has been developed for a few decades, and ANN intellectualized feature fully carry forward respective advantages, so presents an effective way to implement high performance and high reliable protective relay devices. Its principle will be expounded in the 3rd chapter at length.

(3) Fuzzy method

Conventional protection setting is a definite value, but fixed setting is not entirely reasonable. The settings should be properly adjusted according to operating condition to increase protection reliability. Fuzzy criteria can compound advantages of different kinds of inrush criteria, and adjust the influence of each criterion through weight factors. Even if a certain imperfect criteria make a mistake, it will only cause fuzzy quantity membership function to depart, and will not lead to a false result. Consequently, protection performances greatly increased.

Paper [13] analyses conventional protection criteria, and uses fuzzy set theory to improve scalar product restraint differential protection criteria. New criteria sets fuzzy coefficient according to operating rule, and introduces the correlation coefficient, so as to adapt two-winding, three-winding transformers, as well as different kinds of operation mode.

Paper [14] introduces a two-CPU microcomputer two-winding transformer differential protection based on fuzzy theory. The differential protection operating criteria integrates both scalar product restraint principle and sudden change principle. Fuzzy control coefficient is revised by software in time. The protection can guarantee a high sensitivity of internal faults, especially in turn-to-turn short circuit, and reliable non-operation during external faults conditions.

Papers [15, 16, 17] develop a multi-rule algorithm based on fuzzy decision. This algorithm synthetically uses several judgment methods, and increases protection reliability. If the fuzzy membership function is well chosen, protection selectivity can be greatly increased, and it can solve problems that conventional protection cannot deal with. Papers [18, 19] put forward a complex criteria fuzzy logic microcomputer transformer differential protection method, introduce typical protection criteria and fuzzy settings, and establish fuzzy decision of the compound criteria. Paper [20] takes transformer protection as a process of synthetically fuzzy judgment. While judging, at the start, divide preclusive external fault into four categories, synthetically judge every category, build judgment sets of objects under judgment, and build single factor judgment. Then according to the effect of each factor, use synthetically weighted method, calculate fuzzy concept membership made of fundamental factor, and process the judgment result. In transformer protection, uncertainty of decision is a frequently encountered problem. Conventional differential protections trade operating speed for selectivity, whereas the fuzzy method can optimize decision-making, so as to obtain optimal combination of speed and selectivity.

Paper [21] synthetically takes into account membership function of second harmonic and its rate of decay, terminal voltage, differential current waveform symmetry, and iron core saturation to inrush current. Weights of each criteria are determined according to its advanced degree and experts' suggestion. Multi-criteria can fully utilize the predominance of every criterion and compensate their shortcoming mutually. Simulation and dynamic model experiment prove that protections of this principle can overcome shortcomings of conventional transformer protection, and give attention to operating speed and selectivity more reasonably.

Application of fuzzy theory to transformer differential protection is through the way of multifactor fuzzy criterion and inrush current waveform identification. But some problems also exist, for example, how to build up fuzzy membership matrix, and its setting rule is different from the conventional protection, which will certainly impede its application and generalization. Although membership function can be obtained through training using samples and neural networks, it cannot represent all the actual field condition.

(4) Wavelet method

Application of wavelet theory to transformer protection has main aspects such as signal processing and waveform character extraction, for example, using wavelet theory to measure dead angle and identify inrush current.

The computation of inrush current usually uses Fourier analysis method. This method has been used in the anti-inrush design of transformer differential protection. Paper [22] gives an internal and external fault analytical approach based on wavelet method that has a higher reliability and computing ability.

This paper applied wavelet method in the anti inrush current design of transformer differential protection to distinguish between transformer internal fault and external fault. Papers [23, 24] use quadric B-spline wavelet to analysis simulation data of EMTP and Canada TEQSIM company real-time digital-analog mixed simulation system, then use wavelet decomposed coefficient to construct protection criteria to distinguish inrush current and internal fault. Paper [25] applies wavelet transform to the dead angle measure of transformer differential protection, and discusses a new method of dead angle measurement through wavelet transform local maximal. Paper [26] presents a new inrush current identification algorithm based on wavelet packet transform. The algorithm can correctly distinguish magnetizing inrush current and transformer typical internal faults. Meanwhile, it will not misjudge external fault as an internal fault, and can guarantee correct identification of inrush current. Furthermore it has a possibility of real-time implementation. Paper [27] puts forward a new method to distinguish inrush current and short-circuit current based on wavelet theory. It extracts sudden change point characteristics of inrush current and short-circuit current through filtered wavelet modulus maximal, thereby clearly distinguishes inrush current and short-circuit current. Computer simulation confirms its validity. Paper [28] gives a new wavelet theory based principle of inrush current and short-circuit current distinguish. This method uses wavelet theory to extract inrush current character. In these circumstantiate, it extracts inrush current dead angle characteristic using wavelet local modulus maximum feature. On this foundation, it distinguishes inrush current and short-circuit current qualitatively. The principle is very robust to CT saturation.

Practical wavelet technical application in transformer differential protection still needs further study, and how to guarantee computational real-time and operating reliability is a relatively important problem.

1.3 Primary coverage of each chapter

Chapter 1 Introduction

Introduce correlative technique of digital protection.

Chapter 2 Digital differential protection

Introduce digital differential protection principle, including generator and transformer differential protection, especially scalar product principle theory and applications in generator and transformer differential protection. Research implementation method of multi-side transformer differential scalar product principle, and solve multi-branch differential current selection problem.

Chapter 3 An ANN differential protection research ground on protection

This chapter puts forward an entirely new ANN theory technology applied in relay protection, ANN technique research ground on protection principle. The technique incorporates relay protection theory which has been developed for a few decades and ANN intellectualized feature. It fully carries forward respective advantages, so presents an effective way to implement high performance and high reliable protective relay devices. Its principle will be explained in chapter 3 at length.

Chapter 4 The inrush current solution strategy of digital differential protections

The inrush current problem of high-power transformer differential protection is a problem of differential protections far from a good solution. Nowadays, it even triggers a dispute of transformer differential protection principle within the relay protection domain. However, it is impossible for differential protection research to bypass the inrush current problem. Therefore, how to use digital protection intelligent methods to distinguish and meet the requirement of high-power transformers is the research emphasis of this chapter.

Chapter 5 Digital differential protection CT secondary open-circuit strategy

The CT secondary circuit break problem of generator and transformer differential protection has been a controversy for a long time. On the topics such as whether or not differential protections need CT secondary circuit break block, whether the block component is able to block the protection, and what strategy should CT secondary circuit break block take. This chapter will analysis and discuss correlative problems.

Chapter 6 CT transient saturation analysis on digital differential protection

For a long time, the ratio restraint part of ratio restraint curve has been connected with anti CT saturation ability. It thinks that as long as ratio restraint characteristic, the differential protection will not mal-operate in the allowed CT saturation and transient (10% error) range, but in fact it is not the case. Long-term statistics show that some mal-operations of unknown cause are more or less related to CT transient saturation. This chapter analyses dynamic model data of differential protection operations under CT saturation and puts forward the viewpoint that the ratio restraint characteristic cannot keep away from CT saturation, especially while an attenuating DC content exists. Elaborate influence of reasonable trip output judgment times, digital filter algorithm, and data window length selection on increasing differential protection anti CT transient saturation ability.

Chapter 7 CT transient saturation strategy of digital differential protection

This chapter further discusses digital differential protection behavior under CT transient saturation, then briefly discusses protection mal-operation problem caused by CT saturation. An anti-saturation strategy of differential protection is put forward against CT transient saturation by its characteristic.

Chapter 8 Digital differential protection sensitivity analysis

This chapter analyses relative setting principle of differential protection, and explicitly points out that differential protection sensitivity is actually related to many factors, such as setting, principle, implementation, etc. Sensitivity shouldn't be increased by changing a certain factor (for example, a setting). The influence of every factor should be synthetically considered; otherwise the result will be just the opposite of what one wishes. This chapter discusses the sensitivity coefficient verification, the difference between restraint coefficient and slope, connection and difference of scalar product restraint and ratio restraint, from the viewpoint of the author.

Chapter 9 Modularization of digital differential protection

Early stage digital protection equipment was restricted by the conditions of the time and it was quite functional specific. The product design was not so normative, and had neither a long-term development project. Therefore, it was very adverse to the expansion of protection functions. Presently, with the increase of hardware integration and network communication ability, digital relay protection products are developed towards multi-module, multifunction, high integration. Modular design is the general trend of hardware and software. The OOP (object oriented) technology which is popular in the software development domain can also be embodied in the software design of relay protections. This chapter will analyse and discuss these problems.

Chapter 10 Research of digital automatic differential protection hardware parameters adjustment

Aiming at the high hardware current channel amplitude and phase accuracy requirement of differential protection, this chapter gives a software automatic adjustment algorithm and method. It can turn an inaccurate hardware channel to a high accurate sampling channel whose amplitude and phase can meet the requirement of differential protections by automatic adjustment.

Chapter 11 Prospect of modern digital differential protection

This chapter presents the author's viewpoint about the developing trends of digital differential protection technology and methods.

1.4 Original contributions

Some of the problems encountered are due to the complexity of larger capacity of generator- transformer protection. A modern digital differential protection based on ANN has been developed and the effect of transformer inrush current and CT saturations on it have been considered. A suitable modeling mechanism has been put forward. A summary of the original contributions made in this research is given below:

1. A novel protection principle based on ANN technique has been proposed. Dynamic testing has been carried out to confirm the benefits in using this approach. It breaks through the former ANN application bottleneck in relaying. A better performance in terms of sensitivity, obstructing maloperation in inrush current and CT saturation period has been obtained

2. A new method to distinguish inrush state using multi-condition restraint criterion has been proposed. Incorporated with the introduction of breaker switching state and transformer voltage state, the transformer working state, such as inrush, short circuit, fault-recovery inrush, sympathetic inrush, switching on unenergized fault transformer, and fault right after switching on unenergized transformer etc, can be classified straightforwardly.

3. A new trap technique on anti-CT saturation has been proposed and MATLAB simulation tests have been used to verify the advantages derived from the technique. All these methods possess good performance in actual practice in China. By developing a time-dependent principle, it will be effective to overcome weaknesses during power system transient. It is found that, when an external fault occurs, the relay locus easily enters the action zone but will not stay too long because of continuous transient status of CT transient saturation. So this method will be crucial to avoid the mis-tripping.

4. Development of Object-Oriented software and modeled hardware design method for protection. It will bring forward a platform for digital protection research and applications.

5. A new solution based on the sudden change in negative direction of current to

prevent differential relay maloperation due to CT broken has been proposed. Dynamic testing has been carried out to study the impact of CT breaks on generator protection. It makes great progress on the conventional criterion for CT secondary open-circuit and it does not neglect the fact that when CT secondary circuits break, an arc current will probably occur or the current will decrease to zero.

Chapter 2 Digital Differential Protection

This chapter analyzes physical substance of the differential quantity and restraint quantity in conventional ratio differential protection principle[30-35]. This chapter also concentrates on applications and theory research of scalar product principle at generator and transformer differential protection. Implementation method of multi-side transformer differential scalar product principle, and solution of multi-branch differential current selection problem are discussed. Advantages and disadvantages of all these methods, sensitivity of scalar product restraint differential principles are also analyzed.

2.1 The conventional ratio restraint

The ratio restraint principle has changed a lot in course of its developing to present digital ratio restraint principle[40]. It has following kinds of representations.

1) The curve passes through the origin

The character of this principle is that the restraint factor equals to the slope of the curve and they are also equal in concept. Its sensitivity is lower than the following two representations.

2) The curve does not pass the origin

The curve consists of two parts, unrestrained part and ratio restraint part. It has a higher sensitivity. At this point, the restraint coefficient and the slop of the curve are no longer use the same concept. If the coefficient and the slope are equal in value, the principle 2 has a higher sensitivity than principle 1. If the restraint coefficient and the slope are interrelated in the way described in this chapter, even if the slope is larger than the restraint coefficient, the principle 2 still has a higher sensitivity than principle 1.

3) The curve does not pass the origin

The straight line of restraint part is substituted by three lines connected to each other. Apparently, this mode has the highest sensitivity. However, due to the uncertainty of the CT error, the initial point and slope of the three lines is very difficult to set. The theoretical calculation method and basis are not well developed, and usually simplified setting methods are used. Therefore, the application of this principle is very risky, and could cause mal-operation.

Analysis of generator differential protection of mode 2 is as follows:

The operation equation is

$$\begin{cases} |\dot{I}_N + \dot{I}_T| \geq K_S(|\dot{I}_N - \dot{I}_T|/2 - I_g) + I_q \\ |\dot{I}_N + \dot{I}_T| \geq I_q \end{cases} \tag{2-1}$$

Where,

I_g -- the inflexion point current;

I_q -- the startup current of the curve;

K_s -- slope of the curve;

$\dot{I}_N$, $\dot{I}_T$ -- generator neutral point and outlet current. The current direction flowing into the generator is referred as positive.

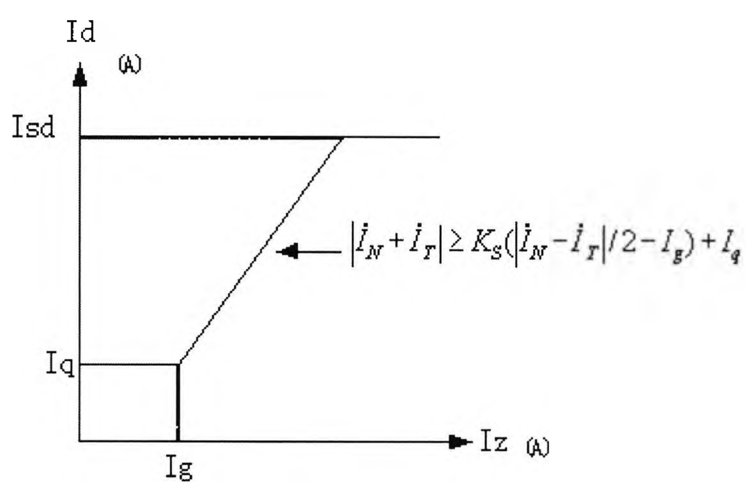


Fig. 2.1 The ratio restraint characteristic curve (not passing through the origin)

From the equation (2-1), it is observed that the startup current and inflexion current are introduced into the operation equation and the restraint curve no longer passes the origin. Thereby, the CT error characteristic is better fitted and the differential protection sensitivity can be further increased.

2.2 New scalar product restraint without auxiliary protection

Strictly speaking, scalar product restraint without auxiliary principle is a kind of ratio restraint principle. Only the restraint signal is substituted by the dot product of two signals, and reflects the value of one side of transformer current. Meanwhile, possible complex operations are also avoided. The characteristic curve also consists of two parts, non-restraint part and ratio restraint part. It has higher sensitivity than the ratio restraint principle. In the meantime, it also has the same anti-external fault unbalanced current ability and anti steady state CT saturation ability as the ratio restraint principle.

2.3 Generator scalar product restraint without auxiliary

Its principle is as follows:

The operation equation is

$$\begin{cases} \left|\dot{I}_N + \dot{I}_T\right| \geq K_S(\sqrt{I_N I_T Cos(180^\circ - \theta)} - I_g) + I_q \longleftarrow Cos(180^\circ - \theta) > 0 & (2\text{-}2) \\ \left|\dot{I}_N + \dot{I}_T\right| \geq K_S(\sqrt{0} - I_g) + I_q \longleftarrow Cos(180^\circ - \theta) \leq 0 & (2\text{-}3) \\ \left|\dot{I}_N + \dot{I}_T\right| \geq I_q & (2\text{-}4) \end{cases}$$

Where,

I_g -- the inflexion point current;

I_q -- the startup current of the curve;

K_s -- the slope of the curve.

From equation (2-2), it is obvious that $|180^\circ - \theta|$ must be less than 90°. That is to say, to avoid negative radical calculation, while the radical part of (2-2) is negative, (2-3) should be used and the restraint part should be turned to 0, for the safety of differential protection. It is unnecessary to turn the restraint to the actuating quantity. It is known that zero restraint is sensitive enough for the protection.

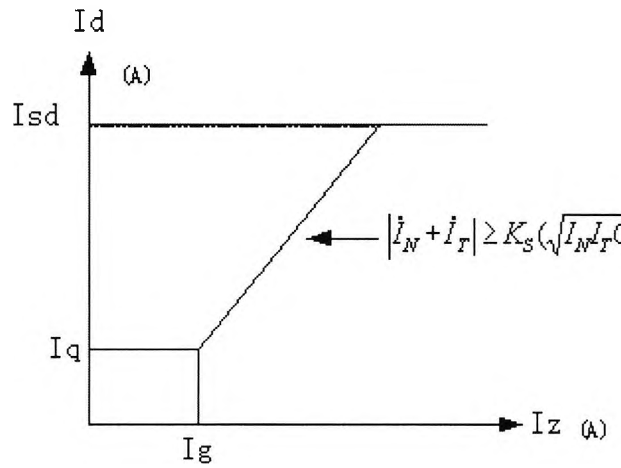


Fig. 2.2 Generator differential protection based on scalar product restraint

2.4 Transformer scalar product restraint without auxiliary restraint

The realization of transformer scalar product restraint pilot differential protection is much more difficult than generator scalar product principle. Because transformers are generally not only of two sides, it is difficult to obtain multi-side dot product.

According to the differential protection principle, the restraint should respond to one of side of current. For multi-side transformers, current of each side is not equal to each other. Which side on earth should be taken to form the restraint current? Analysis shows that taking that the side, which may causes maximum error while external fault (i.e. the maximum fault current pass through), can prevent differential protection mal-operation at external fault. In theory, if the differential protection can guarantee no mal-operation at maximum CT error, it would certainly not mal-operate under CT error of other arms having smaller current. Therefore, transformer scalar product principle should find the maximum current side when fault takes place.

2.4.1 Maximum current side decision

To prevent mal-operation during external fault, the arm of maximum error CT should be found out. It is the key for realizing the scalar product in transformer. But the maximum error side may change to fault position. Therefore, for every fault, the CT maximal fault current passed through must be found.

$$I_{max}=Max\left(\left|\dot{I}_1\right|,\left|\dot{I}_2\right|,\ldots,\left|\dot{I}_n\right|\right) \tag{2-5}$$

Where, $\dot{I}_1$, $\dot{I}_2$, ... is the current of each arm.

According to I_{max}, maximal current can be chosen dynamically, then the current phasor of $\dot{I}_{max}$ can be obtained.

2.4.2 Obtaining the scalar product of the two current phasors

The scalar product restraint principle is an inner product of two phasors. Equation (2-5) shows that the maximum current arm is used as one phasor $\dot{I}_{max}$ of the inner product. Another phasor is the sum of all the currents except the maximum current $\dot{I}_{\Sigma-1}$.

$$\dot{I}_{\Sigma-1}=\sum_{i\neq k_{max}}\dot{I}_i \tag{2-6}$$

Where k_{max} is the branch series number of the maximum current.

If the CT error and transformer error is neglected in external fault, then

$$\dot{I}_{max}=-\dot{I}_{\Sigma-1} \tag{2-7}$$

Therefore, during transformer internal faults the restraint current using $\dot{I}_{max}$

and $\dot{I}_{\Sigma-1}$ is the maximal arm current because the maximal arm current is one phasor of the scalar product. It is likely that $\dot{I}_{max}$ and $\dot{I}_{\Sigma-1}$ are in phase. Thereby it will enhance performance of differential protection and obtain high sensitivity accordingly.

2.4.3 Scalar product principle

The principle also consists of two parts, the non-restraint part and the ratio restraint part. Its principle is given as follows. The operation equation is

$$\left|\dot{I}_1+\dot{I}_2+.\right| \geq K_s\left(\sqrt{Max\,(I_1/I_2..\left|(\dot{I}_1+\dot{I}_2..-Max\,(\dot{I}_1/\dot{I}_1..\right|Cos(180-\theta)}-I_g\right)+I_q \leftarrow Cos\,(180-\theta)>0 \quad (2\text{-}8)$$

$$\left|\dot{I}_1+\dot{I}_2+.\right| \geq K_s(\sqrt{0}-I_g)+I_q \leftarrow Cos\,(180-\theta)\leq 0 \quad (2\text{-}9)$$

$$\left|\dot{I}_1+\dot{I}_2+.\right| \geq I_q \quad (2\text{-}10)$$

Where,

I_g -- the inflection current of the curve;

I_q -- the start up current of the curve;

K_s - - the slope of the curve.

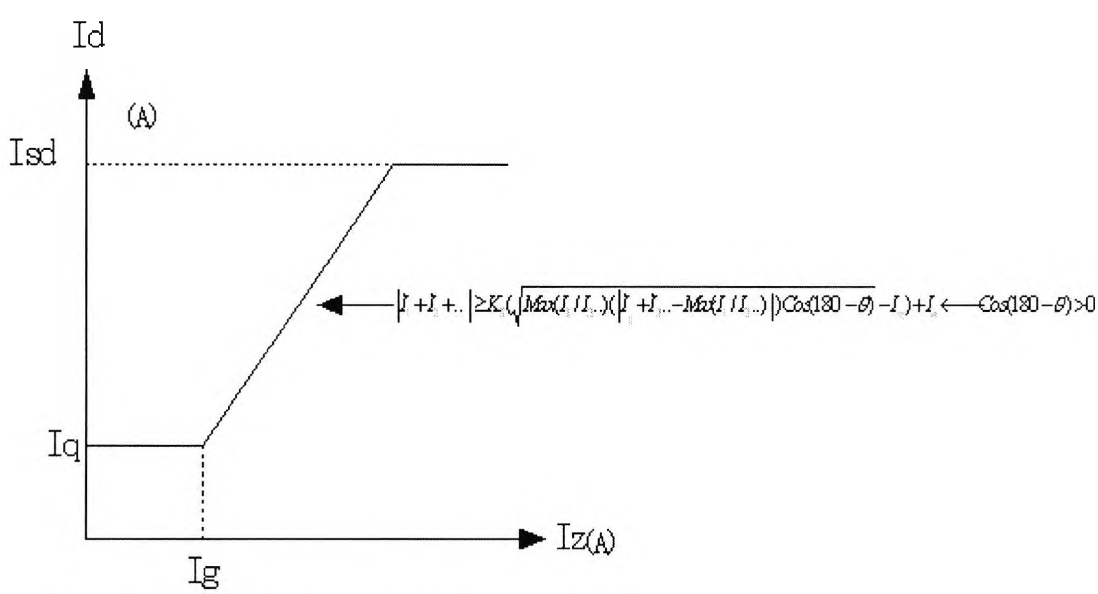
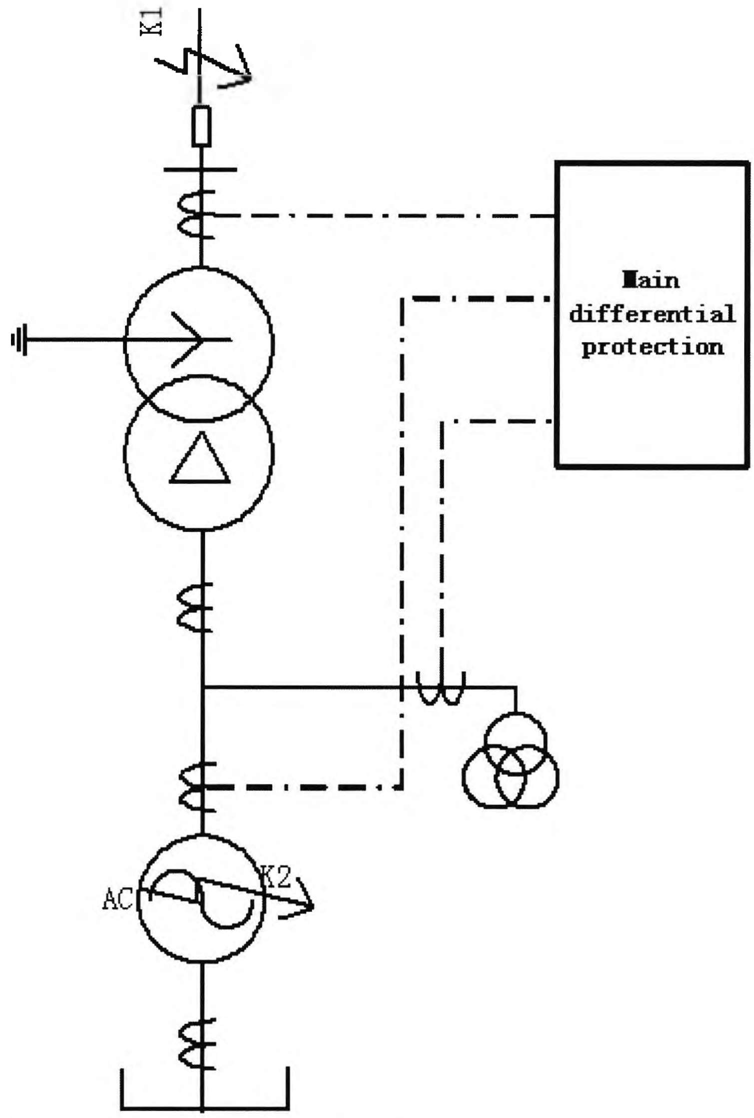


Fig. 2.3 Scalar product restraint characteristic curve

2.4.4 The necessity of choosing $\dot{I}_{max}$ and $\dot{I}_{\Sigma-1}$

There is a conventional concept that the transformer differential protection should choose the current of the smaller system side as the restraint arm. In this way, the restraint is small or even zero in transformer internal fault. Thereby, the sensitivity of the transformer differential protection is increased. This viewpoint is correct to the two sides differential of two-winding transformers, but it should be analyzed in detail for multi-side differential in addition to a two-winding transformer.



K1: System side fault point; K2: Generator side fault point

Fig. 2.4 A block of two-winding transformer with three side differential protection

Fig. 2.4 shows the scheme of a two-winding transformer - generator unit connection in a power plant. Its transformer differential protection is a three-side differential protection (generally this mode is commonly used in power plant).

a) The traditional ratio restraint principle

If proper current is not chosen as restraint arm, and assume that the minimal system current arm is chosen. Then auxiliary transformer side must be chosen as restraint arm. Apparently the sensitivity of transformer internal fault is very high. But when an external short circuit (K1) occurs on the high voltage side of the main transformer, because the restraint is zero or a very small load current, the differential protection works in the non- restraint region and it will certainly mal-operate.

b) The scalar product restraint principle

If $\dot{I}_{\max}$ and $\dot{I}_{\Sigma-1}$ are not chosen as restraint arm, and assume that the auxiliary transformer side and other sides are chosen. Similarly, when a external fault occurs on the system side (K1) and the generator side (K2), the auxiliary transformer side has no power source, and cannot supply short-circuit current to the fault node. Meanwhile, the current of generator and system side is very large. Their magnitudes are substantially equal but their direction is opposite, so the sum is very small. Therefore the restraint of scalar product differential protection is also zero or a very small load current, the differential protection works in the non-restraining region too and it will certainly mal-operate. So scalar product differential protection restraint current must adopt the maximum current $\dot{I}_{\max}$ and current of other $\dot{I}_{\Sigma-1}$ in reality.

2.5 The relationship between the slope Ks and the restraint coefficient

The restraint slope K_s of the scalar product restraint principle is different from customarily called restraint coefficient K_z in concept. In theory, to guarantee reliable restraint during an external fault condition, K_s and K_z are inter-deducible. And the conversion relationship between them is

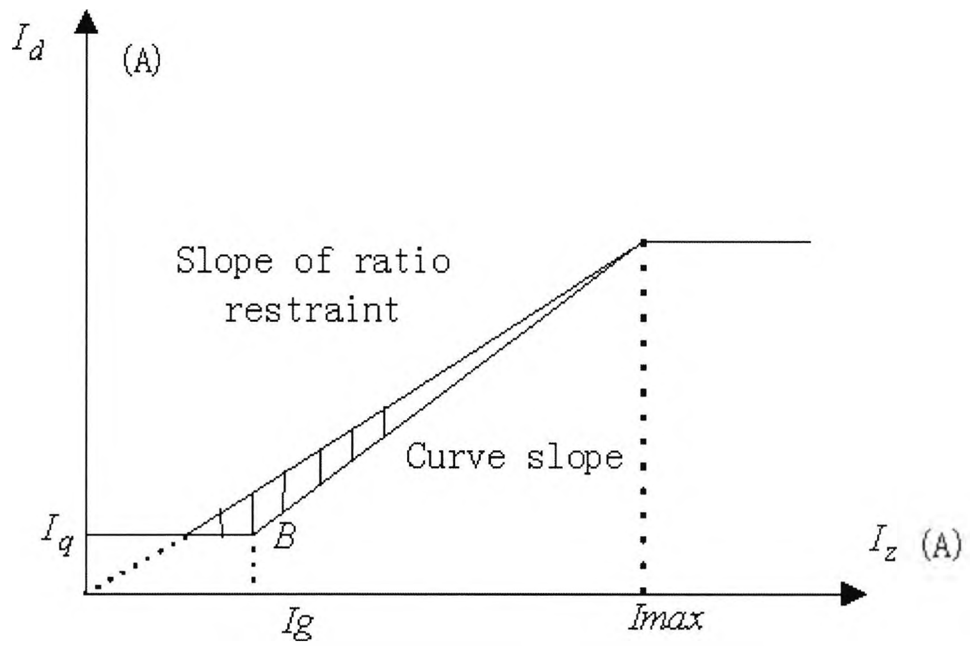
$$K_s = K_{z.\max}(1 + (I_g - I_q / K_{z.\max})/(I_{\max} - I_g)) \tag{2-11}$$

Where,

I_g -- inflexion current (A);

I_q -- startup current (A);

$I_{\max}$ -- external short-circuit maximal out-of-balance current that must be endured.



The shaded area is the prominence of the sensitivity

Fig. 2.5 Sensitivity comparison of Ks and Kz

As stated above, Kz and Ks can be inter-converted, but it does not mean they have the same sensitivity. Actually, Ks can be calculated using (2-11) and the value is usually larger than Kz, which will bet more sensitive in all aspects. The formula (2-11) only shows that in the most severe external failure, it can be guaranteed that the scalar product differential protection would not mal-operate. Fig. 2.5 shows that although Ks converted by (2-11) is larger than Kz, its actual sensitivity is higher as shown shaded area in figure.

2.6 Scalar product restraint without auxiliary reliability analysis

The safety and reliability of protections include several aspects, e.g. principles, settings, device manufacture, device maintenance, extended service verification. The scalar product restraint reliability analysis here is based on the analysis to traditional differential protection extended service experience. The conventional ratio restraint principle protections have been put into field service for decades, and ample operating experience has been gathered. The conventional ratio restraint principle has been accepted by operating and R&D staff, and there is not a widely accepted new non-differential principle that can be used as replacement for the moment. It is observed that the conventional differential protection has a good stability. Such stability comes from the safety and reliability of the principle and practice are proved for decades. Its safety and reliability is undoubted. It can be seen from the analysis of conventional ratio restraint principle that the differential protection falls into actuating quantity and restraint quantity. Because the actuating quantity is differential current, it has not only the characteristic of full quantity, but also the characteristic of sudden change signal (i.e. the now so-called industrial frequency variable signal principle). So the differential current is an excellent actuating quantity. In the research of new differential protection principle, this part is often kept unchanged. The part, which may be improved, is the restraint quantity and the scalar product restraint principle. Its difference current is identical to that of the traditional one; the difference is at the restraint part. However, the restraint part of the scalar product principle has a characteristic same as the traditional differential that they react to single arm current at normal condition and external fault. If the error is neglected, they are equal. Equations (2-12) and (2-13) have fully proved this point, that is to say, in these cases, they have the same behavior. So the safety and reliability of the scalar product principle is the same or similar to the conventional principle. Therefore the scalar product principle has a very high reliability.

Theoretical restraint quantity of generator differential during the normal condition and external faults conditions is as follows: For

Traditional differential protection

$$\left|\dot{I}_N - \dot{I}_T\right|/2 \xrightarrow{\text{During the normal condition and external faults conditions}} \left|\dot{I}_N\right| \qquad (2\text{-}12)$$

Scalar product differential protection

$$\sqrt{I_N I_T Cos(180° - \theta)} \xrightarrow{\text{During the normal condition and external faults conditions}} \left|\dot{I}_N\right| \qquad (2\text{-}13)$$

2.7 The high sensitivity of scalar product restraint without auxiliary principle

The actuating quantity of the scalar product restraint principle is same as the ratio restraint principle, and the difference is their restraint quantities. The high sensitivity of scalar product restraint principle comes from the change of the restraint principle. Many papers and theoretical analysis consider that the scalar product restraint principle and the conventional ratio restraint principle are the same kind of principle, and this thesis has deduced inter conversion formula in section 8.4. But this does not indicate that they are the same in the sensitivity. Such formula relationship is a mathematical equivalent relationship of the input signals. This relation is true in certain condition, but it has no relation with the sensitivity.

$$K_s = \frac{2K_z}{\sqrt{(4-K_z^2)}} \qquad (2\text{-}14)$$

Where,

K_s -- the restraint coefficient of the scalar product restraint principle;

K_z -- the restraint coefficient of ratio restraint principle.

Such derivation is purely theoretical, and reflects a steady state theoretical correlation. It is observed from (2-12) and (2-13) that the ratio restraint principle and restraint principle react to single arm current at external fault, i.e. their behavior is same or similar. This has been proved by simulation and dynamic model experiment. Therefore, in application, $K_s = K_z$ can be selected. Equation (2-14) indicates that

$K_s > K_z$ is a certainty. The characteristic can reach the conventional principle on the condition that the value of K_s is selected to be larger than K_z. Moreover, according to the analyses in section 2.6, K_s can be set to K_z. Analyzing inversely, because the sensitivity equals to the ratio differential while $K_s = K_z$, according to (2-14) during an internal fault condition K_z is smaller. It indicates the scalar product is more sensitive. From another point of view, when an internal short circuit fault occurs to a generator or transformer, because the capacity difference between the generator and system or between the systems is large, the restraint part of the traditional ratio restraint principle is likely to be very large. Therefore the sensitivity is greatly reduced, whereas the operating point of the scalar product principle at internal fault is in the restraintless area, especially at a severe fault. It is apparent that its sensitivity is very high.

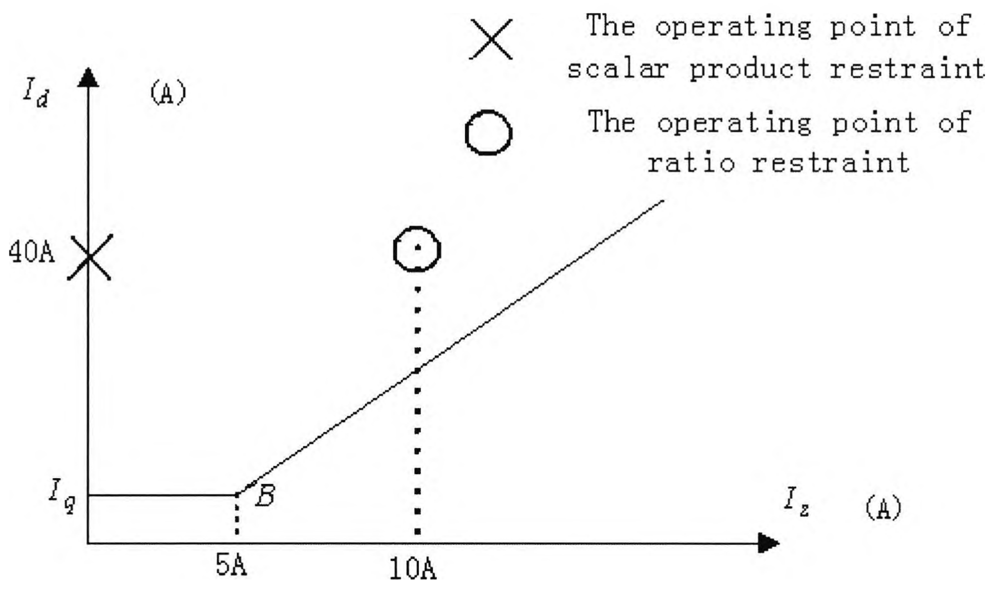
The sensitivity of the scalar product restraint principle can be seen from the following aspects.

a) The restraint quantity of the scalar product restraint principle and the ratio restraint principle react to the amplitude and phase of the arm current theoretically. But formally, the scalar product restraint principle puts stress on reacting to the phase characteristic. Although the scalar product restraint principle has the same behavior as the ratio restraint at external fault, they are completely different at internal fault. Because the restraint quantity reacting to the current phase cosine, when the phase is less than 90 degree, it turns to negative (set to 0). Zero restraint quantity is non-restraint in concept; therefore the sensitivity of internal fault is greatly increased whereas the restraint quantity of the ratio restraint principle is always greater than zero.

b) By analyzing the restraint curves, the phase is less than 90 degree at internal fault, the scalar product restraint operating point will be on the ordinate whereas the ratio restraint operating point generally will not, and operating point changes according to the fault type and mode. Therefore, the operating point of the scalar product restraint principle is further away from the operating boundary than the ratio restraint principle. As shown in Fig. 2.6, it presents a higher sensitivity for an identical fault.

c) Theoretical calculation shows that even at a slightly internal fault of a generator, the phase of the restraint quantity is still less than 90 degree. Therefore, the sensitivity of the scalar product restraint principle is very high.

d) The internal short-circuit occurs before the generator synchronizes and closes only has neutral point short-circuit current. Therefore the restraint quantity of the scalar product principle is zero, whereas the restraint of the ratio restraint principle is not zero apparently, the scalar product principle operating margin is larger, and it avails to the operation.



Suppose I_N=10 (A), I_T= 30 (A), internal angle $180^\circ - 0 = 180^\circ$

Fig.2.6 The sensitivity comparison between scalar product principle and ratio restraint principle for the same internal fault

(It is shown that zero restraint current in scalar product principle as compared to 15A restraint current in conventional principle)

e) The sensitivity of the differential protection corresponds to not only the operating boundary, but the distance from the operating point to the boundary at fault. Actual short circuit is complicated include transition resistance, electrical arc and harmonic. So the further distance between the operating point and the boundary is, the stronger the ability to overcome such drawback is.

2.8 The potential insufficiencies of the scalar product restraint without auxiliary principle

The scalar product restraint principle has both high sensitivity and security. It is more sensitive to the current phase than the tradition scalar product principle because the restraint quantity of the scalar product principle utilizes both current amplitude and phase. So if a large external short-circuit current severely saturates CT, its adaptability is comparatively poor. Fortunately, the differential protection does not completely depend on it to endure severe CT saturation. Therefore, this problem can be compensated. Chapters 6 and 7 of this thesis will discuss this issue in detail.

2.9 Conclusions

This chapter analyses the new transformer and generator scalar product restraint principle and analyses the reason that the scalar product differential protection principle is more sensitive than the ratio restraint principle theoretically for the first time.

This chapter also gives the selection method of the scalar product quantity of the transformer scalar product differential protection. The insufficiencies of the conventional restraint current selection are presented too. The relationship between the slope and the restraint coefficient is distinguished. For proper application of the principle, the conversion method is presented. Meanwhile, the potential problem may caused by the phase sensitivity of the scalar product restraint principle is pointed out. So to speak, digital protection technology is almost perfect theoretically. With the rapid development of modern technology, such as artificial neuron technology and syntheses technology, brings newer and better performance to the differential protection. The next chapter will deal with this issue.

Chapter 3 Study on ANN Based Protection Theory

This chapter proposed a new technique and method for application of ANN to protection: ANN based protection theory. This technique combines conventional protection theory developed through several decades with intelligent ANN technique rationally. This combination will promote an effective approach to develop protective relays of superior performance and high reliability.

3.1 Introduction

With the continuous increasing of single generator capacity, mal-operation of relays will impact power system dramatically and even affect power system stability because of weak connection of network in our country. On the other hand, if generator damages occasionally, regardless of active power loss of the system, it will spend a lot of money and manpower for restoring the system to normal operation, since generator is a very expensive machine and one generator costs over 100 million Yuan (RMB). A power plant would not withstand a generator damage of burning iron core. Thereby it is expected generator protection can realize following two functions: 1 Clearing faulty-generator from power system as fast as possible in case of iron core burning. 2 Restraining fault in a definite scope as sensitive as possible to avoid further extension.

Operating environments for main equipment protection nowadays are not very good. It is indicated that correct-operation-rate of protection is 92% on generator and is only 64% on transformer in 1999 according to the EPRI report. Although this rate is increased recent years for the reason of widely using of digital relays in power system, this rate is still lower than those of line protection.

The following reasons cause the above low correct-operation-rate of main equipment protection. Sensitivity concepts of main equipment protection are different from that of line protection; internal short circuit study is far lag to line; power grid structures for main equipment are more complicated and variable than that for line; protection principles for main equipment are more intricate than those for line. A significant reason is that conventional protections for main equipment and also for line are based on single principle. Single principle may be weak against fault in a complicated power system. It is difficult to consider all aspects of a complicated fault by a single principle.

There are many advantages in applying ANN techniques to protection[39]. Parallel processing ability can speed up calculation and decision-making in relays; Tolerance ability can strengthen facility against error data in relay. It may enhance relay abilities in security, reliability and stability when CT-saturation or power system transient occurs during power system faults

At the same time, ANN techniques applied to power system protection also have some shortages for that its intelligence and unexpected decisions may affect mal-operations when situation is not ever met in trained samples.

It is obviously that all knowledge is stored in the weights of ANN network. These weights are determined and trained by known samples. Because it is difficult to obtain fault record data samples in power system for its space is infinitive, and knowledge stored in weights is finite and sometimes is very little. When faults take place in power system, wrong decision may be made if the case hasn't been met before. It is why difficult for ANN to get actual use in power system protection.

On the other hand, conventional protections have accumulated abundant experiences and theory because of its decade years' development. It is all known that different principles have different characteristics. Indeed, it is recognized that the same protections that have different realization schemes (e.g. differential protection) also may behave quite different during faults with CT saturation and decaying transient because these schemes utilize different algorithms and digital filters. They have different effects on D.C. and harmonic components of ANN input variants, so different behaviors and low correct-operation-rate are inevitable. Although conventional principles can assure 100% correct operation rate in theory, they cannot behave the same in fact. A single conventional principle is difficult to meet all the power system requirements. Only the ANN technique can synthesize all advantages of those single principles.

This chapter proposes a combination technique for ANN and conventional protection theory to construct a new ANN based protection theory for purpose of improving protection system in sensitive and reliability

3.2 ANN applications in power system and BP neural network characteristics

Since first conference was held in US concerning Neural Network (NN) in 1987, ANN techniques have stepped into a rapid developing epoch. ANN has appealed to researchers to pay regard to biology, electronics, computer, physics, signal processing, artificial intelligence. In addition, variety of modeling and computing methods for ANN are proposed and ANN techniques have been widely realized in many of research fields. Some ANN chips are developed and put into production. In recent years, variety of new techniques and knowledge are introduced to power system for coping with complicated problems. These new techniques and knowledge are widely used in many aspects of electric system according to their characteristics. ANN technique is one of them. The ANN abilities of self-organizing, adaptation on line, dealing with non-linearity, parallel computation, robust and tolerance, pattern recognition and function interposing has interested researchers working in power system. ANN has been applied or will be applied in load forecast, security assessment, power planning, fault diagnosis, system control and the like.

The back-propagation network (BP) has a continuous and differentiable transfer function and its output is also a continuous value representing probability of this category. This classification method is reasonable and can meet requirement of realistic world. These probabilities represent possibility of faults in power system when BP is applied to protection. The procedure of BP making decision is just like that of protection.

For multi-layer BP network, with non-linear transfer function, classifies the input vectors with non-linear super-plane and these super-planes are smooth and can be of any shape. Its facility is prior to those of linear classification and has strong tolerance ability.

In addition, another advantage of BP network is that it is always stable in theory and has distinct training method. Above all, it may be a productive developing direction in applying ANN to protection.

3.3 Guidelines of ANN based protection theory

The input vector of BP network and connections between input layer and hidden layer are determined by mature conventional protection theory. It is clear that to connect every node (this paper supposes unlinked neurons have zero weights Wij=0) is not necessary. Every non-zero weight has apparent physical concepts (such as restraint coefficient Kres and pickup current Ipickup in differential relay). All these characteristics reflect applications of protection theory in ANN.

ANN based protection theory has following comprehensible characteristics

a) It inherits advantages of conventional protection theory

b) It possesses robust and tolerant characteristics that are the properties of ANN

c) Its input vector is easily determined. It simplifies selection of input variants by using conventional protection theory.

d) Its network structure between input and hidden layers is also determined with conventional protection theory. As ANN network performance is strongly related to its structure (such as number of neurons) and, the technique will be helpful for determining ANN structure.

e) It can synthesize and improve different principles' characteristics and overcome their weakness or disadvantages

f) Its classifications are more reliable than those single conventional principles. This is a basic foundation for actual application of this technique to protection.

g) Local or global convergence problems are not a problem. As its input and hidden layer are constructed based on conventional protection, convergence can be always considered to be global if we expand convergent point to a region.

3.4 Combination technique of BP network and conventional protection theory

We know that conventional protection theory has served power system for decades and has made great contribution to power system. If we assume settings are weighs, these weights have been trained on line for several decades by real recorded fault data.

ANN based protection Theory has following principles

a) BP network is fully designed according to protection principles.

b) Connection schemes between input and hidden neurons of BP network represent protection principles. According to the principles, some neurons have not connections or these interconnection weights are zero.

c) Protection settings have been transferred to weights in BP network, such as restraint coefficient in differential relay.

d) Pickup setting or definite-time settings are also transferred to weights with 1 as their inputs.

e) Variable transfer function in BP network can be taken into account when complicated protection principles are used.

f) No-equivalent-restraint conditions are introduced. Every weight is constrained in a proper scope.

g) Equivalent-restraint conditions are introduced, some weights, if necessary, keep constant all the time.

h) The most important property is that structure and weights between input and hidden layers have significant and definite relations with power system protection theory.

On account of higher security and reliability requirements in relay, a new proposed principle must be correct thoroughly and cannot make any mistake in theory. Since ANN technique has strong self-learning ability and can make decision in every occasion, it implies that conclusion may be uncertainty sometimes. If we cannot resolve problem of 'uncertainty' properly, it is inevitable that ANN application research work will stop on theoretical stage only.

ANN based protection theory can eliminate shortages and develop advantages in both ANN and protection. Relays' settings can be transferred to weights accurately and trained again. That will make protection more reasonable and optimized.

ANN based protection theory has solved the following significant technical problems in applying BP network to power system protection.

a) BP network design

As we know, it is difficult to select input vector and hidden layer in BP network generally. ANN based protection Theory can easily select them and assure the best option.

b) Convergence in training BP network

Training a BP network is convergent certainly in theory. However, it can't assure convergence is global. ANN based protection Theory can guarantee its classification is always excellent.

c) Security

ANN based protection theory overcomes 'uncertainty' problem in ANN and improves protection security and reliability.

d) Setting

Relay's settings are transferred to weights in BP network, they can be optimized through learning, so the settings (weights) will be more effective and reasonable.

3.5 ANN based protection theory application in generator differential protection

ANN based protection theory provides a new scheme that combines ANN technique with conventional protection theory effectively and practically. This scheme can be used in lots of protection aspects. Typical applications of input vectors include: 1. same principle but different algorithm; 2. same protection but different principle; 3. different protection and different principle and the like.

In order to express these characteristics distinctly, a simplified generator differential protection module is proposed.

Input layer selection

Mature proportional and scalar product restraint differential protection principles are selected as input vector of BP network because conventional protection theory is the foundation of ANN based protection theory. Different algorithms in same protection are considered to reduce the negative effects of transient and saturation on protection.

Inputs 1 and 2: IN1 and IN2 – operating quantity and restraint quantity of proportional and scalar product restraint principles respectively. Their algorithms have sound behavior in power system transient period.

Inputs 3 and 4: IN3 and IN4 – operating quantity and restraint quantity of proportional and scalar product restraint principles respectively. Their algorithms have sound in CT saturation period.

Input 5: IN5 – restraint quantity of scalar product restraint principle. Its algorithms have sound behavior in power system transient period.

Input 6: IN6 – restraint quantity of scalar product restraint principle. Its algorithms have sound behavior in CT saturation.

Output layer selection

Two elements in output vector i.e. internal fault and external fault are enough in power system protection. However, in order to obtain more classification information from BP network, 5 elements are defined.

Output 1: O1 - internal serious faults. Suppose fault current is over 2 times generator rating current (including 2 times).

Output 2: O2 - internal slight faults. Suppose fault current is below 2 times generator rating current.

Output 3: O3 - transient state. It represents the ability against power system fault transient.

Output 4: O4 - saturation state. It represents the ability against CT saturation.

Output 5: O5 - external faults. It stands for external power system fault.

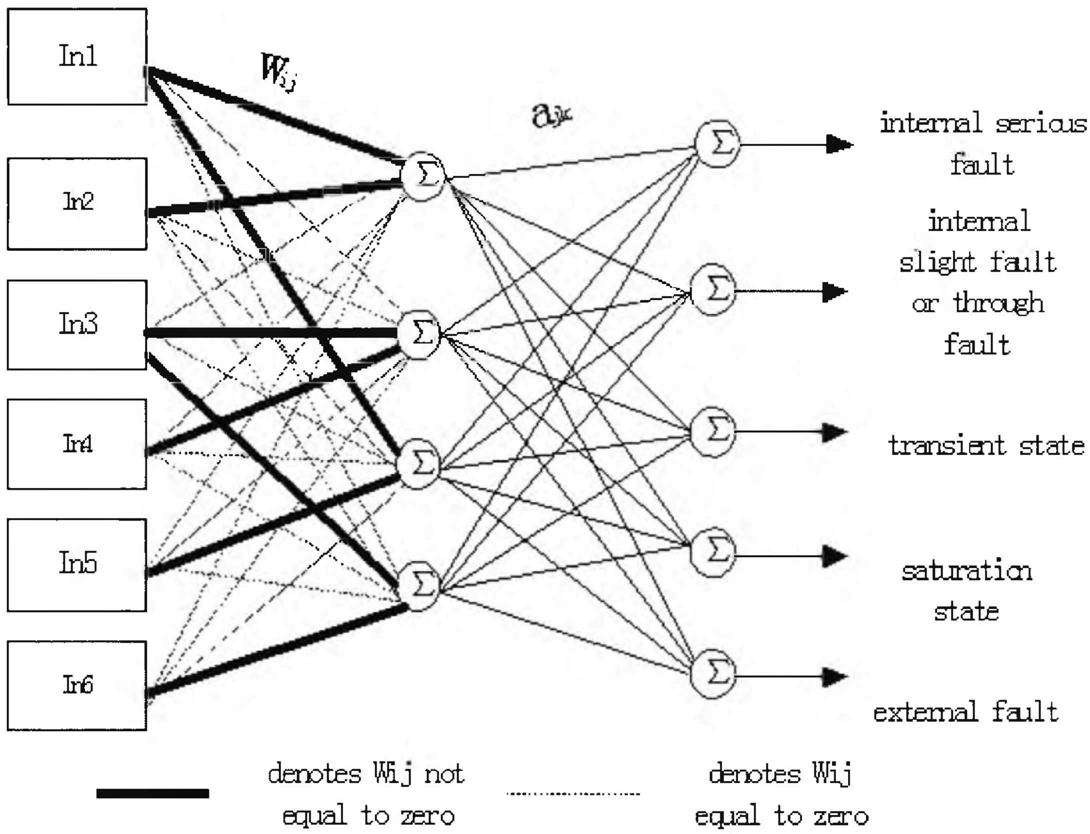
Hidden layer selection

Neurons in hidden layer denote directly protection principles.

Neurons 1 and 2: H1 and H 2-- Proportional restraint principle. Its algorithms have strong ability against transient and CT saturation respectively.

Neurons 3 and 4: H3 and H 4-- scalar product restraint principle. Its algorithms have strong ability against transient and CT saturation respectively.

Fig. 3.1 shows BP network of ANN based protection theory for generator differential protection.



W_{ij}--Weight of first layer. Subscripts i and j denote input and hidden neuron number respectively

A_{jk}--Weight of second layer. Subscripts j and k denote hidden and output neuron number respectively

Fig.3.1 BP Network on ANN based protection theory for generator differential protection

Weights restraint conditions

Weights between input and hidden layers have their clear physical concepts. They can be constrained directly according to their respective principles

Weights are restrained as follows (reference to figure 3.1)

a) Un-equivalent restraint conditions

W_{21} /W_{11} and W_{42} /W_{32} equal to proportional restraint coefficient K_Z. They can be restrained in the range of 0.2—0.5.

W_{53} /W_{13} and W_{64} /W_{34} equal to scalar product restraint coefficient K_b. They can be restrained in the range of 0.8—1.2

b) Equivalent restraint conditions

In addition to those un-equivalent restraint conditions, other weights are all zero.

W_{12}; W_{14}; W_{22}; W_{23}; W_{24}; W_{31}; W_{33}; W_{41}; W_{42}; W_{44}; W_{51}; W_{52}; W_{54}; W_{61}; W_{62}; W_{64} =0

It is obviously that BP network can be easily trained to an ideal convergent area.

3.6 Test results

A prototype has been developed on ANN based protection theory. In order to entering into Chinese power system market, the prototype should pass through EPRI's

(Electrical Power Research Institute, Beijing) dynamic simulation test, which is authorized by the government.

The prototype was tested on a model of generator- transformer system connected to a 220kV transmission line, which has 192 km long (see table. 3.2). Parameters of components in the module see the following tables.

Table 3.1 CT secondary current at rated capacity

220kV	18kV and neutral side of generator
2.63A	4.528A

Table 3.2 Parameters for generator and transformer

Component names	Parameters	Values
Connected power systems	Source 1	5600MVA
	Source 3	13000MVA/6500MVA
Generator	Pn	300MW
	Vn	18kV
	In	11.32kA
	Power factor	0.85
	X_d'	0.359 pu
	X_d"	0.2542 pu
	X_d	2.663 pu
Transformer	Sn	360MVA
	Un	242±2X2.5%/18kV
	Connection	Yo/Delta-11
	X_k	0.133 pu

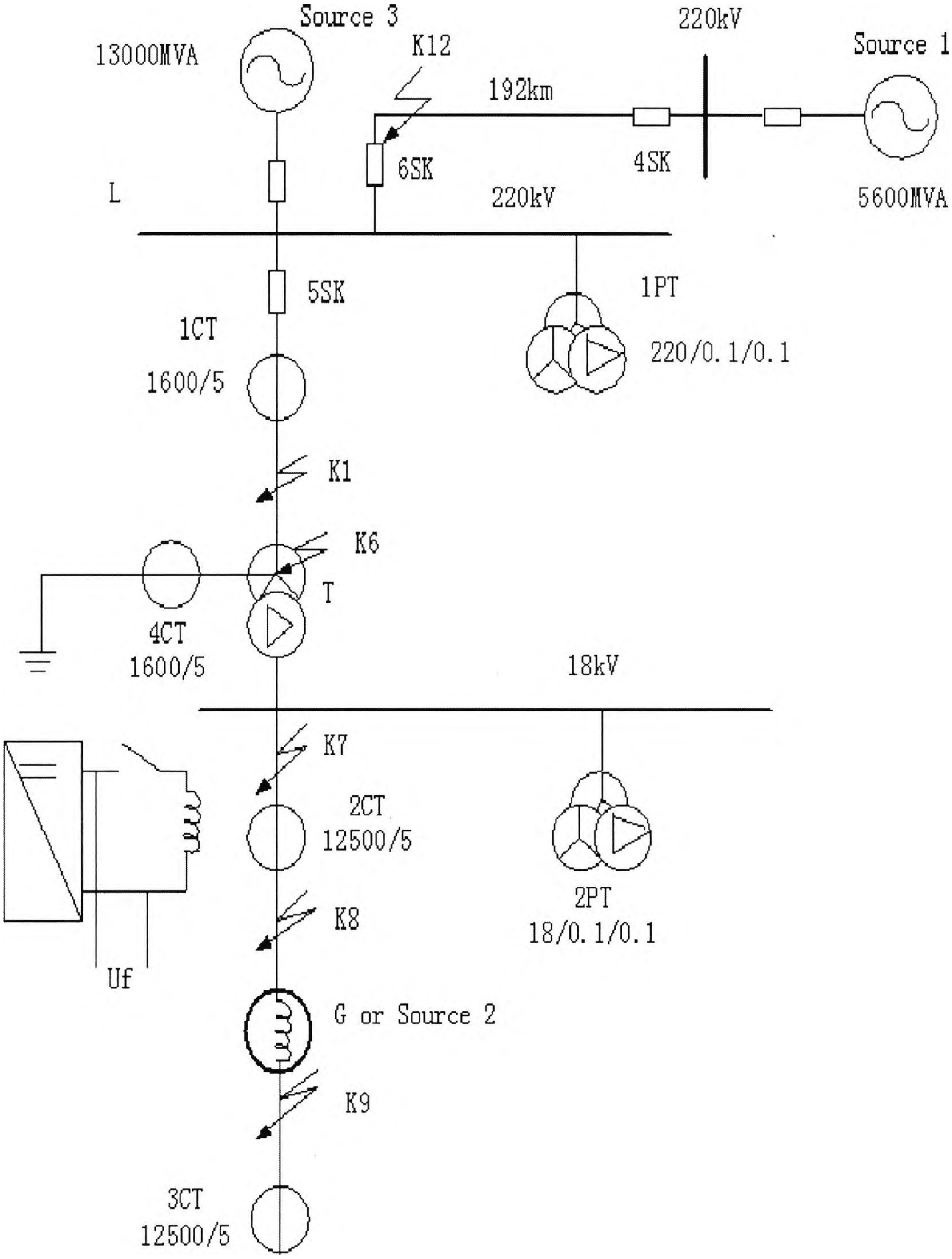


Fig.3.2 Simulation system module for generator and transformer protection test developed by EPRI

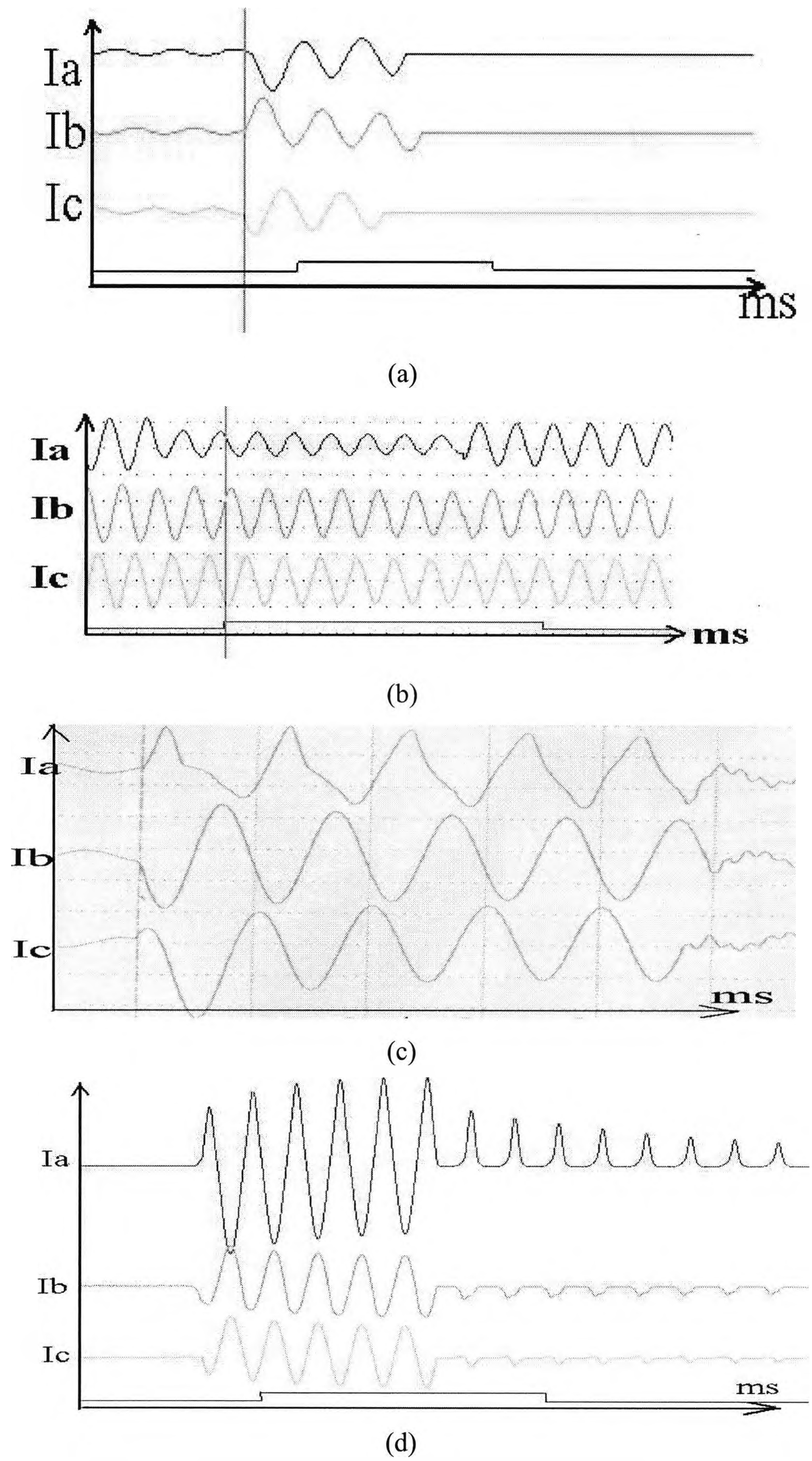


Fig. 3.3 Recorded waveforms for generator-transformer protection prototype test

From tested record waves, it is showed that when a single-phase short-circuit (K_1)

through a resistance of 100Ω take place at high voltage inner side of transformer, tripping times of differential relay are about one cycle (about 20ms) (Fig. 3.3.a); when 3% inter-turn short-circuit takes place at 220kV side of transformer, tripping times of differential relay are about one and a half cycle (about 30ms) (Fig. 3.3.b); when CT saturation angle is over 54°, differential relay remains stable and no trigged signal was given (Fig. 3.3.c); when switching on an un-energized transformer with 3% inter-turn short-circuit fault, after going through many tests, it was found that differential relay tripping times were among 20-64.4ms and less tripping time was correspondent to small inrush current (Fig. 3.3.d).

3.7 Conclusions

ANN-based protection theory combines power system protection theory with ANN techniques successfully. This is one of the best schemes to achieve high reliable, high stable, high sensitive relays.

a) ANN-based protection theory integrates main advantages of convinced conventional protection with ANN techniques. It improves relay's function.

b) Security and reliability of ANN-based protection theory are higher than that of conventional protection theory.

c) ANN-based protection theory can make BP network convergent to an expected range with the restraint of conventional theory.

d) ANN-based protection theory optimizes settings coordination between different principles and algorithms.

e) According to ANN-based protection theory, it is easier to develop a BP network for protection.

Chapter 4 Digital Differential Protection Strategy for Magnetizing Inrush

The inrush problem of large transformer differential protection is not so far solved satisfactorily. Nowadays a dispute has even arisen in the protective relaying field. However, to investigate the methods for differential protection, it is impossible to ignore the problem due to magnetizing inrush. Intelligent approaches of digital protection are emphatically discussed in this chapter to distinguish magnetizing inrush exactly and to meet the requirements of large transformers.

4.1 Magnetizing inrush of power transformers

Nowadays differential protection is undoubtedly the primary protection of large transformers and it has the duty on tripping the various internal faults of transformers and the faults happened to lead and bushing. With the wide use of large transformers, especially 500kV transformer on power system, a severe challenge is presented to transformer differential protection based on conventional second harmonic restraint and dead angle restraint. Differential protection based on second harmonic restraint has already faced the problem of how to calculate setting in some cases, because the characteristic of the second harmonic content is less obvious than before when switching an unloaded transformer on. This brings about potential risks of correct operation of differential protection.

Large transformer differential protection is also facing the dilemma about mal-operation and non-operation. At present, protective relays engineers have strived hard to make great progress at this point and some problems causing mal-operation have been solved. However, all kinds of methods and means are simple and separated so that they cannot meet the requirements of the protected transformers. In this chapter, the intelligent features of digital protection are fully utilized according to the characteristics of transformers when faults happen, to recognize transformer state and to identify whether transformer protection is during faults or during magnetizing inrush[36,37,38].

The new problems met by differential protection of large transformers are as follows:

(a) Improvement of transformer manufacture

The core of large transformers is generally made of cold-rolled silicon steel with orientating crystallization. The characteristic of the core is not only “steep” but also “hard” and the peak value of magnetizing current is over than ten times of the rating at most. Therefore it is useless to recognize the magnetizing inrush with the mean of fixed setting (e.g. fast saturation method).

(b) Second harmonic restraint

With the improvement of power transformer manufacture, the second harmonic current content level of magnetizing inrush is comparatively less, sometimes only 5~8% when switching a transformer on. Therefore, it is not proper to use this content level to distinguish whether magnetizing inrush or internal faults occur to transformers.

(c) Short-circuit during magnetizing inrush or over-excitation conditions

In general, transformer differential protection is simply restrained from tripping during magnetizing inrush or over-excitation conditions. At that moment internal faults of transformers, however, will probably happen. Therefore, the operation of restraining differential protection simply will probably delay tripping time of these internal faults.

4.2 Features of digital protection

Nowadays many theories and approaches of digital protection, in general, still follow the idea of conventional protection. Although great progress has been made in many algorithms and approaches and the intelligent features have also been applied, it is far away from making full use of the features of digital protection. The reasons for this are as follows: (a) The thinking of conventional protection once established is not changed easily; (b) There is a process needed for a new approach to be applied; (c) It is difficult to calculate setting for a new approach; (d) The existing regulations have restrained a new approach for applications.

In the past, conventional differential protection of power transformers has been widely accepted by customers, but the problems exposed on transformer protection are turned out. Fortunately with the development of digital signal processing, much better effect will probably be achieved by digital protection to solve those problems. For instance, differential protection based on symmetry principles of waveforms was advanced on the basic of digital protection.

Using digital techniques it is easy to realize the intelligent process such as memory, logic judgment, deduction and so on. But digital protection cannot deduce like whatever expert system do. As we know that expert system builds deduction on the knowledge database. Obviously the feasibility of this deduction depends on the quantity and correct combination of knowledge. In fact, the condition in which protective relays mostly work is when a short circuit or a fault occurs, and hence it seems difficult to obtain all information about faults, in particular, how much all kinds of knowledge function is still not described in quantity. In contrast, the digital approach building on sudden change can recognize faults exactly.

Digital techniques can take advantage of the multi-variant and multi-characteristic conditions. Multiple characteristics will appear when a short circuit or magnetizing inrush happens. The conventional differential protection based on fast saturation theory only use the feature that the direct current component deviated form the time axis is comparatively large during magnetizing inrush conditions and thus it restrains differential protection from mal-operating (of course it will cost tripping time delay of differential protection). The differential protection based on conventional second harmonic restraint only makes use of the feature that the second harmonic content is obviously larger than other harmonic contents during magnetizing inrush conditions, nevertheless, this approach has made differential protection of power transformers operate securely on site for over twenty years.

Digital techniques can utilize both "transverse" and "horizontal" characteristics. The "horizontal" characteristic is that significant changes probably happen to current, voltage, harmonic, frequency, phase angle, active power, reactive power, impedance and so on during faults conditions, while the "transverse" characteristic is meaningful, consisting of not only the condition that saturation theory cost delay tripping time to restrain protection from mal-operating during magnetizing inrush conditions as discussed above, but also the changing sequence and the changing trend about fault information on the time axis.

These sophisticated characteristics of digital techniques provide the sound basis to solve the problem of magnetizing inrush.

4.3 Restraint criterion of differential protection

Both scalar product restraint and ratio restraint of differential protection will function practically.

The expressions of scalar product restraint are as follows. (See chapter 2).

$$\begin{cases} \left|\dot{I}_1+\dot{I}_2+.\right| \geq K_S\left(\sqrt{Max\,(I_1/I_2..\left|(\dot{I}_1+\dot{I}_2..-Max\,(\dot{I}_1/\dot{I}_1..\right|Cos(180-\theta\,)} - I_g\right)+I_q \longleftarrow Cos\,(180-\theta)>0 \\ \left|\dot{I}_1+\dot{I}_2+.\right| \geq K_S(\sqrt{0}-I_g)+I_q \longleftarrow Cos\,(180-\theta\,)\leq 0 \\ \left|\dot{I}_1+\dot{I}_2+.\right| \geq I_q \end{cases}$$

4.4 Multi-condition restraint for magnetizing inrush

This thesis holds the idea that the basic methods and theories of protective relays should be persisted and new theories and approaches built on the successful algorithms will be better developed and applied than others in the future. The ratio restraint theory presented in this thesis and the theory of protective relays based on ANN potentially apply this idea. So the multi-condition restraint for magnetizing inrush also follows the approach of the conventional second harmonic restraint.

4.4.1 Second harmonic restraint

The second harmonic restraint is based on the fact that second harmonic current content during magnetizing inrush of power transformers is obviously larger than that during faults. This restraint is generally is written as

$$\eta_2 = I_{2\omega}/I_{1\omega} \geq \eta_{2dz} \quad (4\text{-}1)$$

Where generally set η_2=0.13–0.20.

In fact, for a few decades it is the primary restraint for magnetizing inrush of power transformers and it is a well-developed restraint.

4.4.2 Dead angle restraint

This restraint based on dead angle depends on the fact that current is zero during magnetizing inrush of transformers, i.e. dead angle is in existence. Therefore the phase angle corresponding to the time of zero current can be used to decide whether a power transformer is magnetizing inrush or not. And it is written as

$$\theta \geq \theta_{dz} \tag{4-2}$$

Where generally set $\theta_{dz}=60^{\circ}$.

Because this approach of digital protection has a high demand of hardware and this goes against modularization of digital protection hardware, so this has not been widely applied in practice. However it is often used in the integrative protections.

4.4.3 Symmetry principles of waveform

The current waveforms are distorted seriously during magnetizing inrush of power transformers and thus magnetizing inrush can be reliably recognized in terms of the distortion level comparing current waveform with 50Hz sinusoidal waveform.

Obviously the idea of waveform symmetry is highly advanced, but the methods of how to capture the waveform distortion are many. One of the wide applied approaches of digital protection is as follows:

$$\frac{i(n)+i(n-T/2)}{i(n)-i(n-T/2)} > \lambda \tag{4-3}$$

Where λ --symmetry level of current waveform;

When current is only consisting of the fundamental current component completely, $\lambda = 0$, i.e. full symmetry.

The expression (4-3) is one realization of waveform symmetry principles.

From the perspective of digital filters, it is obviously found out that the expression is substantially the ratio of even harmonic current component and odd harmonic current component. Therefore, this restraint still follows the idea of harmonic restraint and no great innovation has been made.

4.4.4 Multi-condition restraint for magnetizing inrush

According to the above analysis, we can draw a conclusion that harmonic restraint is an effective restraint for magnetizing inrush. The restraint (4-3) based on waveform symmetry is only a revision of harmonic restraint.

Generally, conventional second harmonic restraint just needs one setting. To realize multi-condition restraint, setting should be divided into high threshold and low threshold settings according to second harmonic content. High threshold setting is used to recognize magnetizing inrush when initial switching on a transformer while low threshold setting is used to make a further decision with other conditions and states. Thus when second harmonic content is over normal level, differential protection will be reliably restrained from tripping and when second harmonic content is below low threshold setting, it can be easily decided whether a transformer is during faults (including (internal or external faults) or not. In addition, when harmonic content is between high and low threshold setting, then multi-condition restraint will function.

High and low threshold harmonic restraint can be written as

$$\eta_2 = I_{2\omega} / I_{1\omega} \geq \eta_{2h.dz} \tag{4-4}$$

$$\eta_2 = I_{2\omega} / I_{1\omega} \leq \eta_{2l.dz} \tag{4-5}$$

Where,

η_2 -- ratio of second harmonic restraint;

$I_{2\omega}$, $I_{1\omega}$ -- second harmonic and fundamental frequency component content;

$\eta_{2h.dz}$, $\eta_{2l.dz}$ -- high and low threshold settings of second harmonic restraint.

When second harmonic current content is detected between high threshold setting $\eta_{2h.dz}$ and low threshold setting $\eta_{2l.dz}$, a further decision should be made.

It is clear from above analysis that magnetizing inrush and faults completely differ in power system. Magnetizing inrush may be caused by energizing a transformer or by voltage recovery after clearing an external fault. Magnetizing inrush is usually considered as a result of switching an unloaded transformer on.

Analyzing the process of faults or switching an unloaded transformer on, it is discovered that transformer voltage is changing from high to low during faults and voltage waveform is usually asymmetrical. On one hand, when switching an unloaded transformer on, only one switcher of a transformer will trip from "open" to "closed". On the other hand, voltage is generally bursting form low to high during magnetizing inrush due to voltage recovery after clearing an external fault, but it is usually normal and symmetrical. It is feasible that multi-condition restraint consists of transformer voltage and breaker switching state because voltage always flows into the differential protection.

4.4.4.1 Uncertainty restraint

Although voltage will always be inputted digital protection, it may not make sure that digital protection will operate correctly when (a) no voltage is inputted, (b) no signals of switcher states, (c) the state of a transformer is uncertain. So a compromise restraint is presented:

$$\eta \geq \frac{1}{2}(\eta_{2l.dz} + \eta_{2h.dz}) \tag{4-6}$$

The expression (4-6) provides a setting, between high and low threshold setting, which will be used when multi-condition restraint is disabled or during above three conditions. The expression (4-6) is derived from conventional second harmonic restraint, so the performance of this restraint will not be below that of conventional one.

4.4.4.2 Magnetizing inrush recognition when switching a transformer on

The characteristic of voltage when switching a transformer on is quite different and obvious. Before switching a transformer on, there is no voltage of the transformer and after that the transformer has voltage that is close to rating and symmetrical. If there are no switchers between generators and transformers (such as unit connection), it is impossible to switch an unloaded transformer on. If there are switchers between generators and transformers, PTs are equipped with the sides of transformers in some cases, voltage cannot be used to decide whether the operation of switching a transformer on is correct or not. Considering PTs are not usually connected on the sides of transformers but on the sides of bus, the characteristics of transformers occurring cannot be utilized and then another auxiliary state of transformers is needed to act as a criterion.

It is concluded that multi-condition restraint for magnetizing inrush need consist of both sudden change of switcher states and sudden change of voltage.

$$\begin{cases} K_i = 0 \uparrow\rightarrow 1 \\ K_m = 0 \end{cases} \qquad m = 1,2 \ldots m \neq i \tag{4-7}$$

$$\begin{cases} U_a(n - jT) \leq \varepsilon \\ U_b(n - jT) \leq \varepsilon \\ U_c(n - jT) \leq \varepsilon \end{cases} \tag{4-8}$$

$$\begin{cases} |U_a(n) - Ue| \leq \varepsilon \\ |U_b(n) - Ue| \leq \varepsilon \\ |U_c(n) - Ue| \leq \varepsilon \end{cases} \tag{4-9}$$

Where,

K_i -- switcher state of the number i side of breaker;

jT -- Number j cycle;

Ue -- voltage rating.

The criterion expression (4-7), which is based on breaker switching states, analyzes the transition form “open” to “close” of an auxiliary switcher belonging to some side breaker. When no breaker switching state is inputted, this criterion will be disabled.

The criterion expressions (4-8) and (4-9) need to analyze the transition from "zero" to "some" of transform voltage. If no PT is connected with the sides of transforms, this criterion will be disabled.

4.4.4.3 Internal and external faults of transformers

When internal or external faults of transformers happen, voltages of transformers suddenly drop from normal values. Furthermore, Voltage waveforms are asymmetrical during faults because characteristics of most faults are asymmetrical.

According to above condition, voltages can be used to detect whether internal or external faults of transformer happened.

$$\begin{cases} |U_a(n-jT)-U_e| \le \varepsilon \\ |U_b(n-jT)-U_e| \le \varepsilon \\ |U_c(n-jT)-U_e| \le \varepsilon \end{cases} \qquad (4\text{-}10)$$

$$\begin{cases} U_2(n) \ge U_{2.dz} & (4\text{-}11) \\ or \\ U_2(n) \le \varepsilon \text{ and } U_{abc}(n) \le U_{l.dz} & (4\text{-}12) \end{cases}$$

The premise of short-circuit faults occurrence is that voltages are normal before faults happen and this can be written as (4-10), i.e. voltages of three phases are near to rating. And voltages become asymmetrical after faults have happened and can be written as (4-11) or (4-12) corresponding to asymmetrical and symmetrical short-circuit faults.

4.4.4.4 Detection of fault-recovery magnetizing inrush

After clearing external faults, due to voltage recovery, magnetizing inrush of transformers will probably occur and during this period it is an important characteristic that voltages suddenly transform form asymmetrical or comparatively low to normal.

$$\begin{cases} U_2(n-jT) \ge U_{2.dz} & (4\text{-}13) \\ or \\ U_2(n-jT) \le \varepsilon \text{ and } U_{abc}(n-jT) \le U_{l.dz} & (4\text{-}14) \end{cases}$$

$$\begin{cases} |U_a(n)-U_e| \le \varepsilon \\ |U_b(n)-U_e| \le \varepsilon \\ |U_c(n)-U_e| \le \varepsilon \end{cases} \qquad (4\text{-}15)$$

The characteristic of fault-recovery inrush is generally not obvious and hence differential protection will be easily caused to operate incorrectly but using an auxiliary criterion based on transformer voltage. It is a fact that such mal-operation of differential protection has been met for many times in practical application.

4.4.4.5 Reasons for fault-recovery inrush not being obvious

It is difficult for fault-recovery inrush to occur after clearing an external fault. If it does occur, inrush current will not be very large. In theory, the voltage will suddenly recover from faulted voltage to normal voltage just after clearing a fault, and at that moment the flux will act as the residual flux of transformers, so the voltage breaking process is likely to the behavior of switching an unloaded transformer on. For this reason, magnetizing inrush will more easily occur, however, fault-recovery inrush will difficultly happen to transformers in practice. Some reasons below are given to explain this phenomenon. On one hand, after clearing a fault the disappearance of faulted current needs to experience the process of arc extinction which must be completed at the zero point, so the sudden change of voltage after clearing a fault is much smaller than that of voltage when switching an unloaded transformer on. On the other hand, because of the influence of load current, demagnetizing action will make the voltage of source side decrease more. As a result, the voltage recovering speed will decelerate. Due to this kind of slow voltage change, the characteristic of fault-recovery inrush is not significant after clearing a fault.

4.4.4.6 Detection of sympathetic inrush

When switching on an unloaded transformer near the protected transformers, due to the existence of system impedance, magnetizing inrush, in particular, sympathetic inrush, occurs to the running transformers affected by the change of voltage. Protection is easily caused to mal-operate by using single harmonic restraint because the characteristic of this magnetizing inrush is not obvious in harmonics.

The characteristics of voltages are keeping normal during this period.

$$\begin{cases} \begin{cases} |U_a(n-jT)-U_e| \le \varepsilon \\ |U_b(n-jT)-U_e| \le \varepsilon \\ |U_c(n-jT)-U_e| \le \varepsilon \end{cases} & (4\text{-}16) \\ \begin{cases} |U_a(n)-U_e| \le \varepsilon \\ |U_b(n)-U_e| \le \varepsilon \\ |U_c(n)-U_e| \le \varepsilon \end{cases} & (4\text{-}17) \end{cases}$$

4.4.4.7 Switching a faulted transformer on

When switching a faulted transformer on, as same as switching an loaded transformer on, auxiliary connecting points of breakers will change abruptly, at the same time voltage will change too. Because no internal symmetric fault will happen to transformers and three-phase short circuit (e.g. switching-on breaker with grounding) occurring between insides of transformer and outsides of bushing will not cause magnetizing inrush (voltage is comparatively low), only internal symmetric faults are in consideration when switching a transformer on.

The expression (4-19), including that three phase voltages are zero (when PTs are equipped at the sides of transformers) and three phase voltages are equal to ratings (when PTs are equipped at the sides of buses), indicates that three phase voltages should be normal before a fault happens to transformers. The expression (4-20) indicates that voltages are asymmetrical and negative sequence voltages are occurring when switching a faulted transformer. The expression (4-18) shows that auxiliary connecting points of breakers will change suddenly when switching an unloaded transformer on.

$$\begin{cases} K_i = 0 \uparrow^{\rightarrow} 1 \\ K_m = 0 \end{cases} \qquad \mathrm{m} = 1,2 \ldots \mathrm{m} \neq \mathrm{i} \tag{4-18}$$

$$\begin{cases} U_a(n-jT) \leq \varepsilon \text{ or } |U_a(n-jT) - Ue| \leq \varepsilon \\ U_b(n-jT) \leq \varepsilon \text{ or } |U_b(n-jT) - Ue| \leq \varepsilon \qquad (4\text{-}19) \\ U_c(n-jT) \leq \varepsilon \text{ or } |U_c(n-jT) - Ue| \leq \varepsilon \\ U_2(n) \geq U_{2.dz} \qquad (4\text{-}20) \end{cases}$$

4.4.4.8 Faults occur immediately after switching a transformer on correctly

In fact, switching a faulted transformer on does not mean switching a transformer on with internal initial faults, instead, transformer insulation is sound after examination and repair or before the transformer runs. Unfortunately, faults will occur easily because transformer insulation during switching-on because transformer insulation is unable to tolerate the sudden impulse of current. For this kind of fault, conventional harmonic restraint will not adapt, instead, it will delay the tripping time. The statistical data show that the tripping time of transformer differential protection is always longer than that in theory, so the influence of harmonics should not be neglected according to above analysis.

Adding the criterion of voltage, multi-condition restraint for magnetizing inrush will obviously accelerate the tipping time of differential protection.

4.4.4.9 Switching a faulted transformer on and tripping time of differential protection

At present, there are several practical restraints for magnetizing inrush such as second harmonic restraint, dead angle restraint, restraint based on waveform symmetry and so on. In fact, above restraints have no direct relationship with the tripping time of differential protection and their primary function is to distinguish magnetizing inrush from short-circuit faults. However, the means of blocking protection have a close relationship with the tripping time of differential protection when switching a faulted transformer on, that is to say, the tripping speed is relatively slow when blocking three-phase differential protection due to single-phase magnetizing inrush occurrence and the tripping speed is relatively quick when blocking identical phase differential protection due to single-phase inrush occurrence. The view presented in some papers, the restraint based on waveform symmetry will accelerate tripping speed of differential protection when switching a faulted transformer on, is not correct in theory

4.4.5 Restraint criterion for over-excitation

Over-excitation will probably damage transformers due to high temperature. Generally transformers are equipped with over-excitation protection. In theory, transformer differential protection should not trip during over-excitation. It is the duty for over-excitation protection to detect whether a transformer is over heated or not and to decide whether to trip or not. However, it is not the fact.

There are six misunderstandings about over-excitation.

(a) Differential protection should not mal-operate during over-excitation.

In fact, if the ratio of transformer excitation is comparatively high, anti-time over-excitation protection will operate quickly, delaying from several dozens to several hundreds milliseconds. So it has no substantial difference with differential protection.

(b) Even if slight over-excitation happens, transformer differential protection should be blocked.

In fact, biased current waveforms of transformers are shown in figure 4.1 during slight over-excitation. It is difficult to detect whether transformers are over excited, so differential protection will not mal-operate.

(c) Differential protection of over-excited transformer will mal-operate.

In fact, differential protection would not mal-operate during slightly over-excitation because differential protection demands for a starting current.

(d) Whether to block differential protection or not is decided by U/f.

It is not recommended that whether a transformer is over-excited and whether to block differential protection is decided in terms of U/f, because sometimes it has some disadvantages that whether to block differential protection is decided by U/f.

It is known from analysis that U/f is a sympathetic variable which indirectly reflects the over-excitation of transformer, i.e. increase of voltage or decrease of frequency will probably cause over-excitation of transformer, but whether the transformer is over-excited is still indefinite. In addition, the over-excitation states of transformers of the same type and of the same U/f cannot be totally the same due to both the nonlinear characteristic of transformer excitation and the discrete manufacture. So it is reluctant to block differential protection by U/f.

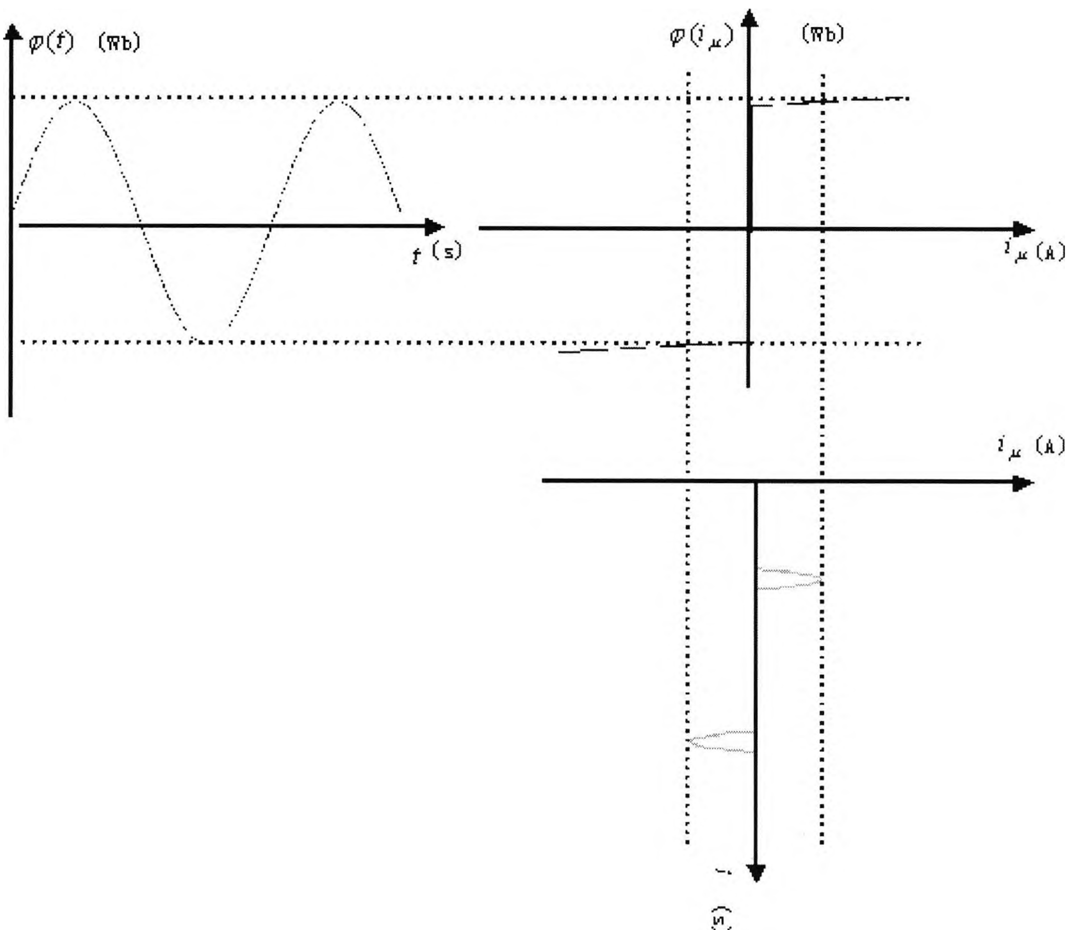


Fig. 4.1 Biased current during slightly over-excitation of transformer

(e) If setting based on fifth harmonic restraint is less than that in theory, mal-operation of differential protection will be avoided.

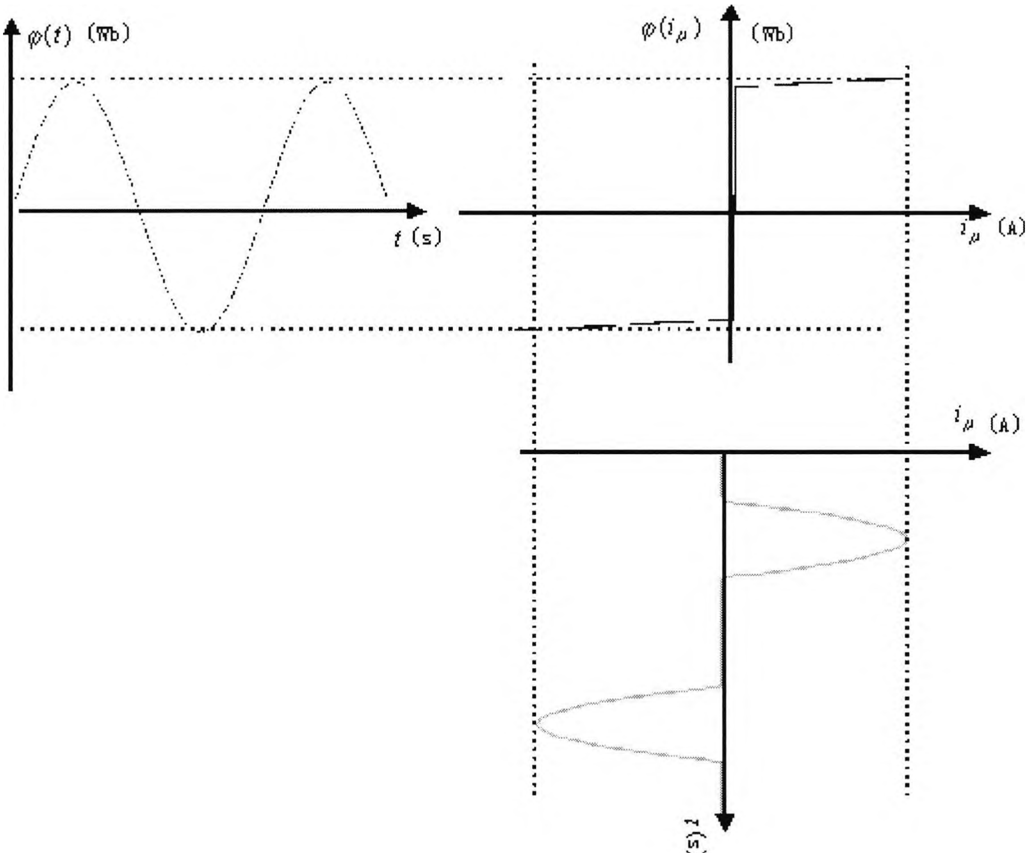


Fig. 4.2 Biased current during severe over-excitation of transformers

This point may result in non-operation of differential protection. In fact, fifth harmonic will occur during both over-excitation and short-circuit faults, because odd harmonics are also the characteristic of short-circuits faults (odd harmonics are mainly caused by negative sequence current).

Fig. 4.2 shows that the more transformers are over-excited the less fifth harmonic content, so fifth harmonic will not function during severe over-excitation, i.e. restraint based on fifth harmonic will not prevent differential protection from mal-operating.

(f) Restraint for over-excitation does not cooperate with over-excitation protection.

Obviously, restraint during over-excitation does not permit protection to trip. However, over-excitation protection is provided with anti-time characteristic, and this kind of protection will trip the protection immediately the time arrives at the given value. Therefore, restraint for over-excitation conflicts with over-excitation protection and they should cooperate with each other, but it is very difficult to do that so far.

From above analysis about misunderstandings, it is concluded that at present both fifth harmonic restraint and restraint based on U/f are unable to solve the problem soundly the over-excitation of transformers.

Differential protection will not mal-operate during slight over-excitation of transformers because differential protection demands for a starting current generally set 30-60% I_e, i.e. transformer differential protection has some ability against over-excitation. If biased current overpasses 30-60% rating current during over-excitation of transformers, transformers are not able to tolerate, because this current is not load current of transformers and will flow into excitation branch circuit of transformers and will become exciting current totally. In order to protect transformers, it is obliged for differential protection to eliminate this kind of over-excitation.

From above analysis we can conclude that transformer protection cannot benefit from fifth harmonic restraint and restraint based on U/f for detection of over-excitation, on the contrary, improper use of above restraints will cause insecurity of transformers. It is not necessary for differential protection to additionally install restraint for over-excitation.

4.4.6 Realization of multi-condition restraint criterion for magnetizing inrush

Multi-condition restraint for magnetizing inrush is advanced on the basic of harmonic restraint. To make a further decision that whether a transformer is during magnetizing inrush or not, this restraint is divided into several states in terms of original harmonic restraint criterion for magnetizing inrush and it will obviously raise ratio of correct detection of magnetizing inrush.

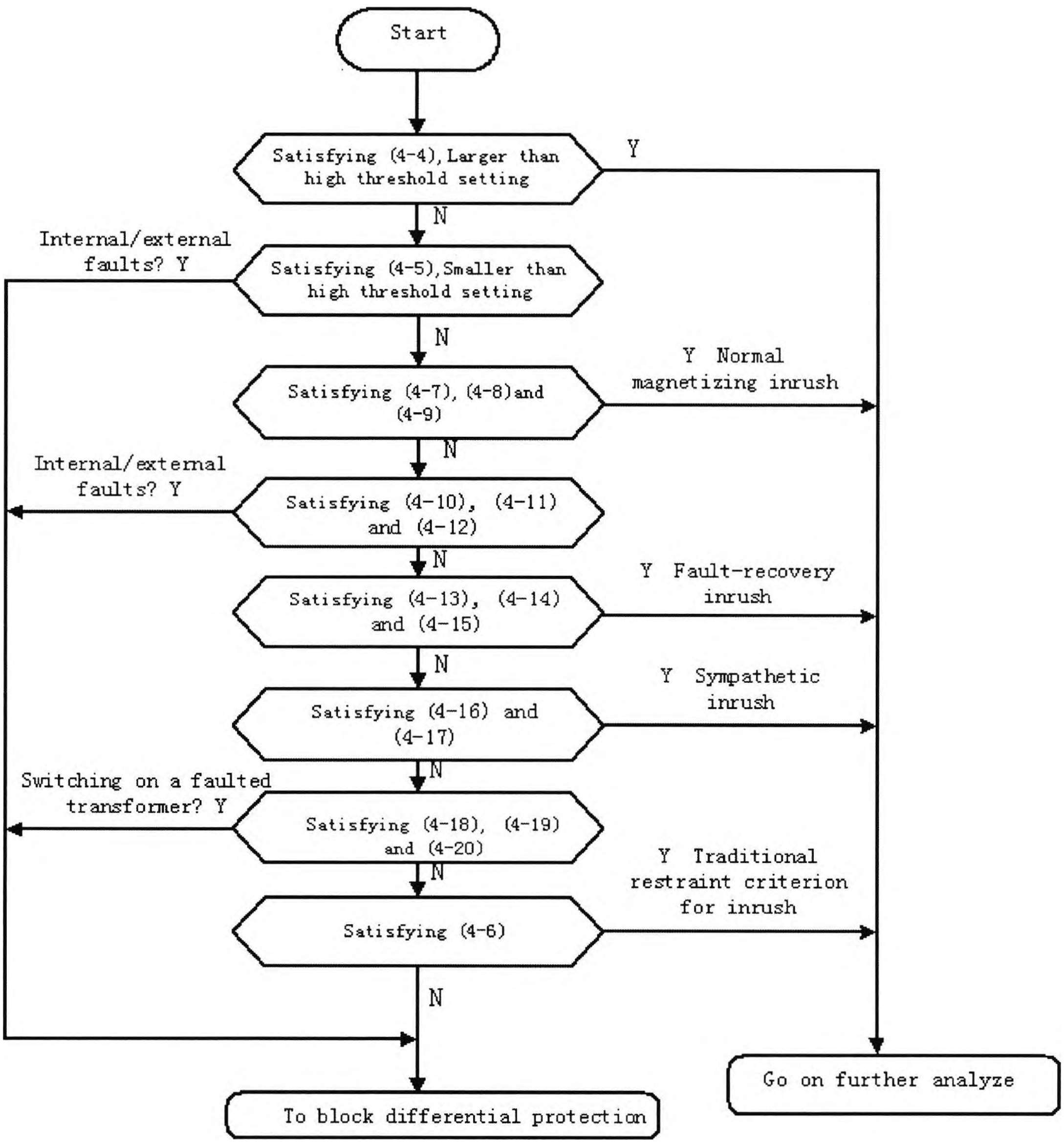


Fig 4.3 Flow chart of mult-condition inrush current restraint mechanism

It is shown in above figures that multi-condition restraint criterion is based on harmonic restraint criterion and it can definitely detect whether a fault or inrush happens in some cases that conventional harmonic restraint criterion cannot do. In other cases, conventional harmonic restraint criterion should be undoubtedly applied.

The realizing flow chart of multi-condition restraint criterion is given below:

4.4.7 Setting of multi-condition restraint

Setting principle can be achieved in terms of multi-condition restraint for magnetizing inrush.

4.4.7.1 High and low setting $\eta_{2l\,dz}$ $\eta_{2h.dz}$ of multi-condition restraint

Setting principle is that when harmonic content is below $\eta_{2h.dz}$, short-circuit faults certainly happen to transformers and when harmonic content is above $\eta_{2h.dz}$, magnetizing inrush definitely occurs.

Generally multi-condition restraint setting follows conventional harmonic restraint setting and only needs to add or subtract 5-8 percent points.

In case that conventional harmonic restraint setting is $\eta_{2.dz}$, thus

$$\eta_{2l.dz} = \eta_{2.dz} - (5 \sim 8)\% \quad (4\text{-}21)$$

$$\eta_{2l.dz} = \eta_{2.dz} + (5 \sim 8)\% \quad (4\text{-}22)$$

For example, if $\eta_{2.dz}$=17%, then

$$\eta_{2l.dz} = 11\% \text{ and } \eta_{2h.dz} = 23\% \quad (4\text{-}23)$$

4.4.7.2 Normal voltage and no voltage threshold ε

The setting principle of normal voltage and no voltage threshold ε is to avoid the normal maximum or minimum voltage of transformers, because power system voltage will not overpass 20%U_e, setting is as follows.

$$\varepsilon = 20\% U_e \quad (4\text{-}24)$$

4.4.7.3 Setting U_{2dz} of negative sequence voltage

The setting principle of negative sequence voltage is that setting can be the maximum negative sequence voltage normally. In power system, normal negative sequence voltage content will not overpass 10%. So setting can be written as:

$$U_{2dz} = (10\% \sim 15\%) U_e \quad (4\text{-}25)$$

4.4.7.4 Setting $U_{l.dz}$ of three-phase low voltage

The setting principle of three-phase low voltage is to ensure that setting can be the value of magnetizing inrush current during internal short-circuit faults or fault-recovery inrush conditions. It can be shown as following:

$$U_{l.dz} = (20\% \sim 30\%)U_e \qquad (4\text{-}26)$$

The problems of differential protection setting selection are as follows:

In theory, the settings of differential protection ought to ensure that protection will not mal-operate during magnetizing inrush, however, the ratio of comparing inrush current with normal current is usually large. So when faults happen to the bushing of lead line, if according to this principle, there is probably no enough sensitiveness because of relatively small ratio. As a result, differential protection will not operate soundly and even will have no operation at all because setting is too high (protection will not operate for ever). In this thesis, the view is that differential protection should consider the characteristics of waveforms to avoid mal-operating during severe magnetizing inrush.

4.5 Real-time dynamic test results

Figs 4.4 to 4.7 show some typical recording curves from a dynamic simulation real testing in a 300MW generator-transformer. The connection and parameters of the simulated power system are given in chapter 3.

It can be seen from the Figures that ANN based differential protection obviously achieved better performance than conventional principle because of ANN 's ability to recognize fault.

It is a common normal operation to switch transformer on or off. Large capacity transformer has smaller margin than small one because of its size and cost. Maloperations occurred occasionally in these large transformers in these years. Fig 4.4 shows a mal-operation occurred in conventional relay as CT situated only in half-cycle. Conventional principle sometimes do not perform well when CT situation occurred according with inrush current. Fig 4.5 shows another mal-operation occurred in conventional principle because of symmetric inrush occurred. It is always difficult to distinguish fault current and symmetric inrush current in conventional principle.

Fig 4.6 and 4.7 show an interturn fault transformer switched to the power system. In the curve, we found conventional relay refused to trip as inrush current occurred in a non-faulted phase. It is easy to block differential relay tripping in conventional principle when inrush current occurs.

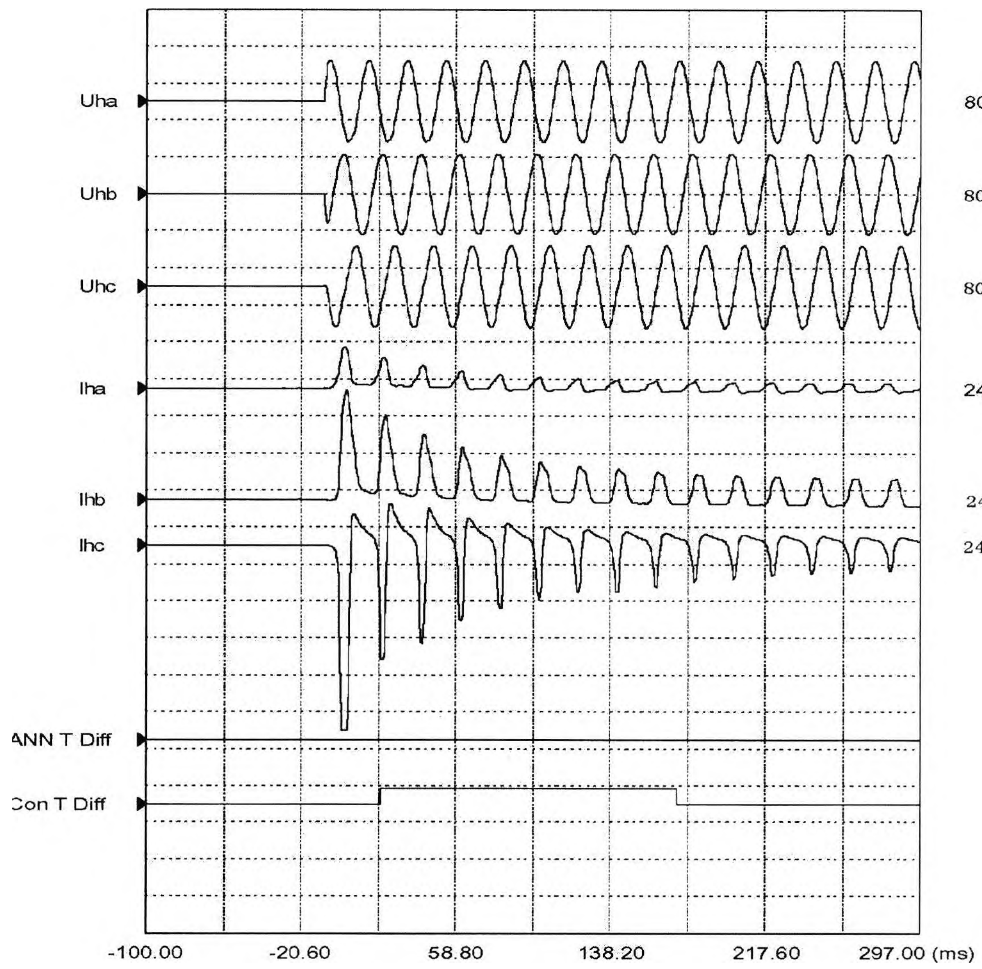


Fig 4.4 Transformer inrush current when switching on
(Conventional differential relay mal-operated because of CT saturated only in half-cycle in phase C)

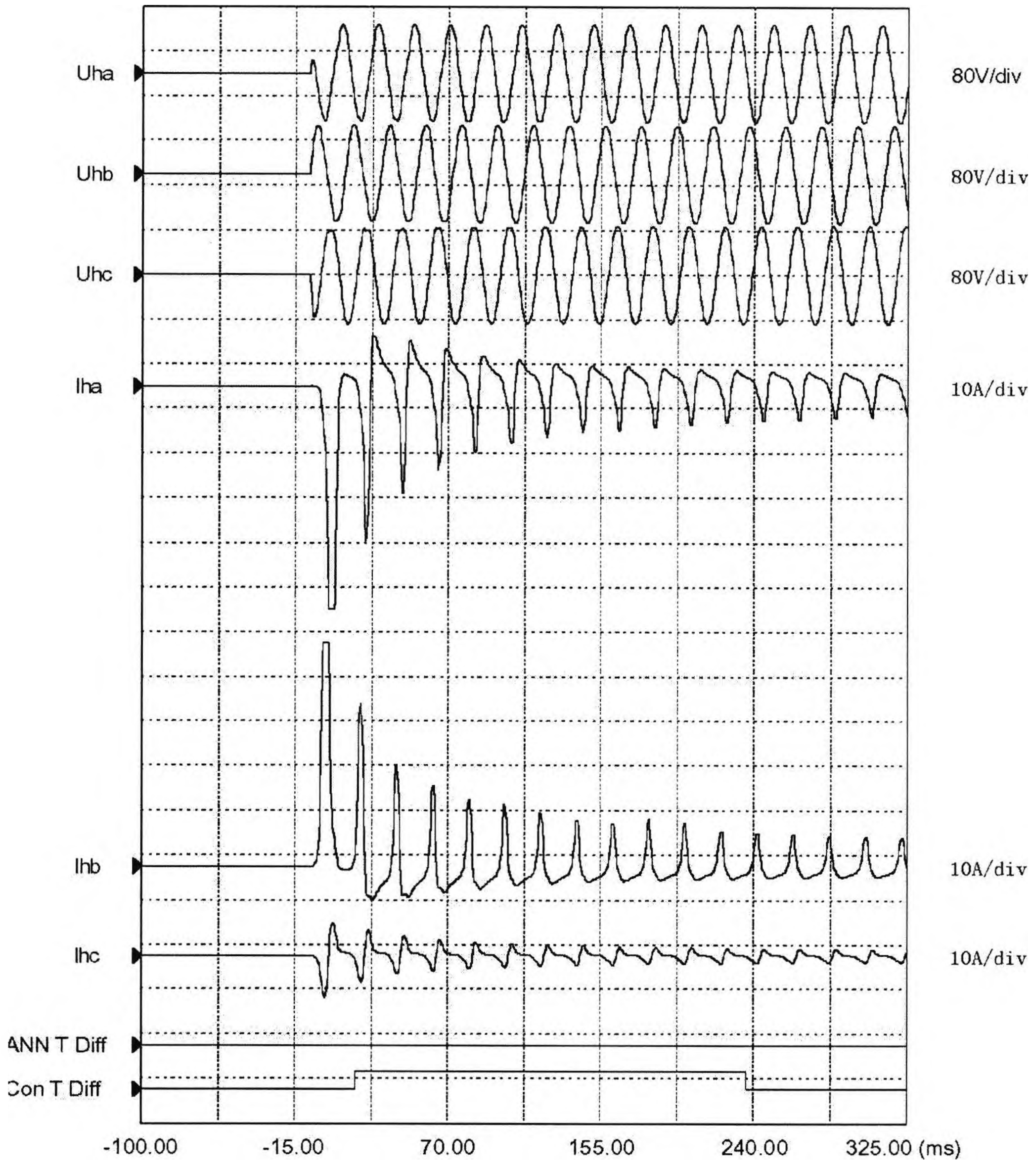


Fig 4.5 Transformer inrush current when switching on

(Conventional differential relay mal-operated because of symmetric inrush current in phase C)

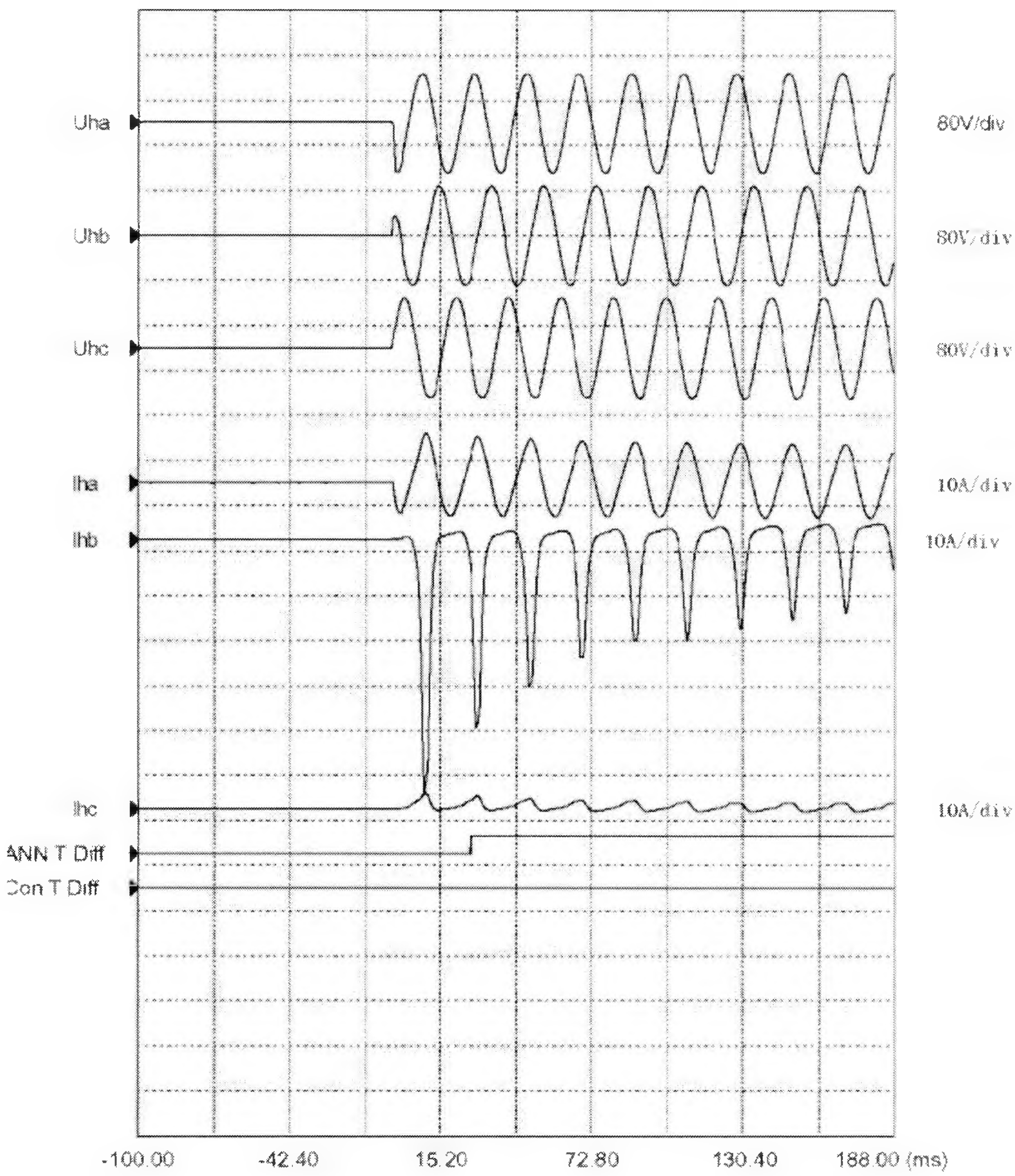


Fig 4.6 Transformer inter-turn fault (2.4%) at high-voltage side when switching on

(Conventional differential relay did not operate because of restraining of inrush currents occurred in non-faulted phases)

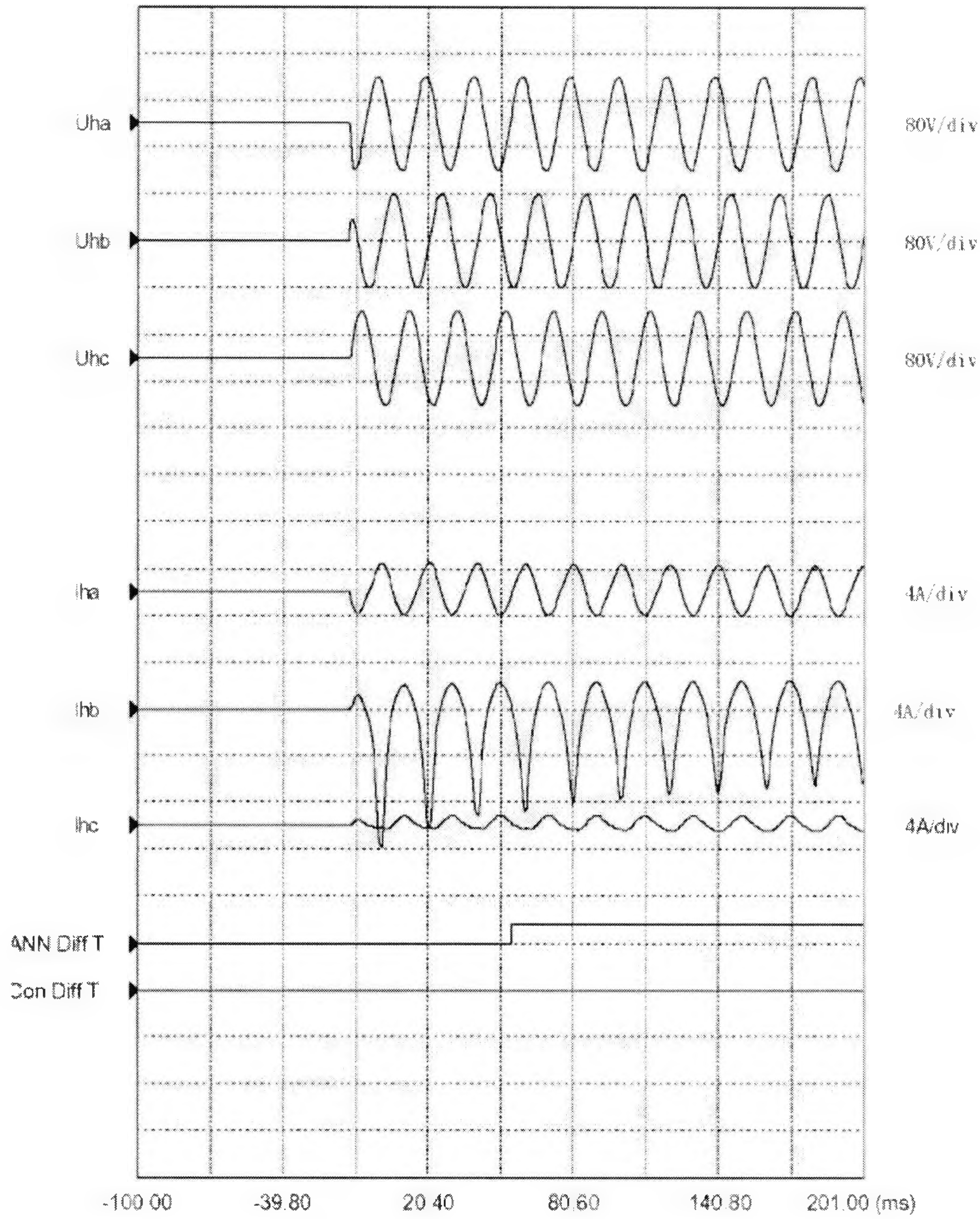


Fig 4.7 Transformer interturn fault (1.7%) in low-voltage side when switching on

(Conventional differential relay did not operate because of restraining of inrush currents occurred in non-faulted phases)

4.6 Conclusions

Conventional differential protection can usually make use of magnetizing inrush restraint theme consisting of single variable and simple theory due to the limitation of the practical means of differential protection. According to the intelligent features of digital protection, in this chapter a new method is presented to distinguish magnetizing inrush by using multi-condition restraint criterion. Incorporated with the introduction of breaker switching state and transformer voltage state, the transformer working states such as inrush, short circuit, fault-recovery inrush, sympathetic inrush, switching on an unenergized faulted transformer, fault right after switching on an unengized transformer and so on, can be differentiated by the multi-characteristics of inrush current.

Multi-condition restraint for inrush overcomes the shortcoming that conventional harmonic restraint, which is applied to modern large transformers, cannot exactly distinguish short circuit and inrush. By making full use of multi-characteristics of inrush current, the disturbing problem about faults and inrush can be solved soundly.

In the chapter it is also pointed out that there are no direct relationship between restraint for magnetizing inrush and tripping time during switching on an unenergized faulted transformer. The very relation is between inrush restraint method and the inrush restraint mean.

Because transformer differential protection has some ability against over-excitation, some proposals about detection of transformer over-excitation is advanced that present over-excitation restraint has insecure effect on differential protection and hence special over-excitation restraint function for transformer differential protection is unnecessary.

Chapter 5 Digital Differential Protection Strategy for CT Open-circuited

Whether to block transformer differential protection when current transformer (CT) secondary circuits are broken is in dispute. Whether and what strategy to block differential protection during CT secondary line broken will be discussed in this chapter.

5.1 Present situation of CT secondary line broken

It is a fact that differential protection would mal-operate when CT secondary circuits break. In our country the operation of differential protection caused by CT secondary open circuit is classified as mal-operation of differential protection. So the function of blocking differential protection ought to be installed to avoid mal-operation when CT secondary circuits break.

In our country the correct ratio of differential protection is ranging from 70% to 80%. Statistical data show that mal-operation of differential protection caused by CT secondary open circuit is the majority and even exceeds the quantity of mal-operation caused by primary equipments. However, the above information is announced officially and the actual data probably are more.

At present, there are two contrary attitudes to CT secondary open circuit.

5.1.1 Necessary to block differential protection when CT secondary circuits break

Ten years ago the view that “Blocking differential protection when CT secondary circuits break” was prevalent because generators and transformers belonging to primary equipments play an important role in power system. For example, once a generator or a transformer is tripped incorrectly, it will cause the instability of power system or the interruption of power supply in the wide area. In order to make power system shun from irrelevant faults, CT secondary faults should not affect the normal working of primary equipments of power system. For this reason differential protection should be blocked when CT secondary circuits break.

If CT secondary circuits break, at the breakpoint there will be arc current and high voltage which may harm people and damage secondary equipments (such as a fire). To avoid these problems, protection for CT secondary open circuit with nonlinear resistance, which is shown in figure 5.1, is equipped on CT secondary sides. This protective relay is open when CT secondary circuits are sound. When CT secondary circuits break and high voltage occurs at the secondary circuits, the nonlinear reactance of this relay decrease rapidly and the voltage at the breakpoint is limited to a reasonable range in order to prevent primary equipments from damaging and to protect people from harming. In fact, the early method is like that.

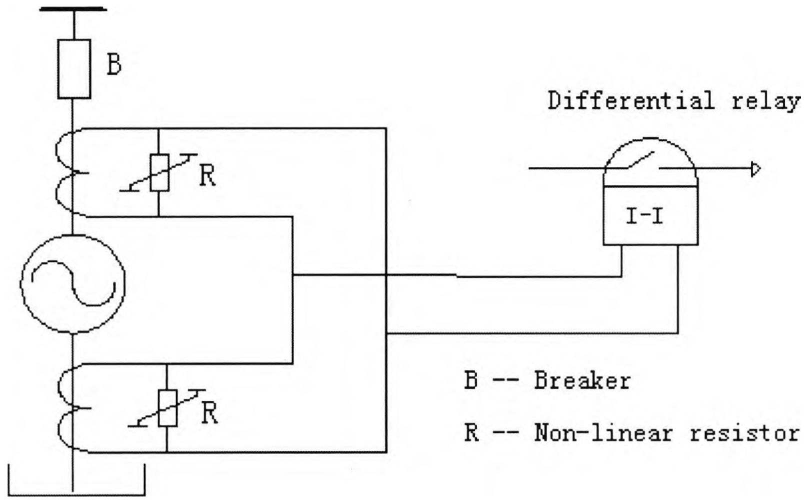


Fig. 5.1 Relays against CT secondary open-circuit

5.1.2 Unnecessary to block differential protection when CT secondary circuits break

With the rapid development of power system in the last decade, one generator or transformer has less effect on power system while the manufacture cost is more expensive than before. Therefore the function against CT secondary open circuit will reduce the security of differential protection and do harm to protected equipments. In addition, it also violates the Regulation of Equipment Security that a generator or transformer is not tripped when arc current and high voltage occur at the breakpoint of CT secondary circuits.

This view is well accepted after the presentation of the investigation report arranged by National Power Department to investigate the conditions of primary equipments of South and North Power System in 1994. This detailed report about the problem of CT secondary open circuit surprised us.

It pointed out that the quantity that CT secondary circuits actually break is very small (because operators clearly know the damage caused by CT secondary open circuit and much importance has been attached to the installment, working and maintenance) and that mal-operation of differential protection, which is originally considered to be caused by CT secondary open circuit, actually is caused by shunt current of protective relays designed for CT secondary open circuit. The report has also pointed out that if protective relays designed for CT secondary open circuit were not equipped, the mal-operation probability of differential protection caused by these relays would decrease greatly, and then total mal-operation of differential protection would also decrease greatly.

However, if removing the function of CT secondary open circuit from protection, it is impossible to limit high voltage occurring at the breakpoint of CT secondary circuits. So considering the removal of this special function, transformer differential protection should trip the breakers when CT secondary circuits break and thus no potential trouble is left.

Although removing the special function from protection will result in tripping the breakers of transformers when CT secondary circuits break, it seems as the chance of tripping for differential protection increases, in fact, it will reduce mal-operation of transformer differential protection. In addition, there is not enough reliability of the criterion for CT secondary open-circuit (Differential protection will probably not be blocked when CT secondary circuits actually break). Therefore, considering all above conditions the mal-operation probability of differential protection will decrease instead.

Nowadays the protection for CT secondary open-circuit has been removed in many stations. However, it must be mentioned that after the removal of this kind of protection, transformer protection should trip the breakers when CT secondary circuits break or there will be a risk to transformers.

5.2 Difficulty in detecting CT secondary open-circuit

In some countries it is generally agreed that if CTs are equipped properly, CT secondary open-circuit will probably not occur. In addition, it is also agreed that open-circuit high voltage will cause damage to personnel and equipment safety. Consequently, differential protection should not be blocked when CT secondary circuits break.

If there were a criterion to identify CT secondary open-circuit reliably and to block differential protection, there would be no dispute described in section 5.1. In fact, no such perfect theory is advanced so far and transformer differential protection will still mal-operate when CT secondary circuits really break.

The following sections will discuss problems for CT secondary open-circuit detection and solutions will be proposed to minimize the risk.

5.2.1 Detection of CT secondary open-circuit should be faster than operation of differential protection

The tripping time of differential protection is usually about 20-40ms, i.e. differential protection belongs to high-speed protection. It is not difficult to detect CT secondary open-circuit through analyzing the process of CT secondary open-circuit; however there is not enough time. On the other hand, the function to detect CT secondary open-circuit and to block differential protection is required to operate definitely before the operation of differential protection. It is meaningless to block differential protection since there is no sufficient time to make a decision.

5.2.2 Principles of preferring to block differential protection unsuccessfully rather than block differential protection incorrectly when CT secondary circuits actually break

The method to distinguish CT secondary open circuit is generally simple and quick for a decision is required to be made in the very short time. Conservative action of not blocking differential protection is usually taken under some uncertain conditions. Once differential protection is blocked at the same time internal faults happen to generators or transformers, it will be extremely dangerous. Consequently it is the principle that preferring to block differential protection unsuccessfully rather than block differential protection incorrectly when CT secondary circuits actually break. As the result, it is not surprising that differential protection is not blocked when CT secondary circuits break.

5.2.3 Actual process of CT secondary open circuit is more complex than that in theory

At present, the theory of detecting CT secondary open-circuit is assumed that the current of open-circuit decreases to zero rapidly when CT secondary circuits break. The tests of CT secondary open-circuit in the laboratory are based on this assumption.

However, the accurate process of CT secondary open-circuit is more complex than that in theory. At the beginning of CT secondary open-circuit, the current will not generally decrease to zero rapidly, because this process is accompanying with interrupted arc. Due to arc resistance, current will partly flow into the protective relays. Under this condition, differential protection will mal-operate definitely. In addition, current flowing into protective relays can even cause current transformer saturation and current phase shift for the reason of the change of CT load.

5.2.4 Shunt current of protective relays

Protective relays are originally designed to function after CT secondary circuits break, however in practice, current leakage of protective relays often occurs. In addition, this kind of shunt current is difficult to estimate so that differential protection would certainly mal-operate.

In short, the criterion for CT secondary open-circuit should consider various conditions and the realization of rapid operation under complex conditions is difficult and complicated.

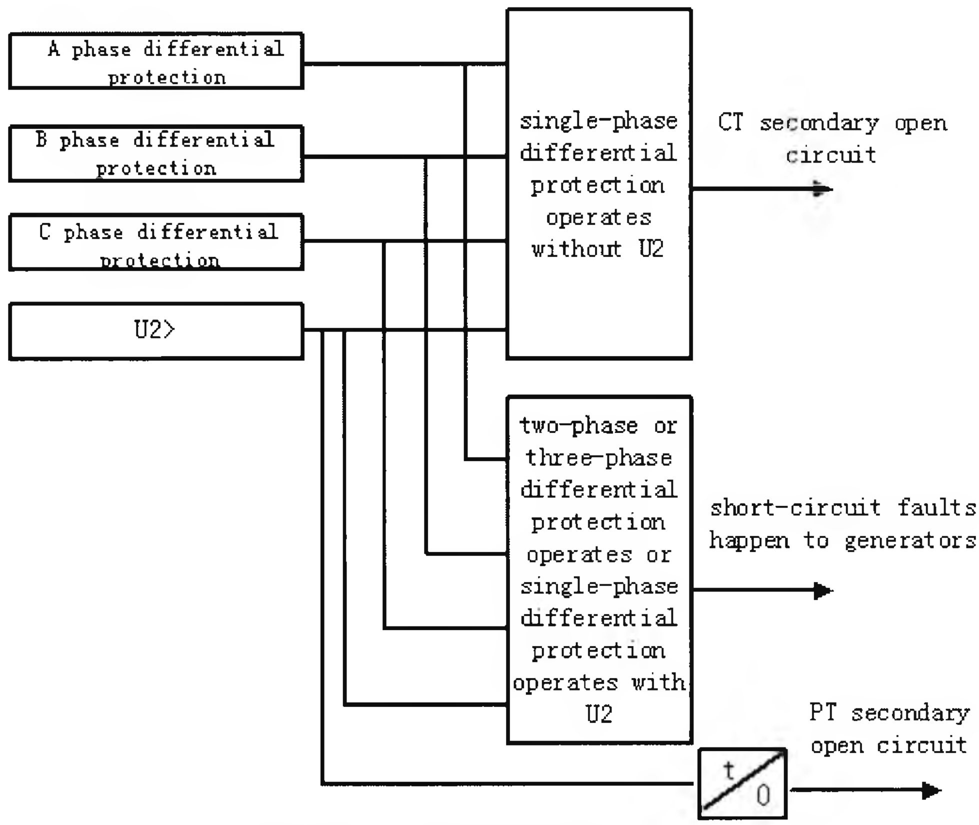
5.3 Strategy for CT secondary open-circuit

In our country whether to block differential protection when CT secondary circuits break is still in dispute so far. The aim of digital protection research is to bring forward new approaches to detect CT secondary open-circuit and to meet the requirements of applications on various occasions.

5.3.1 Circular restraint strategy of generator differential protection for CT secondary open circuit

Because all generators are not directly grounding, a single-phase grounding fault of generators does not mean a short-circuit fault. Only when a phase-to-phase short-circuit fault or another grounding fault caused by a single-phase grounding fault happens, a short-circuit fault actually occurs. Consequently single-phase differential protection will not operate while in contrast two-phase differential protection will operate simultaneously. According to this feature, a reliable restraint criterion for CT secondary open circuit will come into being--circular restraint.

This protection logical chart is shown in Fig. 5.2.



(U2-negative sequence current; t-time delay)

Fig. 5.2 Circular restraint of blocking generator differential protection

As the figure illustrates, the basic principle is that single-phase differential protection operation is considered as a result of CT secondary open circuit while two-phase differential protection operation is considered as a result of short-circuit faults.

To avoid few short-circuit faults that one grounding point is within the protected section while another grounding point is out of the protected section, negative sequence voltage is added to act as an auxiliary criterion, nevertheless this kind short-circuit fault has never happened.

5.3.2 Strategy of generator or transformer differential protection for CT secondary open-circuit

Although circular restraint for CT secondary open circuit is secure and reliable, it can only be applied to generator protection and it is not fit to transformer protection. When internal short-circuit faults of generators happen, the condition of simultaneous operation of two-phase differential protection happens probably, but the sensitivity between two-phase differential protection are not the same considering that two-phase biased current of transformer protection is not the same. In addition, CTs of present transformers are connected in star-connection, so CT secondary open-circuit, connected in delta side of transformers, will lead to two-phase differential protection mal-operation. So this circular restraint will not function on this occasion.

Circular restraint only detecting single-phase CT secondary open-circuit is not well developed, so new approaches of higher performance should be pursued.

5.3.2.1 Strategy based on sudden changing direction of current for CT secondary open-circuit

As we know from above analysis, current decreases rapidly when CT secondary circuits break but not to zero. When slight internal faults of transformers happen, current will only change slightly. The performance of the conventional approach of detecting whether current decreases near to zero, is not satisfied. Through detailed analysis, significant difference in current between CT secondary open-circuit and short-circuit fault is found and a new algorithm was developed.

Sudden change in current direction

Current increase is the characteristic of short-circuit faults while current decrease is the characteristic of CT secondary open circuit. Consequently current changing direction may act as one characteristic to distinguish CT secondary open-circuit from short-circuit faults.

$$\Delta I_i(n) < -\Delta I_{dz} \qquad (5\text{-}1)$$

Where $\Delta I_i(n)$ is single-phase or two-phase current of the number i side of transformers.

$$|\Delta I_{k \neq i}(n)| < \varepsilon \qquad (5\text{-}2)$$

The currents of other sides of transformers, excluding those satisfying (5-1), should satisfy (5-2). The expressions of (5-1) and (5-2) ensure that current of the same side of transformers will only change negatively in direction and exclude the probability of short-circuit faults. Currents changed in direction should be on the same side of CT.

Generally, the criterion for CT secondary open-circuit does not concern the condition that CTs of the different sides of secondary circuits simultaneously break.

(c) The number of currents changed in direction belonging to the same side of CT should not exceed 2. The condition that three-phase CT secondary circuits simultaneously break is not of a concern. The total number of current suddenly changed in direction should not exceed 2.

Regardless of whether current suddenly change positively or negatively, if the number of current changed in direction exceed 2 (3 or over 3), then it is not considered as CT secondary open-circuit.

A novel idea on double setting threshold criterion according to current existence has been proposed by the author. In this concept, all currents should exceed high setting. Three-phase current at least of one side should simultaneously exceed high setting current.

The current of the side of CT secondary open circuit should be symmetrical and the same. Current in the side of CT secondary open-circuit is at least higher and another one phase or two phase current is low. If current in at least one side is above setting, protection should be released from blocking.

When CT secondary circuits break, current on any side should not be higher than the rated current and normal highest current, therefore if current exceeds the rating, a short-circuit fault will probably happen.

5.3.2.2 Analysis on strategy based on current sudden change in direction for CT secondary open-circuit

As we know from analysis on strategy based on current sudden change in direction for CT secondary open circuit, the designing idea for restraint of CT secondary open-circuit still does not change. When CT secondary open-circuit cannot be distinguished, differential protection should not be blocked. However, the state of CT secondary open-circuit is stable, current amplitude should be acted as an auxiliary criterion.

5.3.3 Analysis of restraint of CT secondary open-circuit for application

In the long run, the restraint function will be eliminated from differential protection, i.e. differential protection is entitled to trip the breakers when CT secondary circuits break. However, there will be a transitional stage from blocking differential protection to not blocking differential protection when CT secondary circuits break.

During this transitional stage, corresponded approaches should be applied to differential protection.

5.3.3.1 Completely without the restraint function for CT secondary open-circuit

When CT secondary circuits break, differential protection is kept from tripping and no signal is sent out for CT secondary open-circuit operation.

5.3.3.2 Signal is sent out while differential protection is not blocked

In fact, when CT secondary circuits break, if the load of generators or transformers is not too heavy, differential protection will not be necessary to operate and signal can be sent out to indicate that CT secondary circuits have already break. Because there is enough time to calculate, it can be distinguished easily and securely that whether CT secondary circuits break.

If current is arising to the setting of differential protection during CT secondary open circuit, protection will trip the breakers. At the same time, the indication of signal will help faults analysis.

5.3.3.3 Restraining function for CT secondary open circuit are controlled by operators

Differential protection is allowed to be blocked but is controlled by operators. Of course, signals can be sent out or not when differential protection is not blocked.

5.3.3.4 Differential protection is blocked when CT secondary circuits break

The usual operation is that differential protection is blocked when CT secondary circuits break, but this operation will gradually be given up.

5.4 Conclusions

Whether to block differential protection is still in dispute when CT secondary circuits break. In developing point of view, the probability of CT secondary open-circuit is small. Considering the restraint criterion for CT secondary open-circuit is not well developed, it is a trend that the restraining function for CT secondary open-circuit will be eliminated in the future.

To meet the requirement of present differential protection, according to the physical process of CT secondary open circuit and the present state of existing restraint criterion, a new restraint criterion based on current sudden change in negative direction is presented. In addition, it makes great progress on the conventional criterion for CT secondary open circuit and it does not neglect the fact that when CT secondary circuits break, arc current will probably occur or current will decrease to zero.

Chapter 6 CT Transient Saturation Analysis for Digital Differential Protection

It was believed for a long time that the characteristic of ratio restraint always involves with the capability of CT anti-saturation and within the permissive range of CT saturation or transition effect in design (about 10%). Differential protection based on ratio restraint will not mal-operate according to traditional concept. In fact, it is not true in digital relay. The operation statistical data shows that some unknown mal-operations are always concerned with the CT transient saturation. Through the analysis of differential protection dynamic simulation test designed for CT anti-saturation, this chapter presents the view that ratio restraint will not certainly overcome CT transient saturation especially with the decaying direct current component. How to select trip judgment times, digital filter algorithm and width of data window, which have a direct impact on the performance of differential protection for CT anti-saturation is studied in detail.

6.1 Introduction

Current Transformer (CT) is one of most important sensors in power system and is widely applied to protection, measurement, monitoring and control and so on. In addition, the requirement of CT characteristics varies with application fields. Usually the accuracy of instrument CT is sufficiently high under steady-state conditions, nevertheless protection is always required to operate correctly under short-circuit fault and power system unsteady-state conditions. That is to say, sufficient accuracy of instrument CT for protection should be provided under short-circuit fault conditions while definite accuracy is required under normal conditions. CT error current is mainly caused by the current of exciting branch circuit. Under normal conditions CT works in the linear section of magnetizing characteristic and the exciting current is small and error current is also small. However, transient current under fault conditions consists of decaying D.C. component, exponentially decaying A.C. component and steady-state D.C. component. CT works in the nonlinear section of magnetizing characteristic and enters the transient saturated section. Consequently part of the current flows into the CT exciting branch circuit and the exact state of the primary cannot be reflected by the secondary and it will result in incorrect operation of differential protection.

With the development of digital protection, the operating speed of differential protection makes a great progress. Following this, lots of problems in conventional principle are gradually exposed. For example, the problem of mal-operation due to CT transient saturation is one. If the operating speed of protection is merely pursuing and other auxiliary measures are not correspondingly taken, then the performance of differential protection will be further reduced. In this case, theoretical analysis becomes more and more important. This chapter applies both theory of CT transient saturation and dynamic simulation test to the analysis that how much influence the CT transient saturation has on the performance of differential protection based on digital ratio restraint. Furthermore, the influence on the characteristics of differential protection caused by trip judgment times, digital filter algorithm and width of data window will also be specifically investigated.

6.2 Theoretical analysis of CT saturation

6.2.1 Physical process of CT saturation

Fig. 6.1 shows the simplified equivalent circuit of CT. The primary electrical source is equivalent to an ideal current source and thus the leakage inductance can be omitted. For the purpose of convenience of analysis, the windings of the primary and the secondary are assumed to be the same and then the leakage inductance of the secondary is added to the load inductance L_2. At the same time, the main flux of CT is ψ.

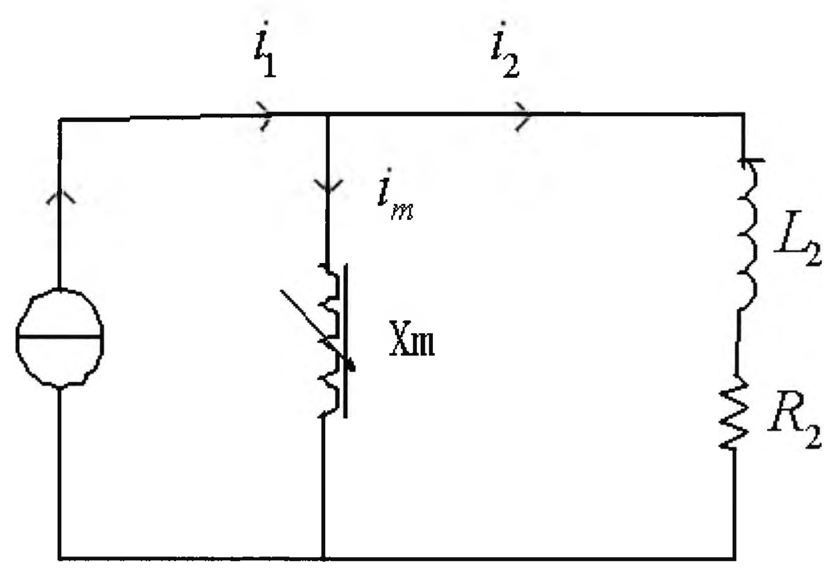


Fig. 6.1(a) CT equivalent circuit

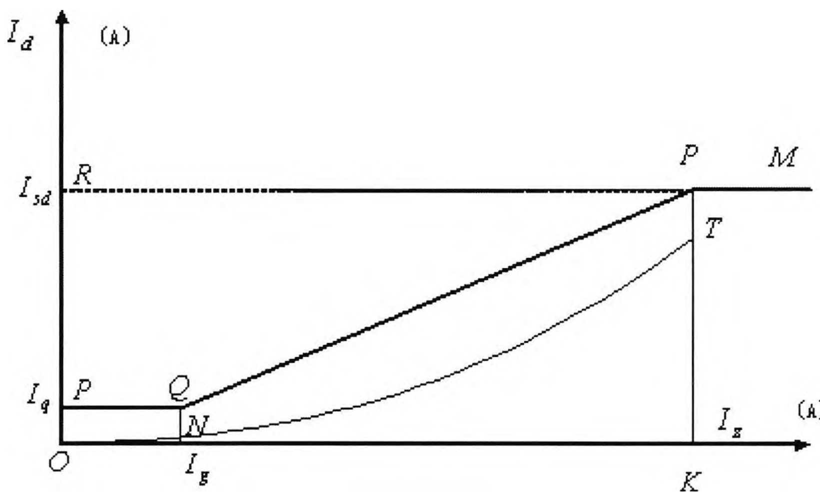


Fig. 6.1(b) Characteristic of differential protection based on ratio restraint

Following the increase of the primary steady sinusoid current, the secondary current is also increasing, and high voltage is produced at the secondary winding connected with load. For maintaining this high voltage, large main flux amplitude should be provided and simultaneously CT should work within the saturation section of magnetizing characteristics due to the high amplitude of magnetizing flux. The exciting branch equivalent circuit changes from the inductance with an iron core to the inductance without an iron core. In this case, the inductance is greatly different from that under unsaturated conditions and result in the primary current flowing into the exciting branch circuit. So the secondary of CT cannot transfer the current of the primary correctly.

The detailed theoretical analysis is as follows:

According to circuit theory the voltage of the circuit is

$$\frac{d\psi}{dt} = L_2 \frac{di_2}{dt} + i_2 R_2 \tag{6-1}$$

Integrating the flux ψ, then the equation becomes

$$\psi(t) = \psi(0) + L_2 i_2 + \int_0 R_2 i_2 dt$$

Now $i_2 = i_1 - i_m$, Substituting i_2 in the equation, then

$$\psi(t) = \psi(0) + (L_2 i_1 + \int_0 R_2 i_1 dt) - (L_2 i_m + \int_0 R_2 i_m dt) \tag{6-2}$$

$$\psi = \psi(i_m) \tag{6-3}$$

As seen from the equation (6-2) the main flux consists of three parts: (a) residual flux; (b) increased flux caused by the primary current input; and (c) decreased flux caused by magnetizing current. Equation (6-3) shows the nonlinear magnetizing characteristic of saturated CT. It is difficult to get the analytic solution of the secondary current but the secondary current, the responds of the primary excitation, will be achieved through the mutual iteration between equation (6-2) and (6-3) with one of the numeral integral approaches.

6.2.2 Testing of exciting response

A saturation simulation test is applied to CT. The transient processes of CT saturation under large fault current condition, under pure resistance load condition and under pure inductance load condition are shown in figure 6.2. i_1, i_2 and i_m are the primary current, the secondary current and the current of exciting branch respectively. As seen from the figure that at the point where current suddenly changes, the primary current can be transfered correctly to the secondary but with the time progressing, the integral part in equation (6-2) always increases until CT flux enter the saturation section, thus all the primary current flows into the exciting branch circuit and the secondary current reduce to zero and cannot reflect the primary current. Thus it can be concluded that the integral flux continuously increases and finally arrives at the saturation critical point and results in CT entering the saturation state. The integral of decaying D.C. component results in CT entering the saturation state. If the direction of residual flux is the same as the functional direction of D.C. component, the level of CT saturation will become more severe. The integral of the fundamental frequency current is equal to zero in a cycle. But adding the decaying DC current, the fundamental frequency current will be working partly in a cycle within one of the saturated sections of the CT magnetizing characteristic, i.e. the current is in saturated section for some time and out of the saturated section for other time in a cycle. This is the CT transient saturation. With the decrease of decaying DC component, the magnetizing current becomes less and less and finally that CT is driven completely out of the saturation and can reflect the primary steady-state fault current correctly. It is believed that when faults occur, CT will be driven into saturation in about half cycle. So it is an important feature for protection to detect whether CT is under saturation condition or not.

The load characteristics have a great impact on the characteristic of CT saturation. For pure resistance load (protection load is generally resistance load), the secondary current under CT saturation condition is suddenly reducing to zero. The reason is that when the integral flux is reaching the saturation flux $\psi_{\max}$ according to $\psi(t) = \int r_2 i_2 dt$, then $i_2 = 0$. As we know from the analysis the integral in half cycle is $2\psi_{\max}$ subject to the change from $-\psi_{\max}$ to $+\psi_{\max}$ or the inverse behavior. For inductance load, the secondary current waveform under CT saturation is the flattop waveform as shown in Fig. 6.2 (c). The reason is that when the flux has reached the maximum value $\psi_{\max}$, then i_2 will not increase subject to $\psi(t) = Li_2$.

As seen from above theoretical analysis and simulation tests the saturation level of CT cores and the amplitude of the primary decaying DC component are closely connected with the decaying time coefficient and the CT secondary burden. The more the DC component in the primary transient current, the more severely the CT saturates and the longer the primary decaying time constant; the heavier the CT secondary load, the more easily the CT will saturate. Furthermore, if the flux direction corresponding to the DC component in magnetizing inrush current is the same with that of the residual flux, the flux of core will be driven into saturation more quickly and more heavily. At the same time, the CT saturation is also affected by the residual flux left in the core, the secondary load and the characteristic of input current.

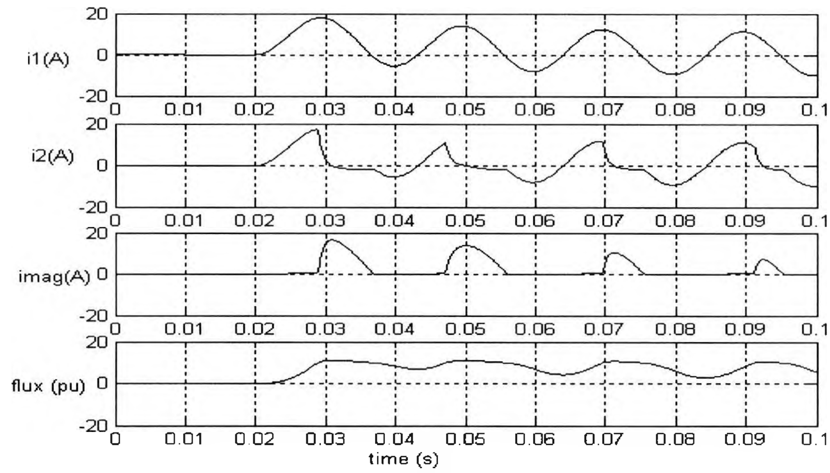


Fig. 6.2(a) CT transient saturation under fault current excitation condition

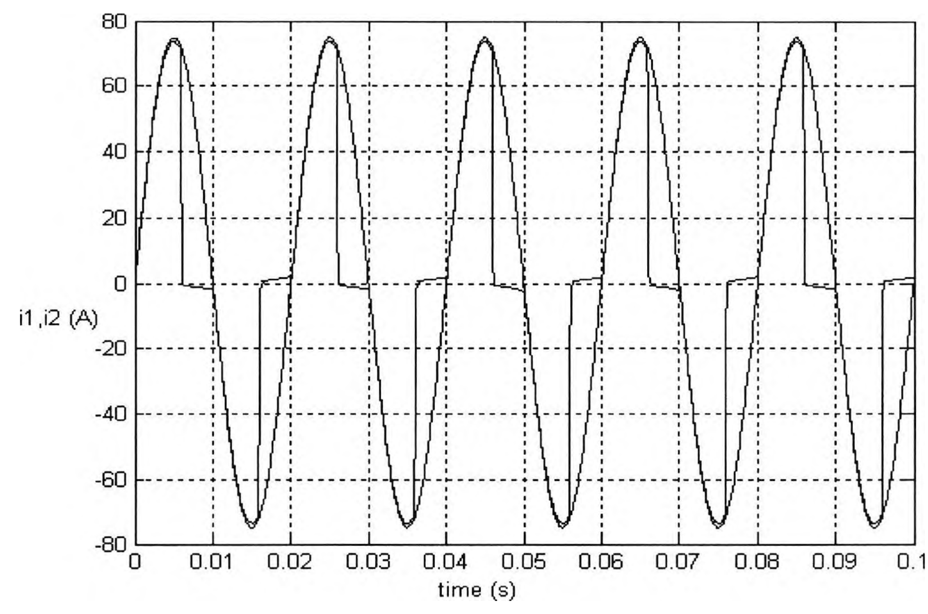


Fig. 6.2(b) CT steady-state saturation under resistance current excitation condition

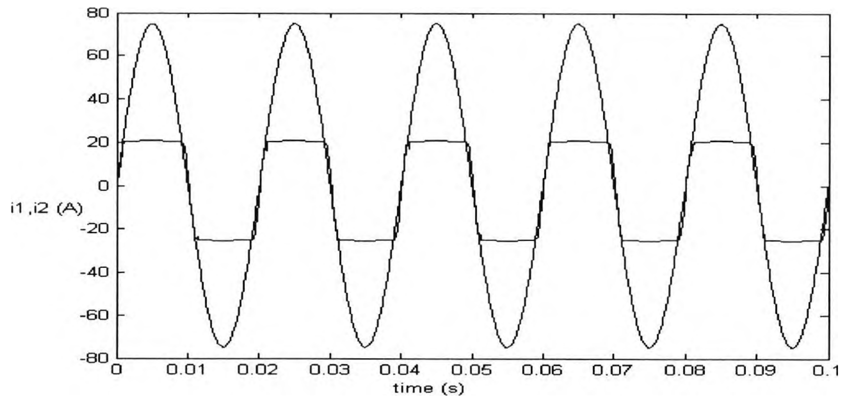


Fig. 6.1(c) CT steady-state saturation under inductance current excitation condition

6.3 Theoretical misunderstanding on ratio restraint

Ratio restraint theory has been analyzed in the above chapters and is not described here again. In fact, biased current is not equal to zero under external fault conditions. When faulted current is relatively small, differential protection is out of restraining regions and error current in biased circuit and biased current are thought to be small. With the increase of external fault current, the current through CT increases correspondingly, and if it exceeds the rated value, error current will increase rapidly (nonlinearly).

However, the ratio restraint characteristic is designed on the basis of the steady-state characteristic of CT error. Under CT saturation conditions, the distortion of the current waveform will drive differential protection into transient state for a long time and result in error far more than that described in theory. High-speed digital differential protection is so far adequate to depend on ratio restraint characteristic to avoid the unbalanced current resulting from CT saturation that it should also utilize the features of digital protection to avoid the increase of this error. The reasons are given in the following sections.

6.4 CT transient response speed

In the last few years, it is reported that differential protection leads to occasional mal-operation when clearing an external fault. In the general point of view, it seems that differential protection should not operate, but the operation of differential protection is correct from the analysis of the recording fault waveform. As can be seen from the analysis of the recorded data that after clearing a fault, transient responses of the instrument CT branches are quite different from each other. Few branch currents have obvious phase shifts, and result in the increase of biased current. Moreover, because the fault has been cleared, differential protection is out of restraint region and can be easily caused to "correctly" mal-operate. The reason that the second harmonic content is relatively low under the recovery inrush conditions should then be included.

6.5 Analysis of mal-operation under saturation conditions

CT severe saturation will probably cause differential protection to mal-operate. However, it violates the characteristic of ratio restraint that sometimes the slight saturation will result in mal-operation of differential protection. Why is it then mal-operation occur sometimes in digital protection?

General electromagnetic relays are different from digital relay. The secondary load of CT used for electromagnetic relays is heavier than that of CT used for digital protection, which should be considered when CTs are selected. In the age of digital protection, the CT secondary load decreases and CT ratio matching is partly completed by digital protection, so other extra- requirements may not be considered when CTs are selected. On the other hand, the primary CT transient tests can only be taken in the minority areas of our country and most design data come from theoretical calculation, so the characteristics of most CTs are based on computational data and have to be quite different from the practical ones.

At present, the primary ratings of CTs for generator differential protection and CTs for transformer differential protection are generally not the same, i.e. the types of CTs are not the same. So the time constant and transient behavior of these CTs cannot be matched and biased current through differential protection will increase resulting from the inconsistency of characteristics of CT transient saturation. In addition, although the secondary load of CT decreases with the continuous elevation of the primary voltage level in the power system, the time constant will increase under short-circuit fault conditions and the dc component decaying slowly will easily cause CT transient saturation. Consequently, the reasonable characteristic of CT will improve the conditions of differential protection greatly.

6.5.1 Dynamic simulation test data

To specifically investigate the practical impact on digital protection caused by CT transient saturation, a lot of external faults have been carried out on the dynamic simulation models.

The dynamic simulation model uses 300MVA generator-transformer-unit, and the transformer is connected in Yo/△-11 mode and its high-voltage side is connected to 500kV power system. CTs on high voltage and low voltage sides of transformer differential protection are connected in Y mode. Obviously, Current phase angle must be regulated in order to obtain current balance in normal or external fault circumstances.

In order to cause CT saturation more easily in the dynamic simulation test, bed performance CTs were selected and more loads for CTs are added.

Fig. 6.3 shows recordings of waveforms for phase A to phase B to ground external fault occurring in the high voltage side of the main transformer. It is obvious to see from the charts that mal-operation occurred with the conventional principle because of CT saturation. In the figure i_{aL}, i_{bL}, i_{cL} are the three-phase currents of the low-voltage side and i_{aH} , i_{bH} , i_{cH} are the three-phase currents of the high-voltage side respectively.

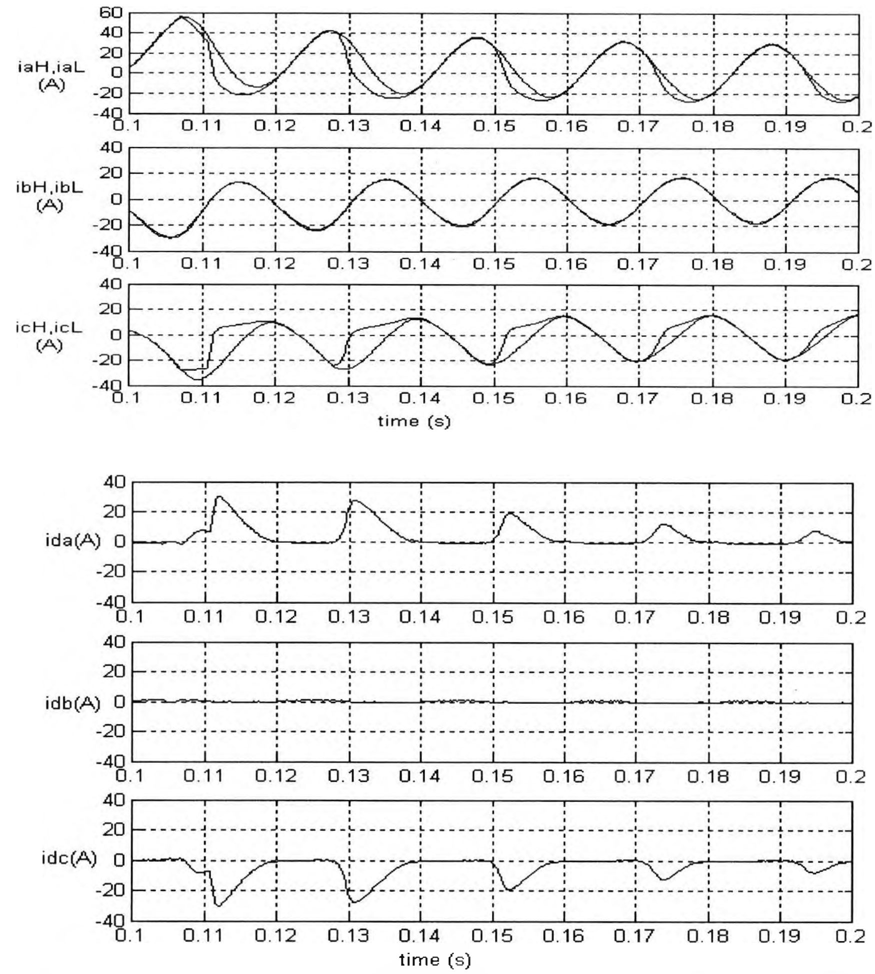


Fig. 6.3 Dynamic simulation test data of AB phase-to-phase fault on the high–voltage side

As can been seen from Fig. 6.3 phase A of CT high-voltage side has transient saturation. So large biased current flows to A-phase and C phase due to transient saturation of A-phase of CT high-voltage side and thus it reaches the operating threshold of differential protection and finally causes operation of differential protection. (Notes: Because CTs for differential protection are connected in Y mode, A phase current is provided to both A phase and C phase differential protection. As a result, saturation of the high-voltage side of CT will result in biased current of phase-to-phase differential protection.)

The recorded data is used for the methods of simulation of differential protection. They are respectively half-wave and full-wave Fourier transform method. The threshold current setting of ratio restraint differential protection is $I_q = 1A$, and the knee-point current is $I_g = 4A$, and the slope is $K_s = 0.5$. The biased current of transform differential protection I_d is as follows while the restraining current is given by the maximum one of branches.

$$I_{dA} = \left| \dot{I}_{AH} - \dot{I}_{BH} + \dot{I}_{AL} \right|$$
$$I_{dA} = \left| \dot{I}_{AH} - \dot{I}_{BH} + \dot{I}_{AL} \right| \qquad (6\text{-}4)$$
$$I_{dA} = \left| \dot{I}_{AH} - \dot{I}_{BH} + \dot{I}_{AL} \right|$$

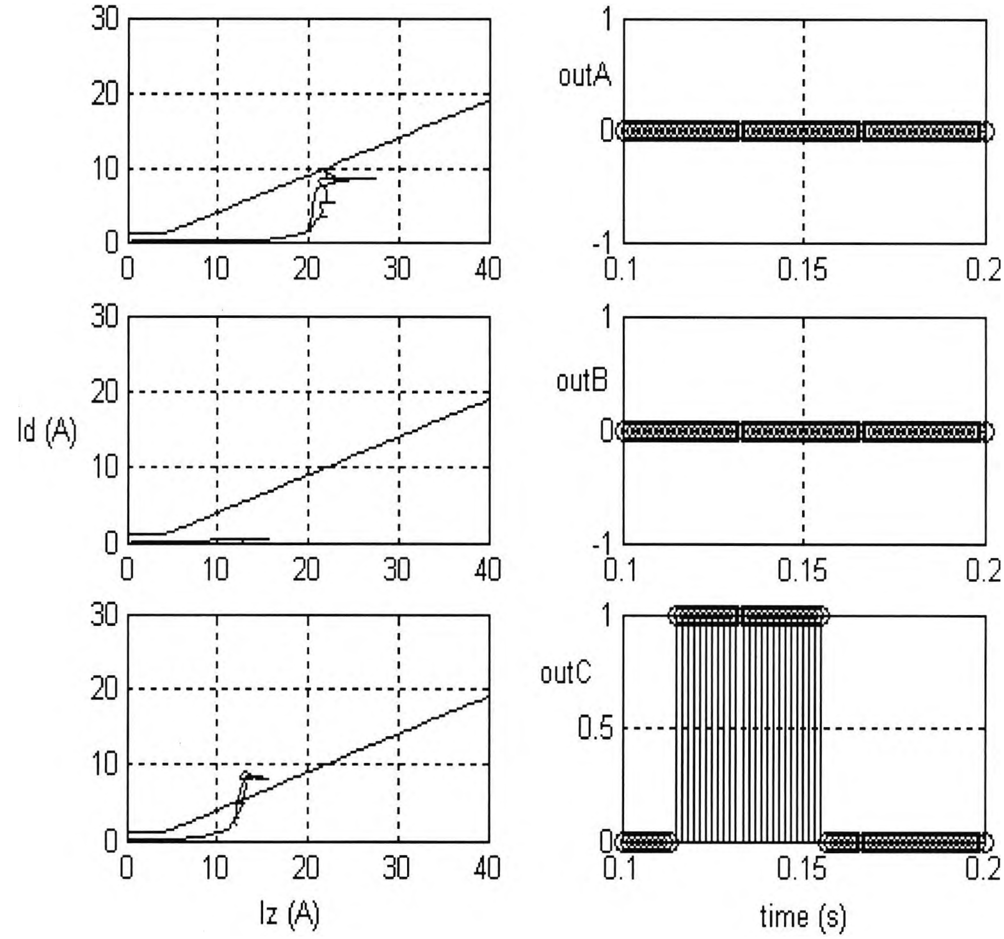
Simulations done by half-wave and full-wave Fourier transform methods in MatLab are illustrated in the following sections and the results prove that mal-operation of protection is of existence.

6.5.2 Half-wave Fourier Transform method for protection

Equation (6-5) is given by half-wave Fourier transform method. The original signal is differentiated and the dc component is eliminated from signal. And at the same time the signal amplitude is rectified.

$$i(k) = i(k) - i(k-1)$$
$$I_{Are} = \frac{4}{N}\sum_{k=0}^{N/2-1}[i(k)\cos(\frac{2\pi k}{N})] \qquad I_{Aim} = -\frac{4}{N}\sum_{k=0}^{N/2-1}[i\ (k)\sin(\frac{2\pi k}{N})] \qquad (6\text{-}5)$$

Fig. 6.4 shows the dynamic curves in the (I_z, I_d) axis of operating point under faults conditions and simultaneously illustrated is the operating edge of ratio differential protection. When an external fault occurs, operating point of differential protection of any phase should be always within the restraining region, but because of CT transient saturation resulting in increase of biased current, the operating point of AC phase-to-phase differential protection exceeds operating edge of the curve, and enters the tripping region, which satisfies the tripping condition of differential protection. If the times of entering the tripping region increase and the lasting time become longer, then mal-operation will occur.



Id (A)
Iz (A)
outA
outB
outC
time (s)

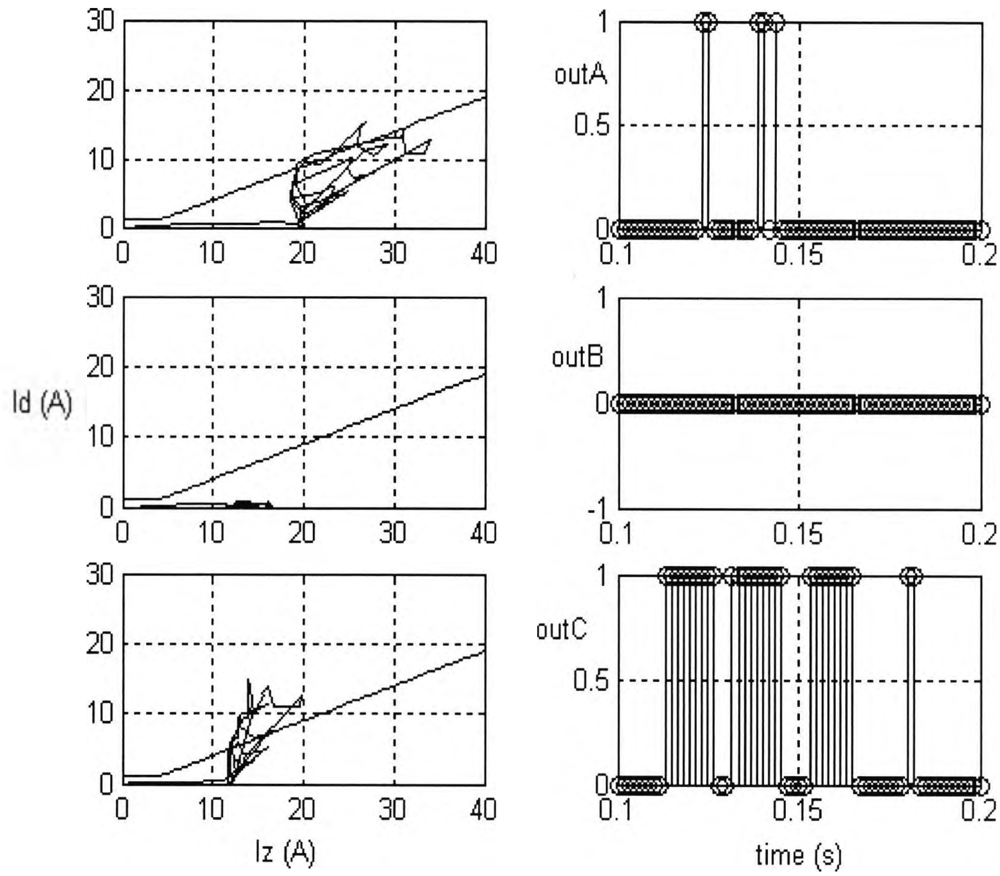


Fig. 6.4 Half-wave Fourier transform result and full-wave Fourier transform result

6.5.3 Full-wave Fourier Transform method for protection

$$I_{Are} = \frac{2}{N}\sum_{k=0}^{N-1}[i_a(k)\cos(\frac{2\pi k}{N})] \qquad I_{Aim} = -\frac{2}{N}\sum_{k=0}^{N-1}[i_a(k)\sin(\frac{2\pi k}{N})] \tag{6-6}$$

Equation (6-6) is obtained by full-wave Fourier transform method with more computational accuracy than others. From analytical results, it can be seen that the operating point behavior using full-wave Fourier transform method does not vibrate so heavily as that using half-wave Fourier transform method for the reason that the filtering performance of full-wave Fourier transform is relatively better. As illustrated in Fig. 6.4 (b) mal-operating points do not occur to A phase differential protection but occur to C phase differential protection and there are even continuous 24 tripping points in the figure. This is a very severe condition. The reason is that the window width of full-wave Fourier transform method is a cycle, in which CT always has the probability to enter the saturation state, and the calculation for a long time is not correct under the condition that differential protection using Fourier transform method is always in the dynamic process of data window. From the above, it can be seen that raising the tripping threshold will not prevent this kind of mal-operation soundly, instead will reduce the sensibility of differential protection.

6.5.4 Relationship between the reliability of differential protection and trip judgment times

A regular phenomenon is found in the dynamic simulation test that the substantial tripping duration of differential protection has a direct effect on the behavior of protection under CT transient saturation. As we know, though increasing tripping time of digital protection will improve the reliability. Obviously the more tripping time is added, the more reliable differential protection would be obtained. However, the substantial tripping duration of protection will also increase. It is verified in the test that when the tripping times reach the fixed value, protection will never mal-operate. In fact, this conclusion has been verified in theory during the above digital simulation.

From Fig. 6.4 we can find that when CT enters transient saturation, resulting in large biased current, protection is not ensured to enter tripping region under an external fault condition. But it is a characteristic that protection does not always remain in the tripping region in a cycle. For digital differential protection, one tripping point does not mean that protection will trip the breakers. To ensure the reliability of differential protection, the tripping breaker demands for continuous N tripping point in the practical applications. So the key problem for differential protection is how to determine a reasonable value N, for different values of N, sometimes mal-operation occurs while sometimes it does not. So the determination of N in the differential protection, satisfying both speed and reliability requirements should be discussed.

On the other hand, the dynamic characteristic of digital filter method has an impact on the reliability of differential protection. For example, the effect between half-wave Fourier algorithm and full-wave Fourier algorithm is not the same. The longer width of data window, although the computational accuracy is high, does not mean that the operating characteristic is better. Half-wave Fourier algorithm with differential filter only uses the data window of 7 points. From the viewpoint of the tripping point and delaying time, although A-phase differential protection causes mal-operation, definite accuracy of differential protection is ensured and the duration of tripping the breakers does not last long because the width of data window is short and correct data is included in the data window for sometime. C-phase differential protection using half-wave Fourier algorithm has the 9 continuous-tripping points. If N is set to 10, then protection will avoid the CT transient saturation, i.e. in this case differential protection will not mal-operate. The width of data window of full-wave Fourier algorithm is that of a cycle, and thus in a cycle, CT is always saturated for sometime. Consequently filter algorithm is always in the transient process itself. There are continuous 24 points to trip the breakers, if subtracting the transient points of digital filter, there are still continuous 24 tripping points. To avoid the mal-operation of differential protection caused by CT transient saturation, N must be above 20. So the optimal algorithm with both right accuracy and width of data window to improve the ability against CT saturation (Such as digital filter algorithm with variable data window) is also worth studying.

At present, considering the problem that the correct operating ratio of differential protection due to CT transient saturation is relatively low, a set of regulation against the original regulations, such as the threshold current setting is raised to $50\% I_e$, is advanced in power management department.

Of course, raising the threshold current setting helps to improve the reliability of differential protection, but it cannot solve the problems thoroughly. The reliability and sensibility of differential protection have relationship with threshold current setting, the inflectional point current value and the characteristic slope. So it is impossible to singly change any variable to improve the reliability and sensibility, which will be investigated in detail in the related chapters. It is illustrated in the preceding figure that the operating point of differential protection is originally in the restraining region under CT transient saturation conditions. If the threshold current setting is raised, correspondingly the tripping curve also shifts higher, the sensibility of protection is reduced when a slight internal fault happens instead, so it is actually worthless. However it is more effective by choosing the appropriate digital filter algorithm, the width of data window and the right trip judgment time to restrain differential protection from mal-operating. At the same time, it does not reduce the sensibility of protection. Moreover, it is also effective through applying the reliable method for detection of CT saturation to improve the reliability of differential protection.

6.6 Real-time dynamic test results

The effect of CT saturation on differential protection is simulated from a dynamic simulation real test in a 300MW generator-transformer. The connection and parameters of simulated power system refer to chapter 3. Some typical pictures recorded from tests are shown in Figs 6.5 to 6.6

It shows the ability of ANN based differential protection in recognizing fault especially when CT saturation occurrs. Delay in operation occurred because of harmonic component in saturation current of CTs.

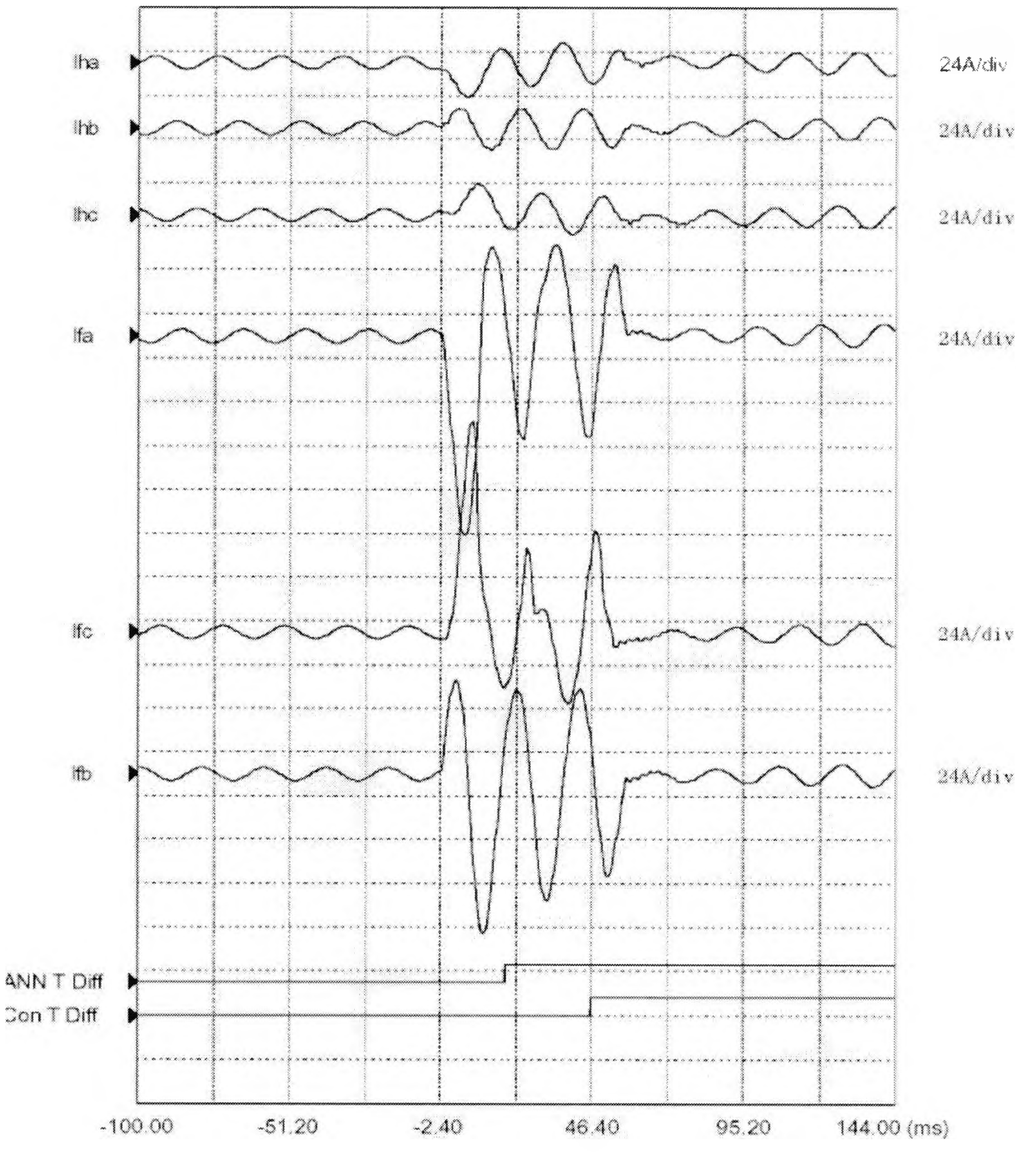


Fig. 6.5 A three-phase internal short-circuit occurred in low side of transformer (Delay tripping occurred in conventional differential principle)

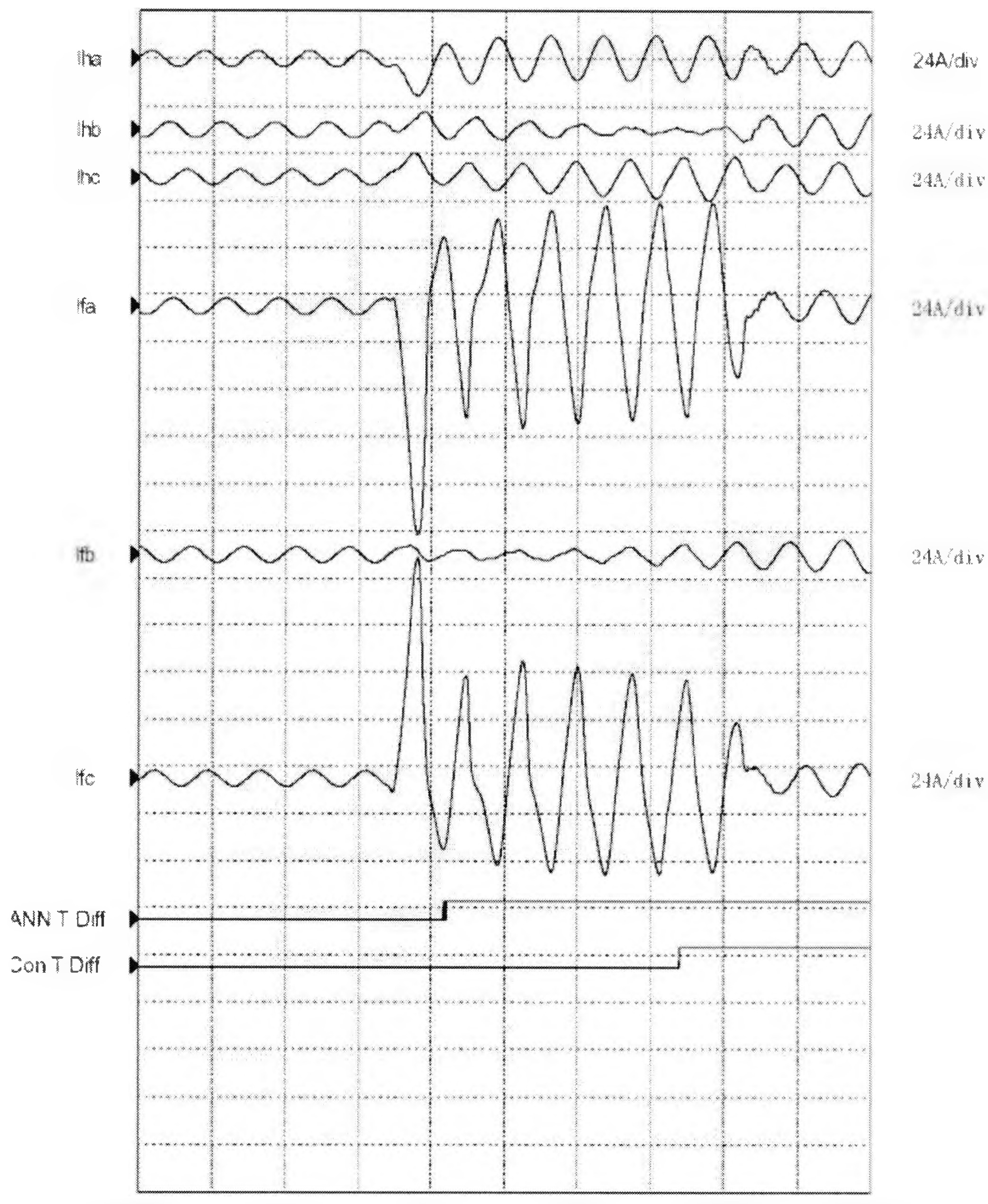


Fig 6.6 A phase A to phase C internal short-circuit occurred in low voltage side of transformer

(Delay tripping occurred in conventional differential principle too)

6.7 Conclusions

In this chapter, the relationship between CT saturation and the performance of digital differential protection based on ratio restraint has been analyzed through theory connecting practice. In the dynamic process of CT transient saturation, because differential protection is in the transient of digital filter algorithm for long, computational operating point is easy to enter the tripping region of differential protection but does not remain for long. Comprehensive considerations should be given to the problems resulting from CT transient saturation, the transient process of digital filter algorithm and the trip judgment times. Simple restraining characteristics will not avoid mal-operation of differential protection completely.

To summarize, the reliability of differential protection, has a close relationship with the accuracy of digital filter algorithm and the width of data window, In addition, it will also be affected by the threshold current setting, the inflectional point current value and the characteristic slope. Furthermore, it can greatly be affected by the performance of the primary equipments such as CT, etc. It is a conclusion that the reliability of differential protection is affected not only by the performance of protective equipment, but also by the performance of integrated control system concluding the primary and the secondary equipments. In addition, the problems of the primary equipment, especially sensors of CT and power transformer (PT), are given protection to solve, because protection should obtain the sensor data directly and correctly and then determines. If the problems of sensors are given protection to solve, protection will attach less importance to the protected equipment, which somewhat neglects the essentials to emphasize the accidentals (Protection aims to solve the problems of generators, transformers and power system). Consequently, it attends to one thing while losing another and finally reduces the performance of protection. So the characteristics and performance of CT itself is also worthy of further study for manufacturers.

Chapter 7 CT Transient Saturation Strategy for Digital Differential Protection

In this chapter, the behavior of digital differential protection under CT transient saturation condition will be further discussed and the problem of mal-protection resulting from CT saturation will be simply discussed. Correspondingly the strategy against CT saturation for differential protection will be presented according to the characteristic of CT transient saturation.

7.1 CT Saturation and digital differential protection

After using digital techniques, the function and sensibility of differential protection has been greatly improved. Generally the short-circuit faults of primary equipments can be separated by differential protection. For electromagnetic differential protection, especially differential protection based on rapid saturation theory, the tripping speed is usually slow; for digital generator-transformer-unit protection, the tripping time is about 20~30ms (excluding the hardware delay time), and the tripping speed rises for times, which is beneficial to the security of transformers. However, with the more and more rapid trip of digital protection, some problems in the practical applications have also been exposed. The detailed analysis has been described in chapter 6.

The time constant of large generator-transformer units is big and the DC components decay slowly, which may easily cause CT deep transient saturation. On one hand, the characteristic of ratio restraint cannot avoid mal-operation of differential protection due to CT transient saturation. In addition, the reliability of differential protection has a close relationship with the trip judgment times, the digital filter algorithm and the width of data window. On the other hand, raising the threshold setting will not certainly improve the reliability of protection. Therefore new algorithms should be developed to enhance the ability of protection against CT transient saturation without the decrease of sensitivity.

7.2 CT anti-saturation theory of speed control

In chapter 6, it has been clearly illustrated that the behavior of differential protection during CT transient saturation has a close relationship with the trip judgment times, the digital filter algorithm and the width of data window.

7.2.1 Performance of CT anti-saturation associated with the trip judgment times

The analysis shows that the algorithm for differential protection is always within the transient process due to CT saturation, and it will bring much error to the calculation. At the same time, it is found out that the mean of this error is within the reasonable range (i.e. the mean of this error is not large enough, reflecting the characteristic of steady-state transient). However, each of the error value fluctuates very much, and the resulting judgment swings between the tripping region and the restraining region. That is to say, the result will remain in the tripping region for long. So the reasonable trip judgment time can prevent differential protection from mal-operating due to CT saturation.

7.2.2 Performance of CT anti-saturation associated with the width of data window of filter algorithm

In fact, the final judgment of protection is affected by the primary system transient behavior, CT transient behavior and data window transient behavior of filter algorithm for digital protection. Among them, operators are unable to control the primary system transient behavior and CT transient behavior. All we can do is to choose the width of the data window of filter algorithm. It is known that the longer the width of data window the poorer the performance of CT anti-saturation. And thus the width of data window of filter algorithm ought to be shorter for the reason that the shorter width of data window generally will reduce the total transient behavior and improve the reliability of calculation.

However, it is not easy to decrease the width of data window of filter algorithm for differential protection, because in theory the algorithm for differential protection demands for a certain width of data window. For instance, the corresponding width of data window is required to filter certain harmonics. On the other hand, the decrease of width of data window will have an obvious impact on the accuracy of the filtering algorithm. As a result, the width of data window of filter algorithm should decrease properly within the permissive range in theory.

7.2.3 Difference in filtering algorithm with the same width of data window resulting in the performance difference of CT anti-saturation

In theory the frequency-domain characterization usually expresses the performance of a filtering algorithm. In fact, the frequency-domain characterization only expresses the steady-sate characteristics of data window. So the steady-state frequency-domain characterization of filter algorithm cannot correctly illustrate the transient behavior of differential protection under CT saturation at all. Both dynamic simulation test and numerical simulation show that the frequency-domain characterization of similar filtering algorithm with the same width of data window is not the same under the condition of CT transient saturation. This is because each sampling data in the data window shows much difference in the ability and function against CT transient saturation. For example, the performance of the algorithm with the same function of each sampling data generally is far away from that of the algorithm with the decaying function of each sampling data even when the width of data window between them is the same.

This has left us a difficult problem. Because there are so far no uniform and effective methods for this transient analysis, and therefore this problem is always non-linear and associated with the faulted phase, the harmonic content, the level of CT saturation, the initial phase of CT saturation and the waveform of CT saturation, the quantitative analysis applies difficultly. Even through dynamic simulation test and numerical simulation, no methods have been found. In fact, even if the worst method is applied to differential protection, mal-operation will not certainly occur under each fault or CT saturation conditions. This is fully to explain the nonlinearity of this transient. But how to solve this nonlinear problem, on one hand, needs the related nonlinear analysis, on the other hand, absolutely necessarily needs dynamic simulation test easily resulting CT saturation to investigate and verify this transient.

7.2.4 Speed control approach against CT saturation

It has been illustrated through above analysis that the performance against CT saturation is associated with the trip judgment times, the digital filter algorithm and the width of data window. The differential protection with speed control has a perfect performance against CT saturation. Difference in performance of CT saturation, caused by the difference of width of data window or filter algorithm, can be solved by full use of differential protection with speed control.

Speed control approach against CT saturation is not only simple but also economical. It can be used under the conditions of no strict requirement of tripping speed. It has been illustrated that this approach applied to transformers without system steady requirements can fundamentally meet the requirements of protected equipments.

7.3 Trap theory against CT saturation

On the occasion that differential protection demands for high tripping speed, speed control approach against CT saturation will not meet the requirements, but sound effect will be achieved by the use of trap techniques.

7.4 The characteristics of CT saturation

As we know that CT will not enter the saturation for the initial half cycle or even a cycle. So according to this characteristic, new theory for CT saturation can be formed.

7.4.1 Internal faults

If differential protection quickly trips the beakers within the range of half cycle near to a cycle, the problem of CT saturation will not occur, and thus differential protection will correctly operate with the rapid speed.

7.4.2 External faults

Differential protection would not mal-operate because CT still has not saturated at the beginning of an external fault. However, with the time lapse, CT will saturate and the probability of mal-operation of differential protection will obviously increase. So other secure measures should be taken to prevent this kind of mal-operation.

7.4.3 Protection start-up

As we know that whenever an internal or external fault happens, the judging function of differential protection should be guaranteed to start up. Although the start-up approach of differential protection may use biased current, for the purpose of the correct operation against CT saturation, it is not necessary only to use the characteristic of biased current abrupt change. In addition, to prevent the probability of no start-up on the occasion of an external fault, each side current should be used as an auxiliary criterion to start protection up.

7.4.4 Criterion of CT saturation

Only CT saturation under an external fault condition is considered.

When the current of each side are normal and the biased current is small, then

$$I_{to} \leq I_{f.\max} \quad \Delta I_{to} \leq \varepsilon \tag{7-1}$$

where,

I_{to} -- the current at time t_o;

$I_{f.\max}$ -- the maximum current;

ΔI_{to} -- the biased current at time t_o;

ε -- the given error.

The current at the time of t_1 (near to a cycle), specially at least one single-phase current of both sides of CT, are large (more than two times of the rating). At the same time, the biased current is small and hence differential protection does nothing.

$$I_{t1} \geq 2I_{f.\max} \tag{7-2}$$

where I_{t1} -- the current of t_1 time.

At the time of t_2, differential protection operates and the current of some sides of CT abruptly changes.

$$\Delta I_{t2-t1} \geq \Delta I_{dz} \tag{7-3}$$

where ΔI_{t2-t1} -- the abrupt current between the time t_1 and t_2.

7.4.5 Trap setting

When a fault occurs, differential protection is allowed to trip the breakers in the first cycle, and then it drops into a trap. Once differential protection drops into a trap, it is regarded that the preceding fault is an external one. Only when reliably identifying that a fault has changed from outside to inside of the protected equipments (be very reliable and exclude other factors such as CT saturation, etc.), differential protection is able to open again. Of course, differential protection should escape from the "trap" by itself and it should be prevented from dropping into the "trap" for long through the fixed-time exit.

7.4.6 Explanations

Any approach has advantages and disadvantages. The setting of "trap" can accelerate the tripping speed of differential protection. However, if the internal faults are improperly distinguished causing protection to the "trap", the tripping time will be delayed and even the delay time may last for long. So the "trap" theme should be carefully applied.

7.5 Decelerating approach against CT saturation

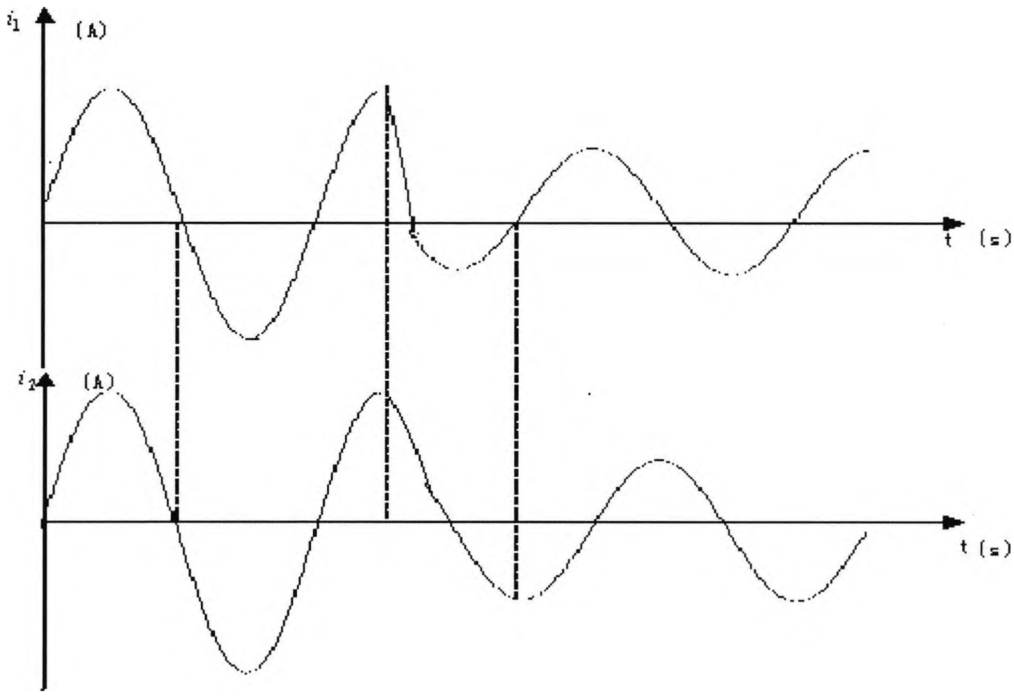
The decelerating approach against CT saturation can be regarded as the integration of speed control approach and the trap theory against CT saturation. This approach makes full use of the reliable and secure characteristic of speed control approach against CT saturation, combing the identifying the trap of CT saturation according to the characteristic that, CT does not easily saturate at the beginning of a fault and protection will immediately switch to function with speed control approach once the CT saturation is confirmed. Therefore this can ensure not only that protection will rapidly operate when an internal fault occurs, but also that protection will not mal-operate when an external fault, causing CT saturation, occurs.

7.6 CT non-saturation transient strategy

7.6.1 CT non-saturation transient

As a matter of fact, the transient process will form if one state is abruptly changed to another state. From the requirements of sensors, the transient process should be timely traced and then the primary transient process will be objectively obtained. However, it is unfortunate that sensors have the response time viz. transient process. For CT, the characteristic that the CT secondary current follows the primary current is one of CT transient non-saturation problems. In figure 7.1, CT actually does not saturate at that time, but because of the difference in the manufacture and CT load, the CT response of the primary transient characteristic is obviously different from the real transient and even a big phase shift occurs for a short time. Fig. 7.1 shows the typical CT non-saturation transient characteristic.

A phase shift occurs in Fig. 7.1 after clearing an external fault and mal-operation will happens to differential protection.



i_1 -- The primary current, i_2 -- The secondary current

Fig. 7.1 CT non-saturation transient

7.6.2 Effect on differential protection of CT non-saturation transient

It is found in practice that CT saturation is a severe transient process, but it is more difficult to deal with the CT non-saturation that causes differential protection to mal-operate more easily. The statistic data have shown that much mal-operation of differential protection was caused due to the CT bed following characteristics. And this non-saturation transient will occur not only when an external fault occurs, but also when sometimes an external fault is cleared. Because after clearing a fault, although power system has recovered, the transient from faulted to normal condition is experienced form the viewpoint of abrupt change, which can result in CT non-saturation transient. If the duration of this transient lasts long, without restraining function for differential protection, mal-operation of differential protection will be easily caused. Of course, recovery inrush as described in the preceding chapter is another cause.

7.6.3 Prevention of CT non-saturation transient

CT non-saturation transient will occur as soon as a fault occurs. So for the protection it is difficult to distinguish CT non-saturation from the generator or transformer internal faults. Because of CT non-saturation transient accompanying with the phase shift, this characteristic confuses us with that of internal faults and thus the effective methods are to adopt adaptive data window or to delay tripping speed.

7.6.3.1 Adaptive data window

Early in 1994, when the author developed the microcomputer generator-transformer-unit protective equipments, the adaptive data window of filter algorithm is advanced for differential protection. The adaptive data window means that differential protection can adaptively increase the restraining curve when a fault justly happens and lacks faulted sampling data, and with the further development of the fault and the further increase of the obtained data, information and calculation accuracy, the method will automatically decrease the restraining characteristic curve to match the accuracy of calculation perfectly. This kind of adaptive restraining characteristic curve finally meets the specified characteristic of custom setting accurately. Therefore, the adoption of this method can greatly improve the tripping speed of a severe internal fault, at the same time, it does not decrease the sensibility for a slight internal fault at all.

7.6.3.2 Delay tripping speed

The reliability of differential protection is achieved at the cost of the loss of tripping speed under the CT non-saturation transient conditions.

7.7 The effect on the trap approach against CT saturation

Described as above, the trap approach against CT saturation is based on that CT does not saturate at the beginning of a fault, i.e. this approach is performed on the premise that CT can correctly reflect the initial primary faulted waveform. However, if CT non-saturation transient occurs at that time, mal-operation of differential protection will be easily caused. The reason for this mal-operation is that before differential protection drops into the "trap", it has already mal-operated.

7.8 Conclusions

In this chapter, according to the characteristic of CT saturation speed control approach, the trap approach and the decelerating approach against CT saturation are presented on the basis of much detailed analysis. Because all kinds of methods and approaches have their own characteristic, different theory against CT saturation should be reasonably determined by the different occasions and requirements. These measures and approaches have already been applied successfully.

The concept of CT non-saturation transient and corresponding solution strategy is presented in this chapter.

Chapter 8 Sensitivity Analysis of Digital Differential Protection

This chapter analyses relative setting principle of differential protection, and explicitly points out that differential protection sensitivity is actually related to many factors, such as setting, principle, implementation, etc. The sensitivity shouldn't be increased by the way of changing a certain factor (for example, a setting). The influence of every factor should be considered synthetically; otherwise the effect will be opposite. This chapter discusses the sensitivity coefficient verification, the difference between restraint coefficient and slope, connection and difference of scalar product restraint and ratio restraint, and then gives the viewpoint of author.

8.1 The complication of the question

In company with the progressive development of the relay protection and the advancement of technology, technologists have a more and more profound cognition about the protection. They begin to reflect on some protection issues already established. At the differential protection sensitivity verification, the directive rules prescript differential protection of the ratio restraint principle does not need to have sensitivity verification, because its sensitivity meets the requirement in nature. Well then what is the sensitivity "in nature meets the requirement"? As it is, to the generator differential protection, it is the sensitivity of the generator terminal two phases short circuit fault. Apparently, the sensitivity can surely meet the requirement. At the field operating, the ratio restraint coefficient and the ratio restraint slope are often mistakenly thought to be equal. What are the difference and connection between them? What is the advantage of the scalar product restraint principle in increasing the differential protection sensitivity? What is its relation to the ratio restraint principle? Are they inter-deducible? This chapter will analyses and discuss these important practical and theoretical issues.

8.2 The definition and verification of the differential protection sensitivity coefficient

Suppose the relay differential current is $I_d = |\dot{I}_N + \dot{I}_T|$, the restraint current is $I_z = |\dot{I}_N - \dot{I}_T|/2$, and the influent current direction is positive, by definition, the sensitivity coefficient of the differential protection is

$$K_{lm} = \frac{I_d}{I_z} \tag{8-1}$$

For a long time, generator differential protection sensitivity is the specific value of the differential current and the operating current under outlet two-phase metallic short circuit condition. In such cases, the fault point of two-phase metallic short circuit on the (I_z, I_d) plane is above the internal fault characteristic line which slope is two, so the operating boundary set according to the directive rules will certainly fulfill the requirement $K_{lm} \geq 2$ of the sensitivity coefficient. Actually, the verifying sensitivity should be the ratio of differential current and operating current under the condition of generator neutral point slight phase-to-phase fault. Therefore whether verifying differential protection sensitivity with outlet two-phase short circuit is reasonable needs further discussions. To research the protection competence under slight fault, the essential problem need to be solved is the precise theoretical analysis of generator internal short circuit fault. The sensitivity is related to many factors, such as settings, principle; implementation approach and so on. In the physical conception, the farther the fault point is apart from the operating boundary of protection, the higher sensitivity the principle will have.

8.3 Differential protection principles with restraint characteristic

8.3.1 Principles

The restraint characteristics fall into two kinds of principle, passing the origin and not passing the origin. The general characteristic of the principles passing the origin is

$$\begin{cases} I_d \geq K_z I_z \\ I_d \geq I_q \end{cases} \tag{8-2}$$

The general characteristic of the principles not passing the origin is

$$\begin{cases} I_d \geq K_Z (I_z - I_g) + I_q \\ I_d \geq I_q \end{cases} \tag{8-3}$$

Choosing different operating current and restraint current, several different principles can be built up, the ratio restraint principle and scalar product restraint principle.

Principles commonly used for the moment are summarized in the Table 8.1.

Table 8.1 Differential protection principle equations

	I_d	I_z
Ratio restraint	$\lvert \dot{I}_N + \dot{I}_T \rvert$	$\lvert \dot{I}_N - \dot{I}_T \rvert / 2$
	$\lvert \dot{I}_1 + \dot{I}_2 + \dot{I}_3 + \ldots \rvert$	$\lvert Max\{\dot{I}_1, \dot{I}_2, \dot{I}_3 \ldots\} \rvert$
	$\lvert \dot{I}_1 + \dot{I}_2 + \dot{I}_3 + \ldots \rvert$	$\lvert \dot{I}_1 \rvert + \lvert \dot{I}_2 \rvert + \lvert \dot{I}_3 \rvert \ldots$

Scalar product restraint	$\left\|\dot{I}_N+\dot{I}_T\right\|^2$	$I_N I_T Cos(180°-\theta)$
	$\left\|\dot{I}_N+\dot{I}_T\right\|$	$\sqrt{I_N I_T Cos(180°-\theta))} \longleftarrow Cos(180°-\theta)>0$ $\sqrt{0} \longleftarrow Cos(180°-\theta)\leq 0$
	$\left\|\dot{I}_1+\dot{I}_2+\cdots\right\|$	$\sqrt{Max\ (I_1,I_2\cdots)(\left\|\dot{I}_1+\dot{I}_2\cdots-Max\ (I_1,I_2\cdots)\right\|\ )Cos\ (180-\theta\ ))}$ $\longleftarrow Cos\ (180-\theta\ )>0$ $\sqrt{0}\longleftarrow Cos\ (180-\theta\ )\leq 0$

Similarly, according to different choices of differential current and restraint current, different expressions can be obtained. Different principles have different characteristics. Protection principle choice should be based on the requirement of the main equipment protected. Even if the principles are same, different setting can cause different performance. Author's viewpoint about several problems is expounded in the following section.

8.3.2 The ratio restraint principle protection with smaller slope is not always more sensitive than larger slope

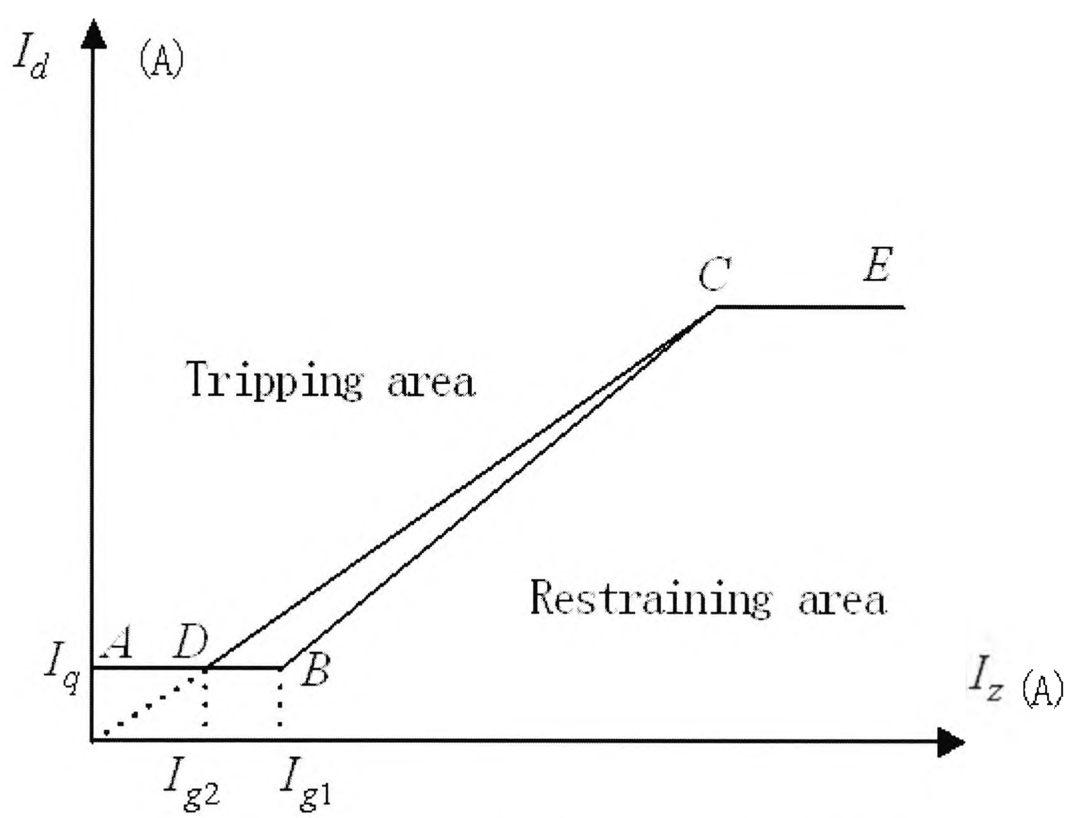


Fig. 8.1 The restraint curves passing the origin and not passing the origin

The ratio restraint characteristic of passing the origin and not passing the origin is shown in Fig. 8.1 above. The operating boundary passing the origin supposes that CT errors are equal whether the current is larger or smaller than the secondary rated current. The unbalanced current linearly varies with the restraint current, so the restraint curve is a straight line through the origin. The restraint curve not passing through the origin considers that CT error is very small under rated current and unbalanced current is also very small and it is assumed to be a very small constant. Whereas while the current is larger than the secondary rated current, the error grows very large, so the unbalanced current non-linearly varies. Such consideration is more practical. Their differences can be seen from the operating region figure. The operating region of the passing the origin restraint characteristic is above ADCE, while those of the not passing the origin is above ABCE. It is obvious in geometry that although the slope of the passing the origin restraint curve is smaller than that not passing the origin, it is more sensitive. Therefore the sensitivity of the differential protection is related to not only the slope, but also the chosen value of the starting current and the inflexion current.

8.3.3 The converting relation of the restraint coefficient and the slope

The restraint coefficient and the slope of the curve are two different physical conceptions. The restraint coefficient K_z of the tradition protections is defined as

$$K_z = \frac{Tripping\ Current}{\mathrm{Re}\,straining\ Current}$$

Where, the largest restraint coefficient equals the largest operating current divided by the corresponding restraint current. K_s is the slope of the restraint curve. Because the restraint curve usually does not pass through the origin, the restraint coefficient and the slope of the restraint curve generally are not equal. They should not be confused together.

The Figure 8.2 gives the geometrical explanation. The slope of the straight line OM is the maximum ratio restraint coefficient, and PM is the slope of the curve. Drawing OC passing the origin parallel to PM and a parallel of OM passing T, based on the geometrical relationship of the figure, it can be proved that their theoretical conversion relation is

$$K_z = K_s - \frac{K_s I_g - I_q}{I_z} \quad K_s = K_z(1 + \frac{I_g - I_q / K_z}{I_z - I_g}) \qquad (8\text{-}4)$$

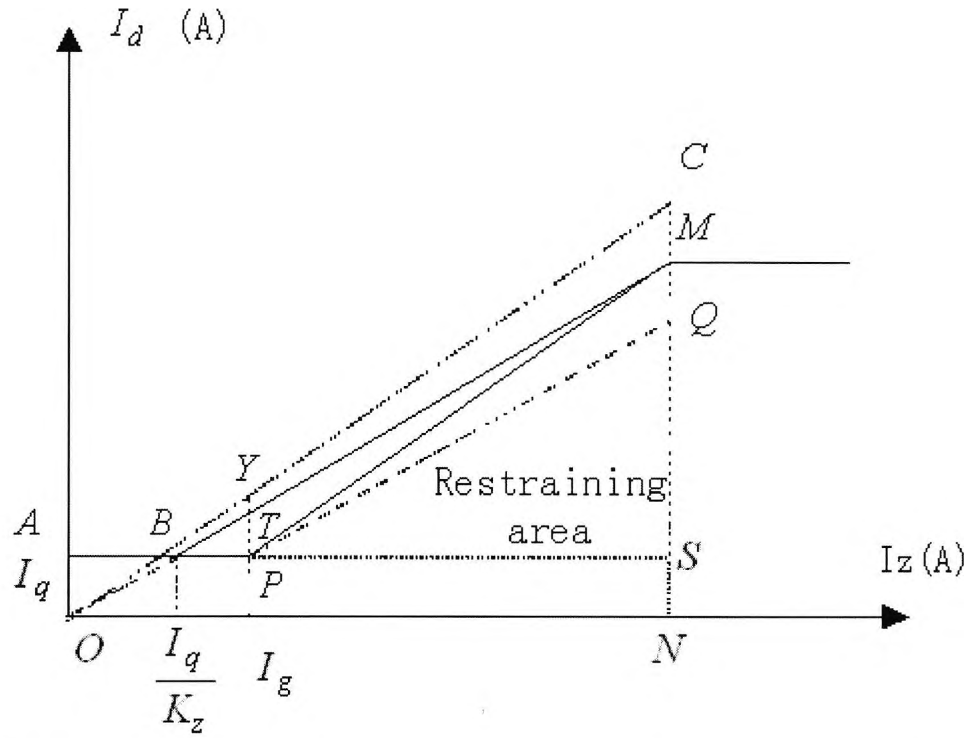


Fig. 8.2 The corresponding relation of the restraint coefficient and the slope

K_z has its maximum while the restraint current is the maximal exterior short-circuit current, K_z reaches its maximal. Substitution $I_z = I_{max}$ in the equation, the maximum $K_{z\max}$ is worked out.

It is observed from the equation above that the ratio restraint coefficient is actually a variable. It changes with the amplitude of the restraint current. The restraint coefficient given by manufacturers usually is the slope of the restraint segment on the restraint characteristic curve, and it is not the restraint coefficient of the setting calculation. The restraint coefficient of practical restraint characteristic curves changes with the variation of the restraint current.

Where,

I_g -- the inflexion current (A);

I_q -- the starting current (A);

I_z -- the restraint current（A）

I_{max} -- reliably endure the maximal external short circuit unbalanced current.

The relationship between the maximal ratio restraint coefficient and the ratio restraint slope is explained by the following example

Assuming that I_q=0.8A; I_g=5A; I_{max}=30A.

Table 8.2 The relation of the maximal restraint coefficient and the slope

$K_{z\max}$	0.2	0.3	0.4	0.5	0.6	0.7
K_s	0.208	0.328	0.448	0.568	0.688	0.808

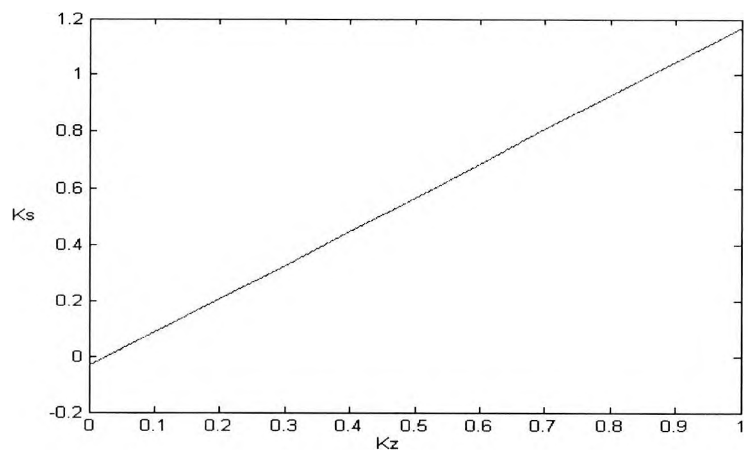


Fig. 8.3 The relation of the maximal restraint coefficient and the slope

It is observed from figure 8.3 that the relationship of $K_{z\max}$ and K_s is a line not passing the origin and Ks generally is greater than $K_{z\max}$ in practice.

8.4 The corresponding relation between the scalar product restraint principle and the ratio restraint principle

8.4.1 The scalar product restraint principle and the ratio restraint principle

To increase the sensitivity of differential protections, the scalar product restraint differential principle is put forward. The best merit of the scheme is greatly increasing the sensitivity of differential protections without any trade off in reliability. The scalar product restraint principle applied for the moment generally transforms operating current and restraint current to the scale same as the ratio restraint principle to reckon. So the square root scalar product restraint principle is used the most in engineering, i.e. the principle 2 in the Table 8.1 or formula 3. Based on this principle, the relation of the scalar product restraint principle and the ratio restraint principle will be discussed in the following paragraphs.

The difference of the ratio restraint and the scalar product restraint principle is the selection of the restraint current and the operating current. They are inter-deducible mathematically. The derivation of the converting relation is given below:

$$\begin{cases} I_d = |\dot{I}_N + \dot{I}_T| \\ I_z = |\dot{I}_N - \dot{I}_T|/2 \\ I_{db} = |\dot{I}_N + \dot{I}_T| \\ I_{zb} = \begin{cases} \sqrt{|\dot{I}_N| \bullet |\dot{I}_T| \cos(180-\theta)} \\ = \sqrt{-|\dot{I}_N| \bullet |\dot{I}_T| \cos\theta} \leftarrow \cos\theta < 0 \\ 0 \leftarrow \cos\theta \geq 0 \end{cases} \end{cases} \tag{8-5}$$

By the trigonometry cosine theorem

$$-I_N I_T \cos\theta = -(|\dot{I}_N + \dot{I}_T|^2 - |\dot{I}_N - \dot{I}_T|^2)/4 = -(I^2{}_d - 4I^2{}_z)/4 \tag{8-6}$$

viz.

$$I_{db} = I_d$$
$$I_{zb} = \begin{cases} \sqrt{(4I_z^2 - I_d^2)/4} & when \quad 2I_z > I_d \\ 0 \quad when & 2I_z \leq I_d \end{cases} \tag{8-7}$$

So the scalar product restraint quantity and operating quantity can be obtained from the ratio restraint quantity and operating quantity, as shown in figure 8.4.

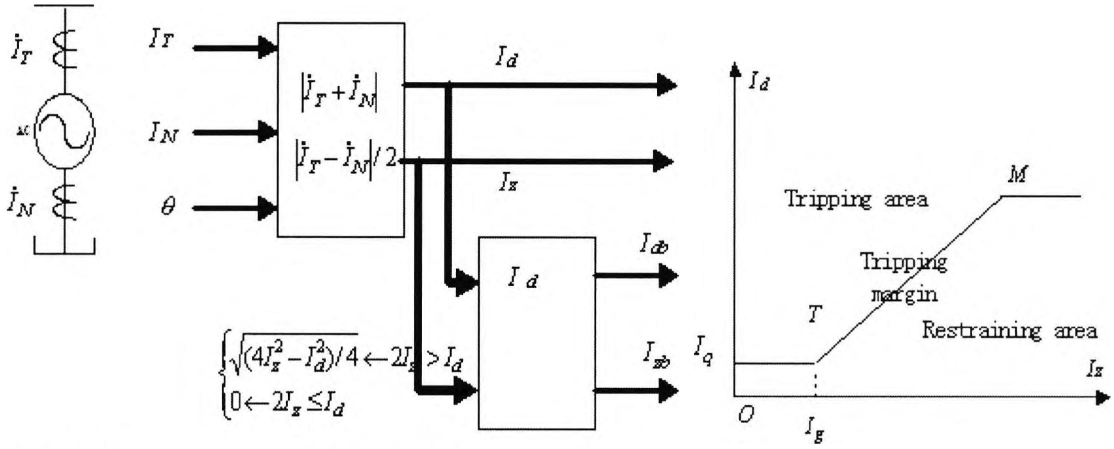


Fig. 8.4 Corresponding scheme diagram

The following sections will discuss the converting relation of the scalar product restraint principle and the ratio restraint principle. To simplify the discussion, first of all let's probe the linear relationship of the ratio restraint principle $I_d = KI_z$ and scalar product restraint principle.

$$\frac{I_{db}}{I_{zb}} = \frac{I_d}{\sqrt{4I_z^2 - I_d^2}/2} = \frac{2KI_z}{\sqrt{(4-K^2)}I_z} = \frac{2K}{\sqrt{(4-K^2)}} \leftarrow 2I_z > I_d \tag{8-8}$$

This shows that for a straight line of slope K in the ratio restraint principle, its corresponding slope in the scalar product restraint principle is $\frac{2K}{\sqrt{(4-K^2)}} \leftarrow 2I_z > I_d$. The points in the region K>2 are correspondingly mapped to straight line Id of the scalar product restraint principle. Discussions are carried out with the following conditions.

During internal faults conditions, the phase angle between outlet current and neutral point current is in [-90, 90] interval in general. In the optimistic case, the angle is 0. For example $I_N = I_T$, to the ratio restraint principle, $I_z = 0$, it is I_d axis, the slop is positive infinite, and the differential protection will reliably operate. If the generator does not connect to the system by that time, i.e. I_T=0, in the ratio restraint plane, it is a fault straight line of slope 2. The protection will also reliably operate. By this time, the operating quantity and restraint quantity of the scalar product restraint principle in the operating plane is I_d axis. In consideration of the extreme case of internal faults in which the phase angle difference is 90 degree, to the ratio restraint principle, it is a straight line OM of K=2 as shown in figure 8.5. According to the scalar product restraint principle, the operating quantity is same and the restraint quantity changes to 0, it horizontally maps to the I_d axis. Thus it can be seen that comparing with the ratio restraint principle the characteristic curve of the scalar product restraint principle rotates counterclockwise, i.e. leaves further from the operating boundary. So the protection is more sensitive for internal fault.

At optimistic case of external faults, they all map to the I_z positive direction. So the reliability of external faults is unaffected.

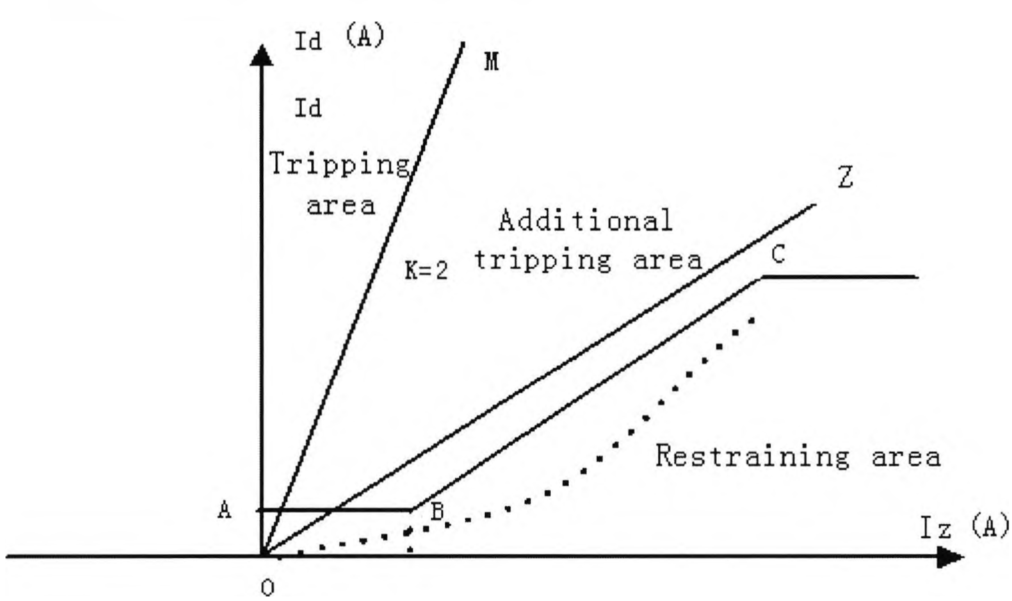


Fig. 8.5 The corresponding relation between the scalar product restraint principle and

the ratio restraint principle

In general situations, the generator protection operating point of the ratio restraint principle falls on operating area at internal faults and restraint area at external fault, i.e. under the CT error curve. But the condition in which there is through current at generator internal faults also exists and the operating point falls on the transitional area. Here the scalar product restraint principle can move the operating point counterclockwise farther away from the operating boundary than the ratio restraint principle, so it has higher sensitivity. For external faults, due to CT ratio error, attenuating DC component at saturated transient course, etc, the operating point may move toward transitional area and it causes mal-operation. But if the setting value is appropriate, the impact can be eliminated.

8.5 The restraint characteristic principle

Implementing differential protection with a straight-line restraint characteristic is comparatively easy in setting. Secondary error is nonlinear in nature and will increase with the external short-circuit current, so the restraint curve actually should be non-linear. This implementation is difficult, so multi-line restraint curve is used in practice to implement the protection principle. In this way, the reliability and sensitivity of differential protection increases.

8.6 Correct starting current of Y/△ transformer differential protection of full star CT connection

When setting with real unit, calculating side of software should be selected as setting reference. If the converting side is Y side CT of the main transformer, the setting value should be multiplied by $\sqrt{3}$.

The reason is that software has to adjust the Y/△ phase and amplitude difference (some protection would take into account $\sqrt{3}$ in setting. This will cause confusion. The straightforward method is verifying setting by experiment).

Experimental verification method: 1) Supply single-phase current on star side CT of Y/△ transformer and the operating value should be $\sqrt{3}$ setting value. 2) Supply symmetric current in ABC phases. The protection should operate at setting value.

8.7 Reasonable starting current of the generator split-phase transversal differential protection

Generator split-phase transverse differential protection setting is comparatively complicated. It is related to CT transformation ratio, and branch grouping mode. When the branch number of two arms is different, it is more complicated. While the differential arms CT ratio discord, the error will increase. The starting current of split-phase transverse differential protection should be larger than complete differential protection starting current.

The setting of split-phase transverse differential protections can refer to the setting guideline of generator differential protections, but the impact of CT transformation ratio should be fully considered. The setting principle is that the protection does not mal-operate during external severe faults conditions with allowable CT error.

8.8 The difference of the generator differential, transformer differential and bus differential sensitivity

The sensitivity of differential protection of different restraint quantity is greatly discrepant. They are all called differential protection, but the sensitivity of principles with restraint quantity $|\dot{I}_N - \dot{I}_T|/2$ is higher than those of restraint quantity $|Max\{\dot{I}_1, \dot{I}_2, \dot{I}_3 ...\}|$, and much higher than those of restraint quantity $|\dot{I}_1| + |\dot{I}_2| + |\dot{I}_3| ...$.

8.9 Incomplete differential protection

Incomplete differential protection is put forward by the literature in bibliography and its content will not be repeated. Some viewpoints of different angle about this principle will be put forward. It is a new protection connection mode. The protection principle used is still ratio restraint differential principle and scalar product restraint differential protection principle.

8.9.1 Features

a) Interturn short circuit problems

The complete differential protection cannot react to interturn short circuit in principle. It is a fly in the ointment of conventional differential protections. For incomplete differential, the generator neutral point short circuit is branch short circuit so as to the two differential arm current loses balance at interturn short circuit and the differential protection will operate. Thereby incomplete differential protections can react to interturn faults.

b) Simplify interturn short-circuit protection

If incomplete differential protection can guarantee enough sensitivity at interturn short circuit, conventional short-turn fault protection can be simplified or cancelled and the generator operation will be safer.

8.9.2 Discussion

a) CT installation site selection

Because the generator neutral point does not supply full current to protections, what kind of current should be selected, i.e. how to group branches current, becomes the largest obstacle in incomplete differential applications. Apparently, different grouping mode causes different current at fault. Meanwhile, due to distribution of generator stator winding, different CT installation modes are not same in differential protection sensitivity, sometimes the sensitivity differs a lot. Therefore, correct and reasonable CT installation site is very important.

At present, many domestic colleges have taken a lot of analyses to generator internal short circuit faults, and developed corresponding computational software packages. In this way, theoretical reference of CT installation site is founded.

However, the theoretical analysis is complicated and fussy. Colleges are also researching simple CT deployment principle. A simplified mode is listed below.

$$a/2 \leq N \leq a/2+1 \qquad (8\text{-}9)$$

Where, N is the branch number of every phase connected at neutral point side.

a is the total branch number of every phase of the generator shunted.

The mode of expression (8 –9) simply takes half of the branches as it is. If the branch number is odd, then it takes a half plus 1. Apparently such mode is a CT deployment mode inclined to safety. To a specific generating set, such mode is not certainly optimal and its sensitivity is not certainly best. It is a compromise between complete differential protection and incomplete differential protection. But it indicates a direction for the application of incomplete differential protections.

b) Relationship with the generator manufacturers

Generator manufactories must consider CT deployment at generator manufacture. If they have not, the incomplete differential protection cannot be implemented. At present, this factor is still one of the main ingredients limited applications of the incomplete differential protection.

c) The sensitivity problem

After differential protection is reconstructed to incomplete differential, can its sensitivity reach the level of differential protection? How much is the sensitivity of the incomplete differential protection could be?

The answer to the above questions must depend on theoretical calculation. This makes the problem very complicated because the generator internal short-circuit fault analyses software has several versions initially and their foundation is very theoretical. It is difficult for relay protection staff to understand and master it in a short time. It may need a long time.

In addition, the analytical software itself is progressively developing and consummating.

8.5 Real-time dynamic test results

In addition to those figures shown before, here are more representative testing results displayed in recording curves from a dynamic simulation real testing in a 300MW generator-transformer. The connection and parameters of the simulated power system have been presented in chapter 3.

In Fig. 8.7, it is a record picture when transformer internal phase A to phase B short-circuit occurred in the low-voltage side. It can be seen, in showed case, that ANN based differential protection is not affected by CT saturation while time delay occurred in conventional relay.

In Fig. 8.8, it is an external fault. Mal-operation triggered in conventional differential principle because of weak ability to deal with CT saturation.

In Fig. 8.9 and 8.10, these two cases are developing-faults from external changed to internal. We have seen ANN based differential protection tripped faster than conventional one. It demonstrated excellent performance in these complicated situations

In Fig. 8.11, it is a single-phase fault occurred in power system and successfully reclosed after fault cleared. It also showed stable of ANN based differential principles

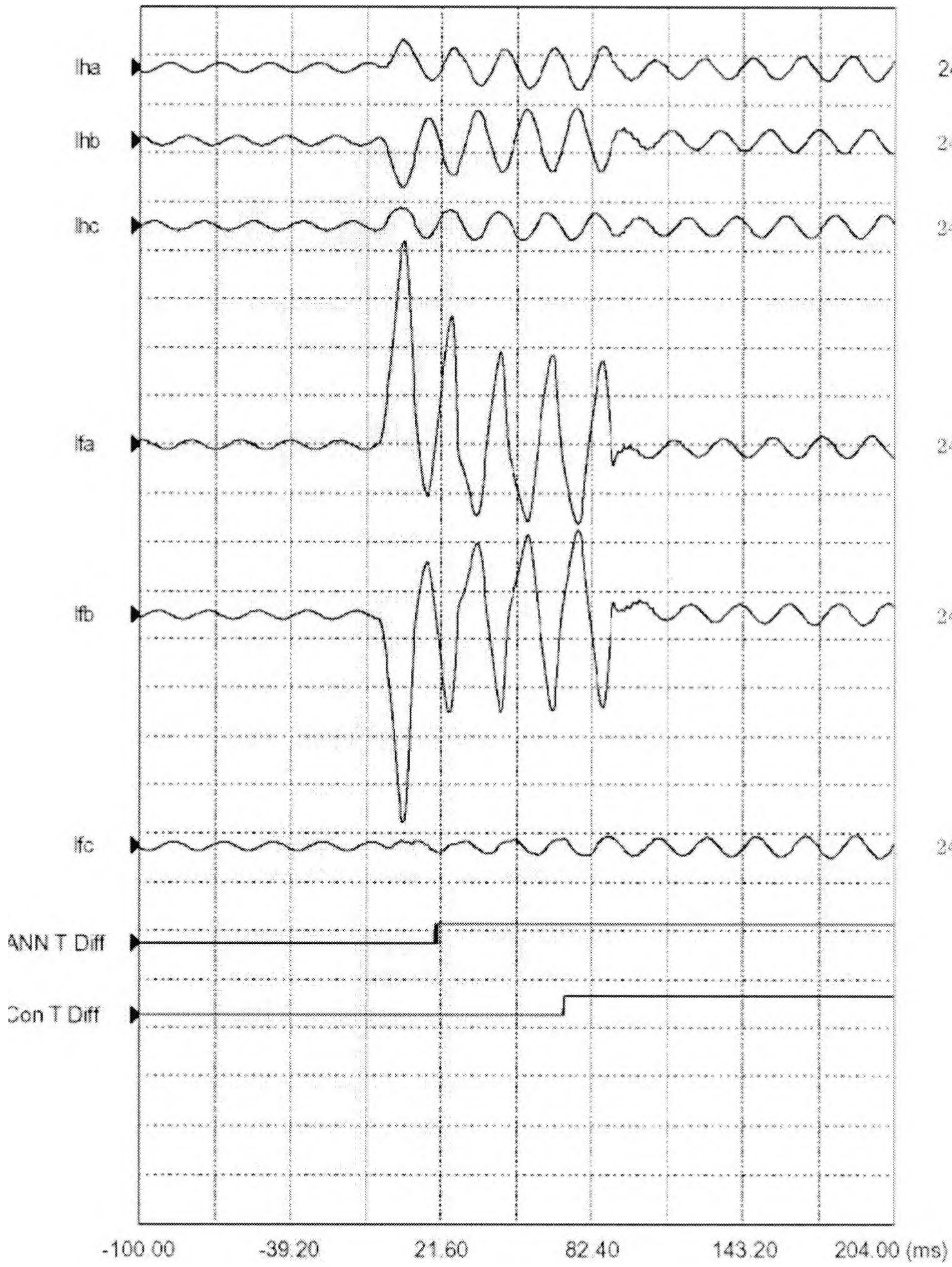


Fig 8.7 Transformer internal phase A to phase B short-circuit in low-voltage side
(Delay tripped by conventional differential principle)

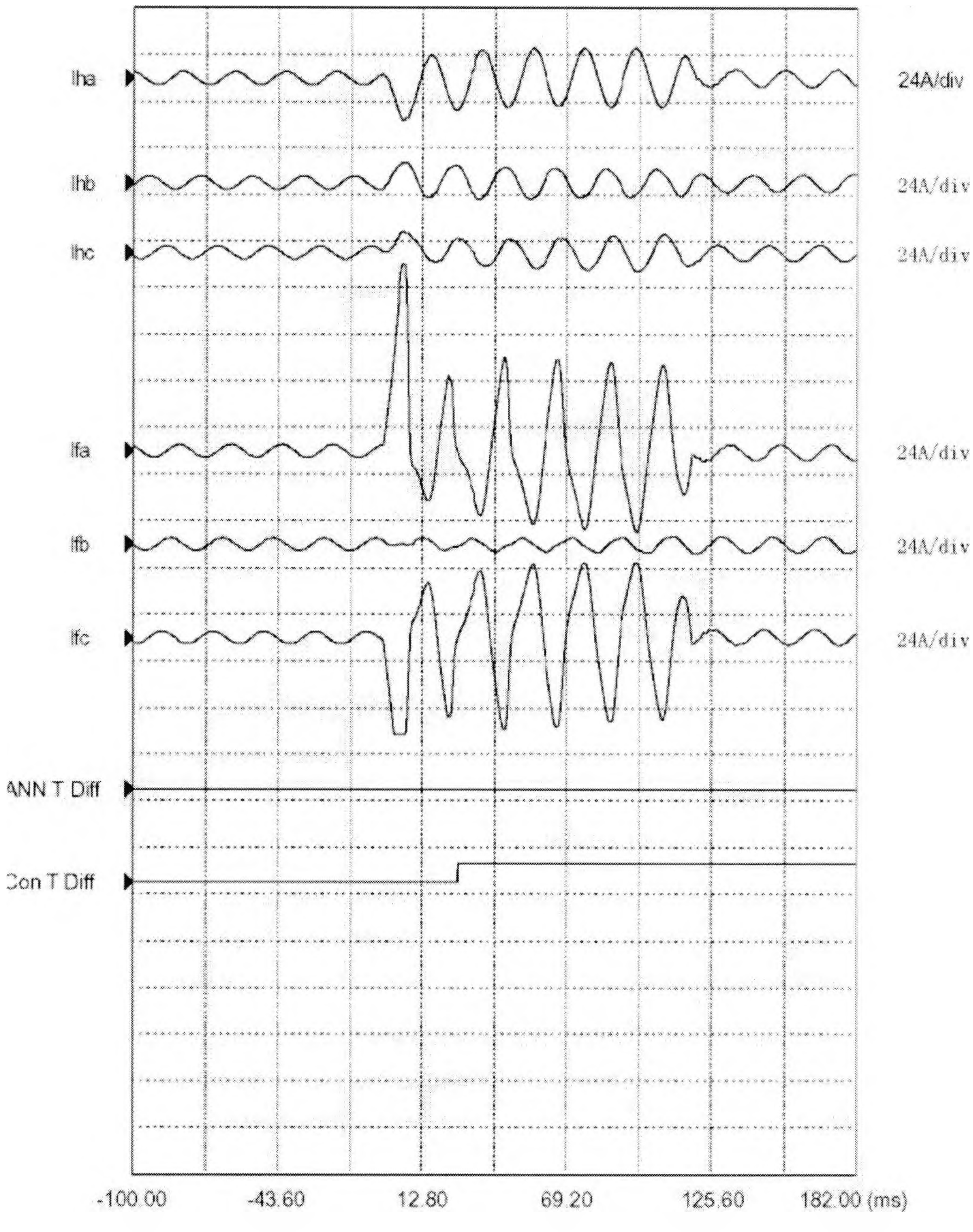


Fig 8.8 Transformer external phase A to phase C short-circuit in low-voltage side (Mal-operation occurred in conventional differential principle because CT saturation occurs too early)

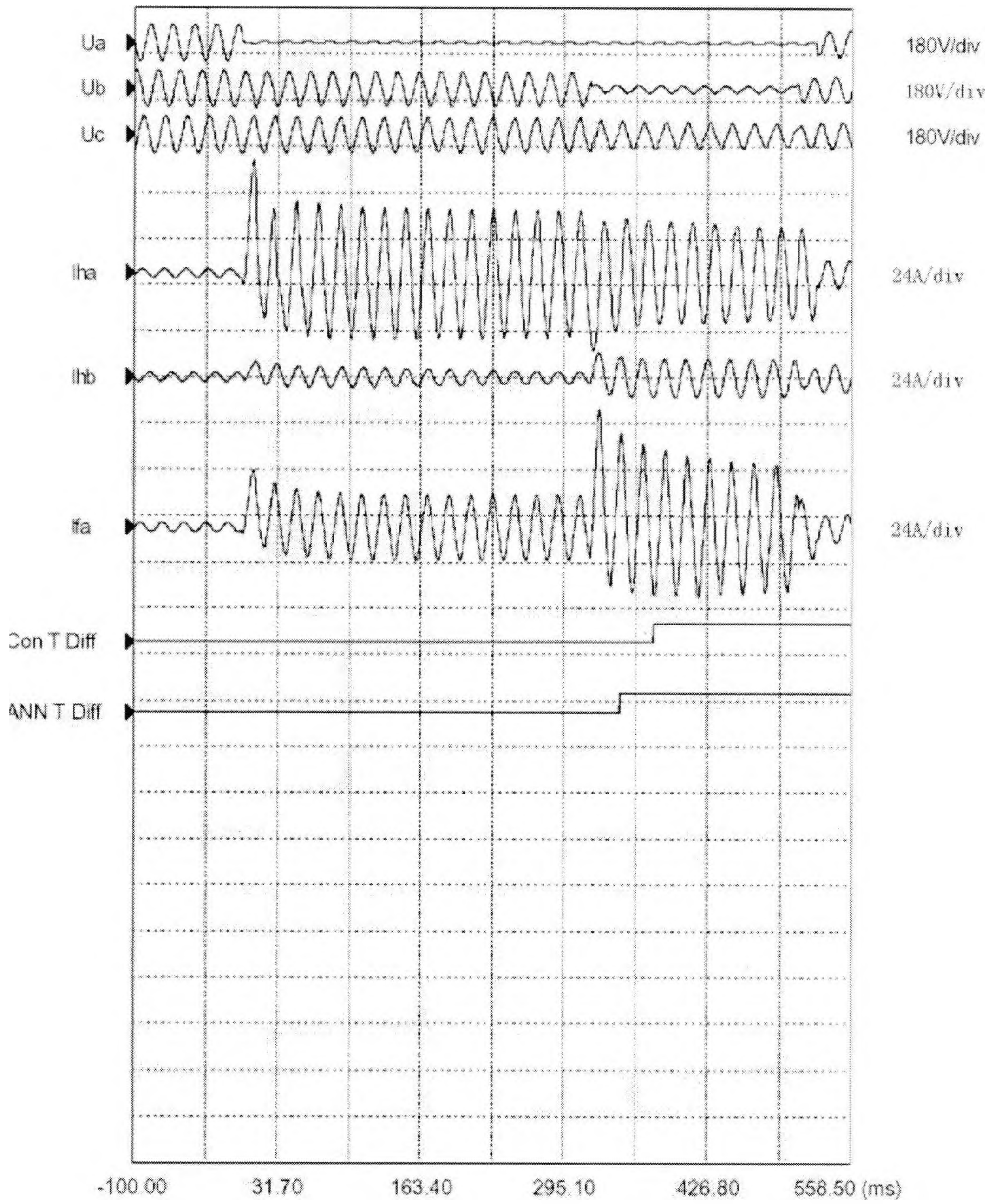


Fig 8.9 A phase A to ground line fault transferred to internal phase A to phase B short-circuit in low-voltage side

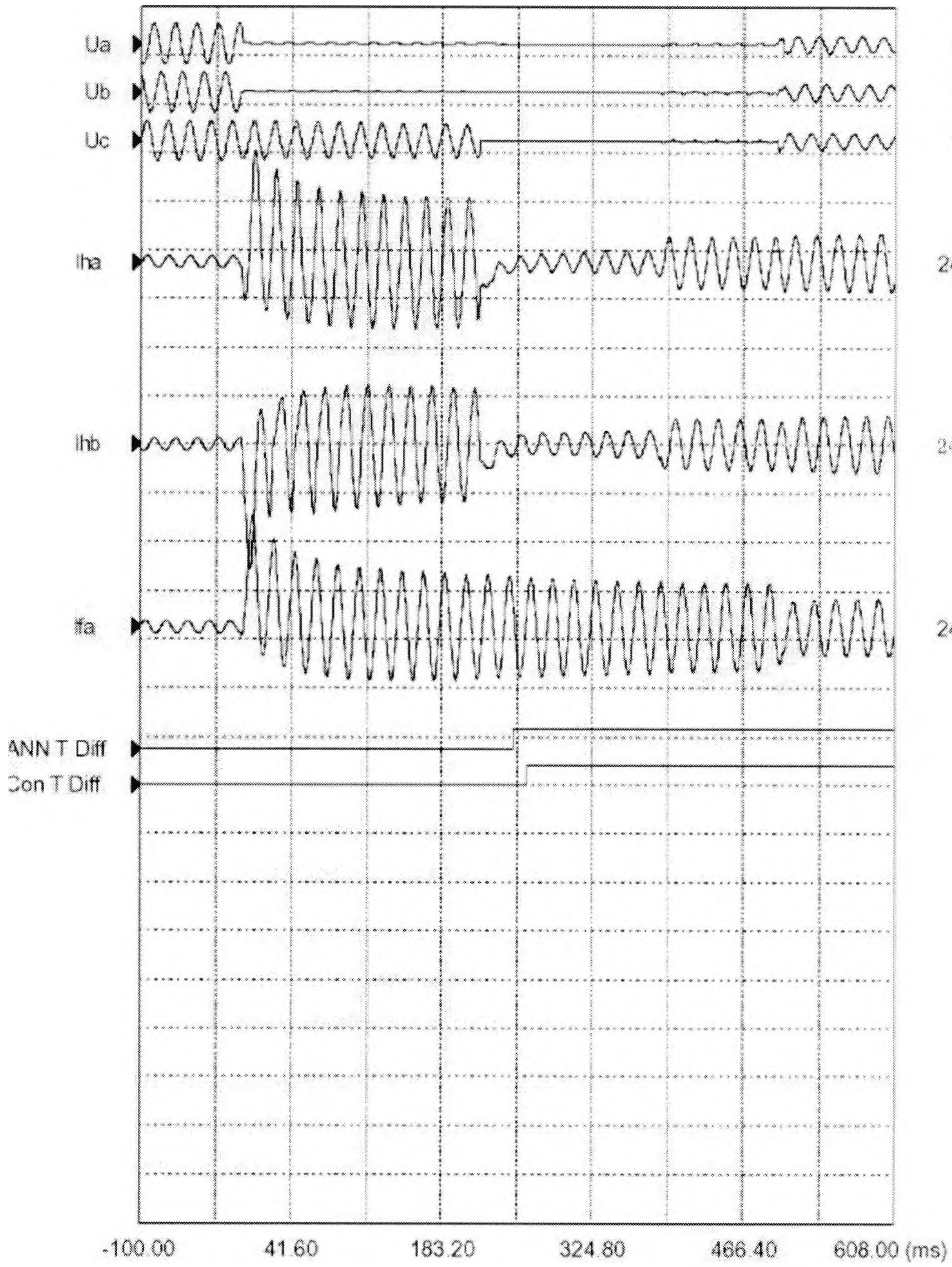


Fig 8.10 A phase A to phase B to ground transferred to transformer internal three-phase fault

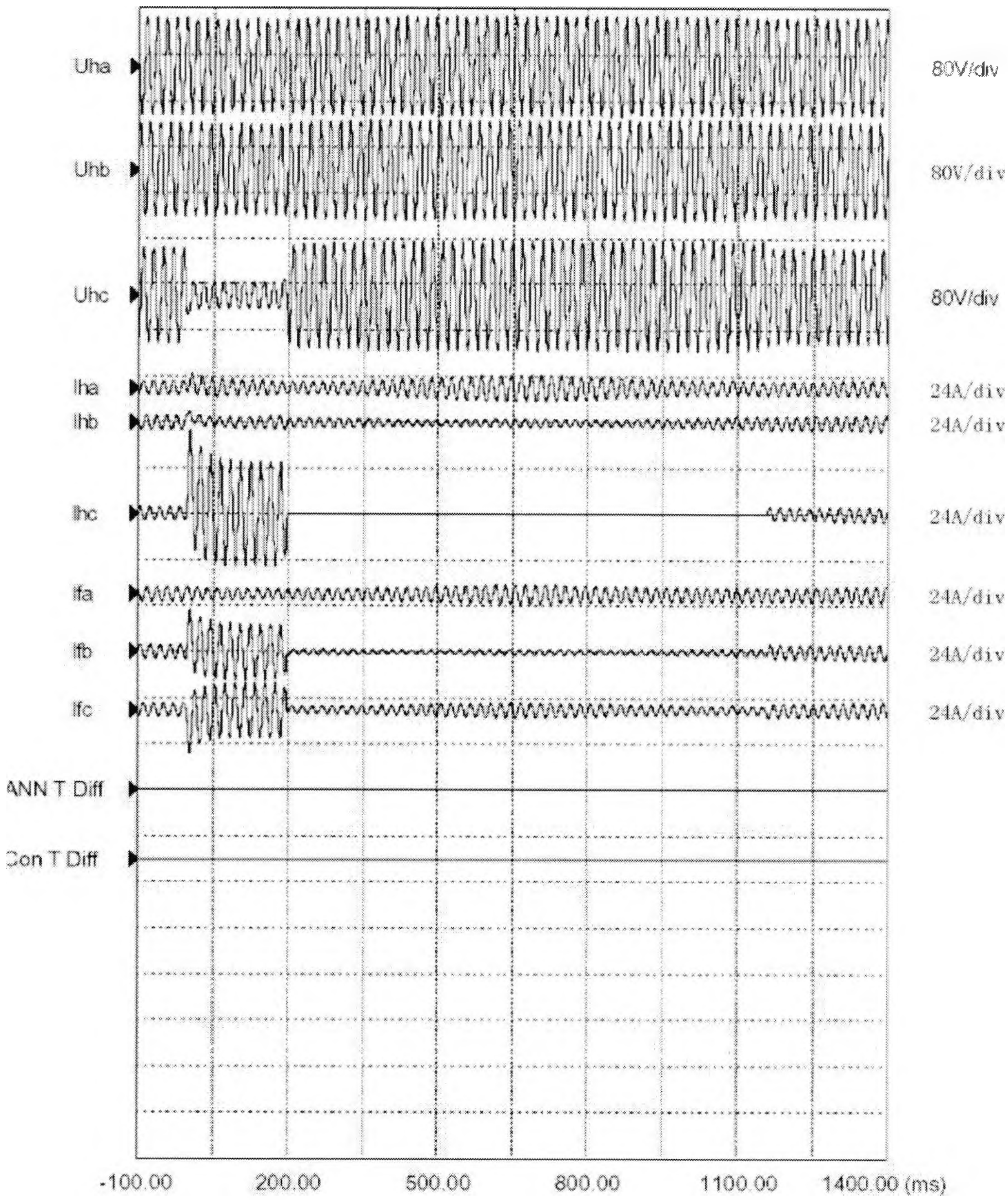


Fig 8.11 Successful reclosed after phase C to ground fault occurred in transmission line.

8.6 Conclusions

This chapter analyses a lot of long-standing problems about generator differential protection in detail. Through the analysis of the signification of restraint curves, many conclusions are drawn. Restraint curves passing the origin is restraint coefficient, those of not passing the origin is the slope of the curve substantially. The slope of the curve and the restraint coefficient have a corresponding converting relation, and are not interchangeable. Different principles actually contain the difference of sensitivity. Decreasing the protection setting blindly cannot increase the protection sensitivity. Selecting proper protection principle has important influence on protection sensitivity. The sensitivity of scalar product restraint principle and ratio restraint principle differential protection is also different. CT error is the only source of generator differential unbalanced current. Therefore, theoretically, the starting current and the inflexion current principally is related to CT characteristic. This chapter also discussed reasonable starting current and inflexion current of Y/△ transformer differential protection full star CT connection and reasonable starting current and inflexion current of generator split-phase transverse differential protection. Through detailed analyses corresponding conclusions are given as far as possible.

Chapter 9 Modularization of Digital Differential Protection

The chapter will investigate modularization of digital differential protection, using OOP (Object Oriented Programming) designing pattern of digital protection software.

9.1 Introduction

Due to the limited conditions, early digital (PC) relay equipment had some defects, such as low criterion product design, absence of long-term development plan, which went largely against expansion of relay function. Presently, with the increasing integration enhancement of hardware and furthermore improvement of network correspondence capability, products about digital relay will be multi-modular, multi-functional and will have high-integration and modularization design is inevitable for relay software and hardware as well. In addition, OOP technology, which is popular in advanced language software development, is suitable for software design in digital relay. For example, each function plug-in or individual relay module can be regarded as object. If it is required to expand function, it is easy to plug objects into slots as ordinary PCs or configure program to suit various requirements of different demands.

9.2 Modularization of hardware

Hardware and software systems in digital relay are explicitly decollated from each other. The former is responsible for truly and reliably changing analog data (DC, AC, harmonics) and transient switching state into digital data, and then quickly transferring differentiated outcome of software to control signals including tripping unit, stepping out, decreasing excitation, and shedding load. Other protection theories are mostly realized by software. Hardware function, hereby, is of much easiness and singleness that establishes basis for modularization design.

Hardware and software in digital relay could be modularized as Fig.9.1. Both hardware about data acquisition and output or software about relay principle are independently modularized.

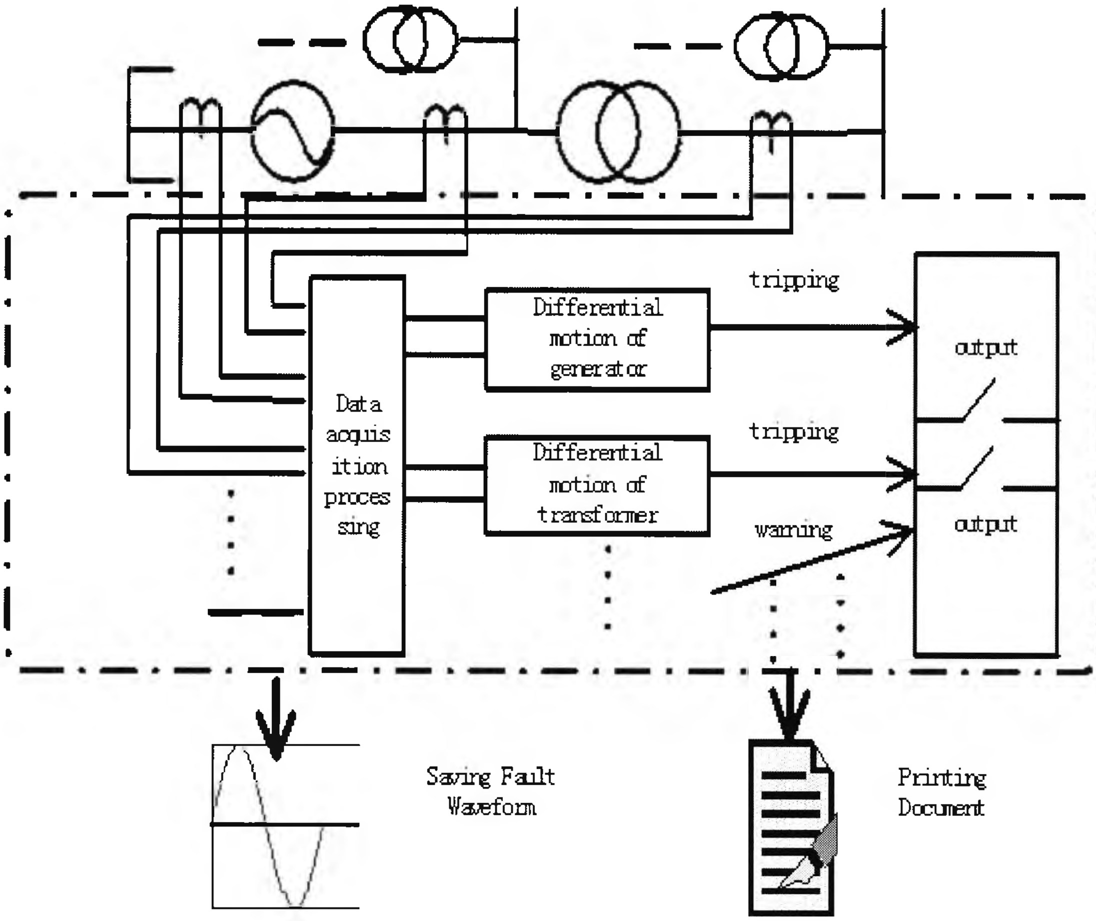


Fig. 9.1 Explicit decollated hardware and software systems

Through modularized design, it is possible to add or delete protection module also possible to adjust and configure tripping mode while meeting the requirement of hardware. In addition, modularized design hardware can automatically form technical document about hardware which is the foundation for auto-designing hardware.

9.3 Modularization of engineering hardware

Relay requires duplicated protection function according to regulations. For line protection, it is easy to double its function because of its simplify of only having four type of principle. For Generator-transformer protection, it is difficult to meet the requirements because of cost and install space. It is inevitable to adopt uniform modularization design for transformer and generation relay.

9.3.1 Entire double configuration

As for uniform modularization design for primary equipment, there are two methods. The first is entire double configuration (shown in Fig.9.2). Generators and transformers are protected by two protection cabinets with the same software and hardware. It is deduced from line relay experience. In design, the two independent cabinets use different CT and PT as current and voltage analogue signal source and protection outputs use different tripping coil of breaker within reasonable extent. Protection DC electrical source of the 2 tanks are also supplied by completely independent sources. Otherwise switching method is utilized for those protections that cannot be equipped with double sets. Switching state protection is additionally considered.

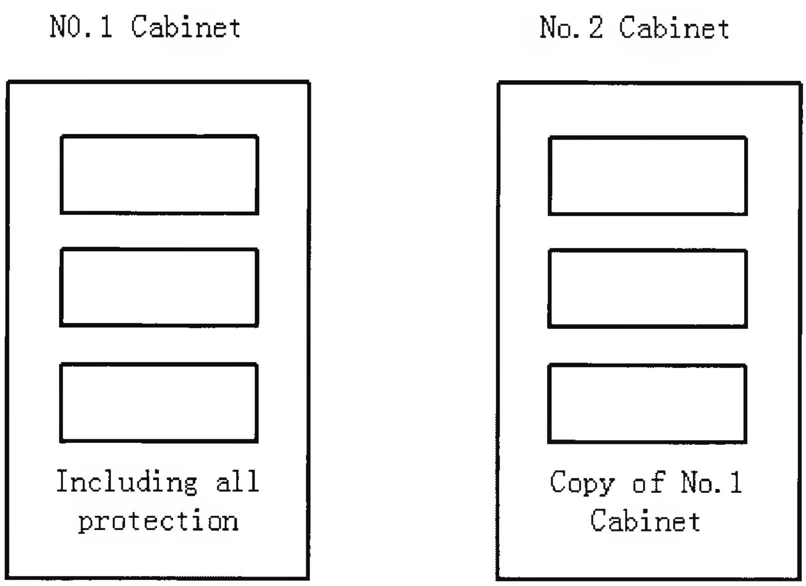


Fig. 9.2 Entire-doubled configuration of protection

From the viewpoint of form, the configuration is seemingly perfect and invulnerable to guarantee device secure running. However, its latent hazard cannot be overlooked so that it should absorb great attention when it is be utilized.

(a) It is easy to arouse mistaken action.

According to statistical material, short circuit of generators and transformers is removed by differential protection in case to spread damage to equipment, and other faults are removed by other protection. Herein, primary equipment protection is mostly used as backup and seldom acts. Additionally, current line protection configuration is with rapid multi-protection, so these backups act either not at all or falsely. In China, the percentage of backup protection right act is low recently, e.g. only 33% about impedance protection one year. If entire double configuration is adopted, it will be lower and more serious for safe production.

Line relay is absent from the problem, because when short circuit occurs, it is possible for every protection to act.

(b) It is easy to arouse principle problem.

Some protection in primary equipment relay cannot run in double configuration mode, such as stator and rotor grounding protection. These protections should be carefully treated. Since not all current operators can flexibly use or switch protection, carelessness will cause unnecessary man-made mistaken action.

(c) Mistaken action increases.

The configuration will inevitably result in that differential and backup protections have same CTs. If there is a fault on CT, It will directly cause differential protection to trip equipments. Therefore the possibility of mal-operation largely increases because of fault or broken in CTs.

(d) Some directional protection confused

Because some protection such as impedance relay possess the direction, it is easy to make mistake because of misuse CT and PT direction. Not good treating will cause extreme dangerous outcome.

(e) Others.

Such as difficult maintenance, too much switching, difficult layout.

9.3.2 Strengthening primary protection and simplifying backup protection

The enhancement of entire double configuration is strengthening primary protection and simplifying backup protection, only differential protection and important protection are duplicated. Thesis believes it is inevitable trend of digital protection to strengthening primary protection and simplifying backup ones. That will be perfect digital protection realization principle.

As a matter of fact, current digital protection module is relatively excellent. Domestic and external large relay manufacturers can flexibly configure cabinets according to different requirements and characteristics of various units so that it is unnecessary for them to turn around. Decades of experience have sufficiently proved that it is true strengthening primary protection and simplifying backup.

The configuration is illustrated in Fig.9.3, where only important primary protection related with equipment safety is doubled. The scheme feature predigests protection configuration, makes layout easy and is suitable for digital relay with advanced hardware and software modularization technology.

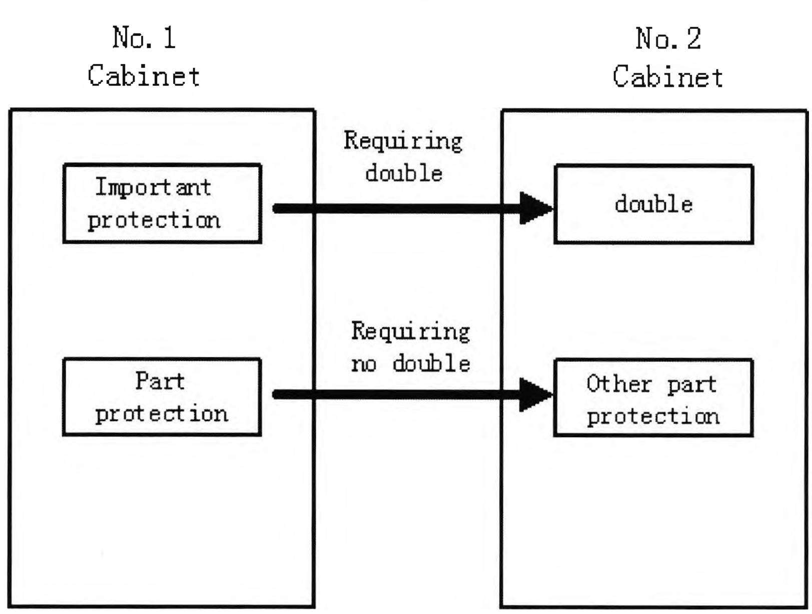


Fig. 9.3 Strengthening primary protection and simplifying backup one Characteristics:

It can predigest protection configuration and improve right action probability without affecting security. It can reasonably select and configure protection according to consumers' requirement. It is of the highest-level modularization. It comprises entire complete double configuration that is with higher modularization level.

Summing up, if it is possible to strengthen primary protection and predigest backup, it is unnecessary to importune consumer to take entire double configuration. However when realization is difficult, it is feasible to take entire double configuration. Thus as digital relay researcher, we should develop high-modularization and high-performance configuration but not ostensible decoration.

9.4 Modularization of software

Modularization of software in digital relay uses the most advanced OOP.

9.4.1 OOP

Object orientation is actually a theory taking objects as a whole. Programming actually realizes encapsulation and inheritance of class. OOP supplies modularization design by establishing partition EMS memory for data and code.

Object can be taken as a part in EMS memory. Usually, EMS memory is parted and then objects are independent form one another.

9.4.1.1 Encapsulation

Every object should be kept independent of each other. It is most essential that any data of object cannot be addressed by other objects. Outside object can acquire data only through corresponding inner object. Then date within object is completely managed and saved by object itself and guarantee its safety.

Once debugging is finished, the most advantageous feature of encapsulated object module is that there is no fault within the object after importing other objects. If fault occurs, it must exist within the imported object module, which is of great importance for large system design.

9.4.1.2 Inheritance

Inheritance is extension of encapsulation. Namely, without change parent object and based on it, designer can own complete father object function and optionally extend and change function.

It puts forward a method to extend function. As things are advancing, it is possible that developed products will be renovated some years later. What should be done is to add required new function but not read up previous programs which are possibly worked out from others. The original function can be easily obtained by inheriting.

9.4.2 Object oriented modularization protection design

Conventionally, digital relay includes soft and hardware and only software moduled well because of cost and chip integration. As generator and transformer protection are varied in quantity and principle, it is more complicate than transmission line protection.

According to object orientation theory, OOP is absolutely possible, then it is unnecessary to match protection number with module number in software modularization. Module number can be far less than protection number.

9.4.2.1 Object classification

Based on object classification principle, protection module can be classified to property.

Differential protection: generator differential protection, primary transformer differential protection, start-up backup transformer differential protection, and excitation transformer differential protection. As a matter of fact, they are all differential protection.

Overcurrent: overcurrent, low-voltage overcurrent, composite low-voltage overcurrent. They are overcurrent in essence and selected according to different requirement and situation.

Single variable: zero sequence current, overload, overvoltage. etc.

Excessive and lack of quantity protection.

Others independent protection can be formed as module, such as impendence, loss of excitation, rotor grounding protection.

9.4.2.2 Reclassification of digital relay object

From the viewpoint of digital protection, object can be reclassified and then module classes reduced.

Through analysis, digital data are current and voltage. Seen from digital protection module, single variable overload and overvoltage is fully same, but with different radical value used for conversing fixed value. These radical values have no directive relation with module so that they can be treated as different value of object attribute.

As above analysis, (b), (c) and (d) in object classification can be reclassified and incorporated to one object module.

9.4.3 Floating pointer

Address in ordinary CPU system especially SCM is absolute. In genetic program module design, visiting data and interim variable visits absolute address that cannot realize object-oriented module.

In order to overcome it, it is necessary to float all visiting data and interim variable to indirect data. That is to say, visiting data becomes relative.

In EMS memory, fixed value and parameter value section should be inaugurated and form blocks as object instance. As shown in Fig.9.4, Settingl, Setting 2, ...; Paral, Para2, ...represent setting block and parameter value block respectively.

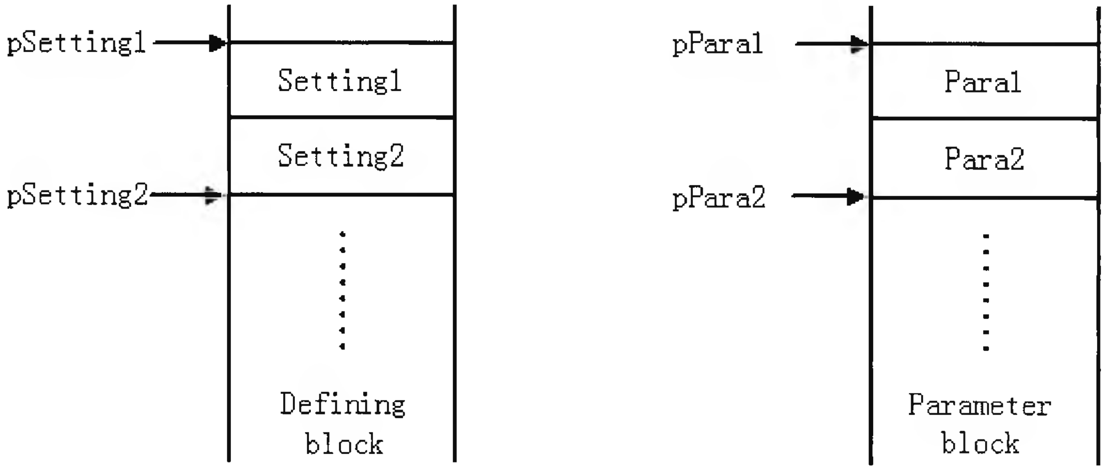


Fig. 9.4 Partitioning of setting section and parameter value

Every instance is assigned with one pointer that point to different setting or parameter value section. pSetting1, pSetting2, ... ; pPara1, pPara2......are the corresponding pointer.

Then multi-instances will be formed.

For example:

If pSetting1, pPara1represents generator differential protection instance; pSetting2, pPara2 represents primary transformer differential protection instance; pSetting3, pPara3 represents plant transformer differential protection instance then, when relay operates generator differential protection, only pSetting1, pPara1 is endowed with object module. Subsequently, differential protection module fetches fixed value setting from psetting1 and saves medial calculation outcome and parameter into pPara1 block, so that differential protection module realizes generator differential protection.

When relay operates primary transformer differential protection, only pSetting2, pPara2 is endowed with object module. Subsequently, differential protection module fetches fixed value setting from psetting2 and saves medial calculation outcome and parameter into pPara2 block, so that differential protection module realizes primary transformer differential protection function.

The rest may be deduced by analogy.

9.4.4 Intel series object instance

CPU of Intel series SCM possesses some features such as easily realized multi-task, multi-users and multi-object. Based on it, object module can be developed more visually, more easily and more conveniently. Here, pointer isn't required to configuring any more. Also program dose not require floating address with pointer and object module can use program mode of direct visiting address the same like only supporting one instance. Then program accords with habits much better and consumes no more pointer (pointer expenses register resource and additional time of CPU).

It is elicited from section address design mode of Intel series CPU chip. Section address mode can randomly segment linear address space with 64K as one maximum section and 16 bits as minimum one. Segmentation is flexible and convenient so that all address accessing is float that is beneficial for object programming to the largest extent.

During design, it can be believed that section address function is the same as pointer but consumes no more additional resource of CPU, because CPU hardware can put section address into seeking address codes automatically.

9.4.5 Realization of object oriented differential protection module

Takes generator and transformer differential protections as an example.

Setting section and parameter section of the fixed values of generator differential protection and transformer differential protection are partitioned to obtain corresponding section address. When differential protection is called, it is endowed with corresponding section address.

Fig.9.5 is partition of section address. Fig.9.6 is application figure of object orientation. Simplified software realization framework is illustrated as Fig.9.7

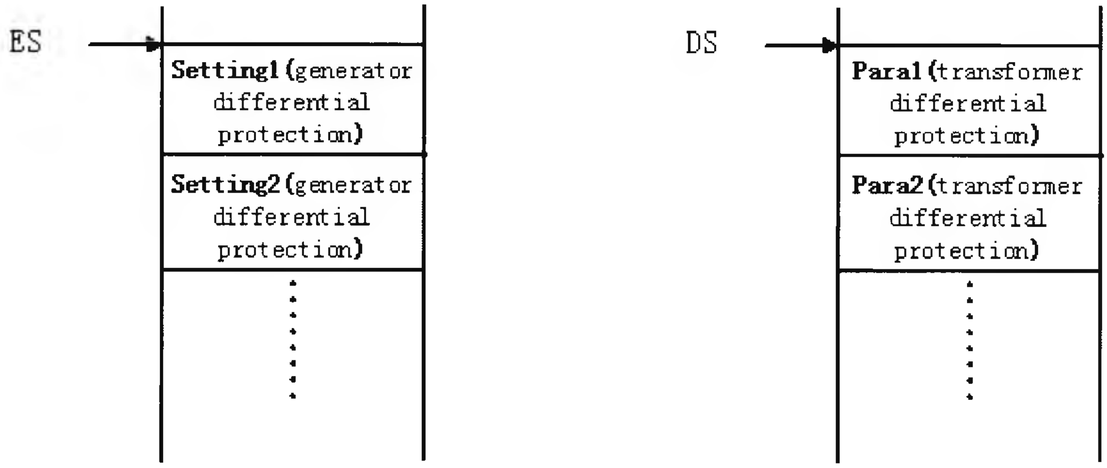


Fig. 9.5 Partition of section address of generator and transformer differential protections

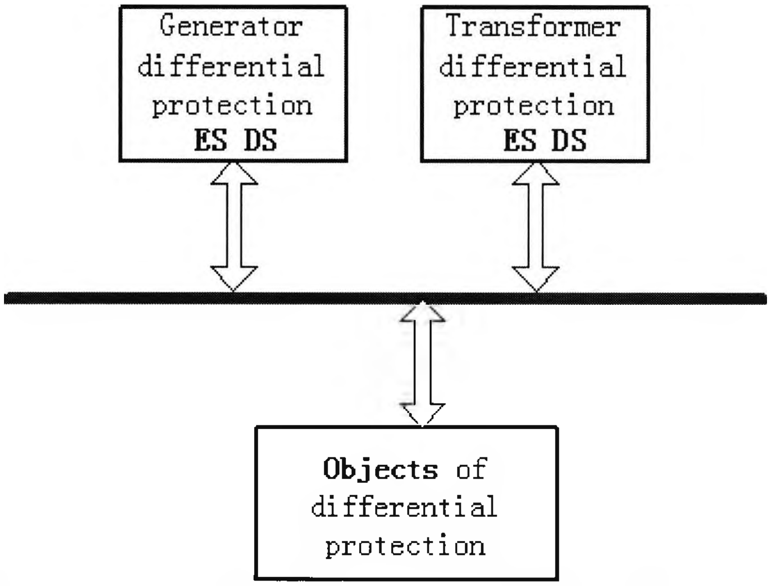


Fig. 9.6 Object oriented application of generator and transformer differential protections

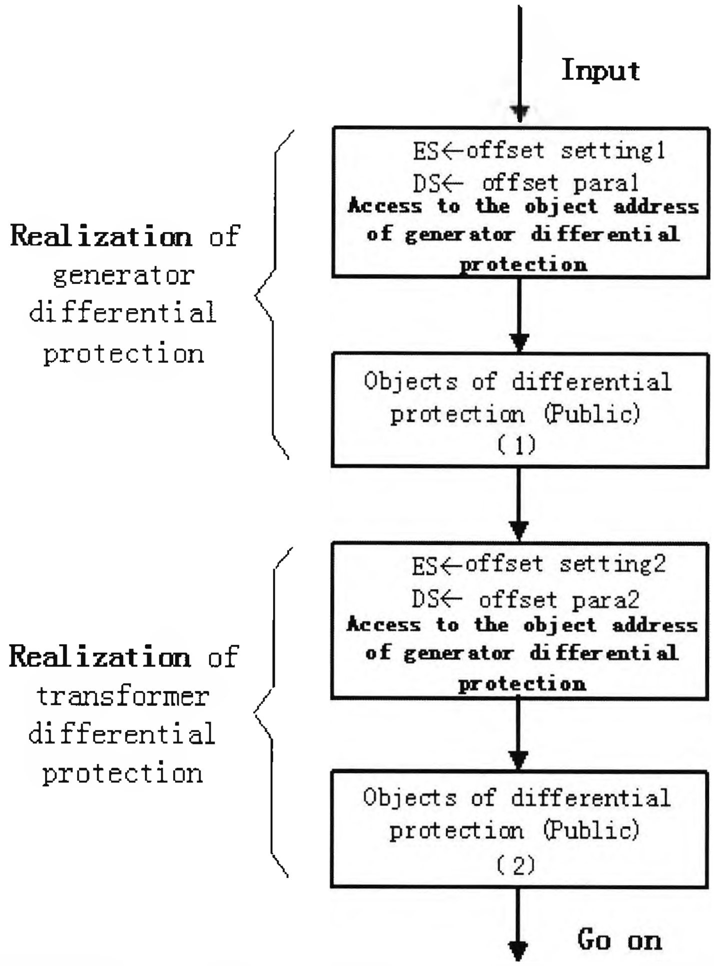


Fig. 9.7 Simplified realization framework of object oriented differential protection software

9.5 Conclusions

Digital protection supplies advantageous chance for modularization of relay. Since hardware and software of digital protection are separated from each other definitely, modularization possesses of preferable basis. Aiming at modularization of software, the chapter introduces object oriented technology and method into protection software design at the first time so that it can reduce resource consumption greatly and while improve protection reliability and security due to large deduction of modules.

At the same time, it indicates that entire double configuration of protection will cause right action probability to fall presently, which is in contrast with strengthening primary protection and simplifying backup protection and is incomplete. However if modularization of software and hardware is done well, for example software here use object oriented programming method, protection configuration can be done by protection object. It is unnecessary to force consumers to use entire unsafe double configuration.

Chapter 10 Automatic Adjustment of Parameters of Digital Differential Protection Hardware

In this chapter, automatic adjustment algorithms and approaches in software are presented according to the requirement that differential protection demands high accuracy for current amplitude and phase sampled through hardware channels. These algorithms and approaches can identify the hardware channels with data error and automatically adjust so that the accuracy of current amplitude and phase meets the requirements of differential protection.

10.1 Introduction

Software of digital protection has already done some tasks originally done by hardware. In particular, differential protection adjust the phase and amplitude of hardware channels. In the past, these adjustment tasks originally done by the potentiometers are so complicated that technicians without high skills can finish the tasks successfully.

To realize the digital protection, the primary current and voltage generally need to be transformed the digital signals for digital protection through several instrument transformers. Because of the exciting current of instrument transformers and the difference of instrument transformer manufacture, error still occurs in the linear range of characteristic of instrument transformers. Therefore, the error including the amplitude and phase inevitably occurs between the digital signals for digital protection and the actual analog signals of the primary systems. In addition, the low-pass filters generally used by digital protection can also bring uncontrolled error to the amplitude and phase due to the discreteness of the circuit component parameters.

The error adjustments of both amplitude and phase through sampled channels are achieved in software. However, there are some difficulties in error adjustment as follows:

(a) Requirement of high accuracy

The system demands high accuracy for sampled data. After the step of error adjustment, the accuracy of sampled data satisfies the requirement of differential protection (Generally the error is limited to 0.5%). There are some difficulties in achieving such high accuracy in software.

(b) Complex operation

The currents though CT are alternative ones and so does the voltages through PT. Sampled data sequences have been affected by the fact of phase, so the calculation of error adjustment needs complex operation.

(c) Designing ideas of oriented object

The channel adjustment is to adjust the data through sampling channels to the expected values. That is to say, if the channel is defined as CT of 1A, then the channel value after adjustment ought to be 1A; and if the channel is defined as CT of 5A, then the channel value after adjustment ought to be 5A. The channel automatic adjustment is just to adjust the unexpected sampled data to the specified range. This is the designing idea of oriented object. Because of the random and uncertainty of channels, the oriented-object adjustments should automatically be adaptive to the changing requirements of channels and it adds more difficulties to the adjustments.

(d) Reiterative adjustment

After the adjustments, if the channel is replaced with another CT or the hardware are exchanged between channels, then the coefficients need to be reset to adapt to the new characteristics of channels. In this case, the channel needs to be adjusted for the second time. There are some differences between the first adjustment and the second adjustment, because the data through sampling channels during the second adjustment are not the original data but the adjusted data after the first adjustment. At this time, it has difficulty in searching the relationship between the expectative data and the original data.

According to the above difficulties, after serious consideration and sufficient research a new approach is presented in the digital automatic adjustment system. For the specific alternative current input channel, this approach is to simultaneously adjust both amplitude and phase in software. This approach with the advantages of quick response speed and short data window can calculate sequence components including zero sequence and negative sequence and automatically change the reference channel so that it is used to process the automatic adjustment of channel parameters for digital differential protection.

10.2 Parameter automatic adjustment of sampling channels

10.2.1 Theory

In order to automatically adjust the parameters of sampling channels, the method in this thesis is to directly process the sampled data and to form new data through the adjustment in software.

10.2.1.1 Least-squares algorithm

Consider N data points (x_j, y_j) (j=1, 2, ···, n), these data can model a m-degree approximate polynomial $P(x)$

$$P(x) = a_0 + a_1 x + \cdots + a_m x^m \tag{10-1}$$

where (m<n), properly select a_0, a_1, ..., a_m, and then minimize over a_0,

a_1, ..., a_m

$$\varphi(a_0,a_1,\cdots,a_m)=\sum_{j=1}^{n}\left[P(x_j)-y_j\right]^2 \tag{10-2}$$

Now we can get fixed value a_0, a_1, ..., a_m. This is the familiar least-squares algorithm. Equation (10-1) is the least-square fitting polynomial.

Least-squares algorithm gives a measurement of curve fitting. According to this measurement, to get the best-fit coefficients $a_i(i=0,1,\cdots,m)$ through the N point data (x_j,y_j)(j=1, 2, ···, n) should minimize the function $\varphi(a_0,a_1,\cdots,a_m)$. This function can be solved by the eigenvalues of multi-variable function. The solution process is as follows:

$$\varphi(a_0,a_1,\cdots,a_m)=\sum_{j=1}^{n}[P(x_j)-y_j]^2=\sum_{j=1}^{n}\left(\sum_{i=0}^{m}a_i x_j^i-y_j\right)^2 \tag{10-3}$$

Differentiate a_k $(k=0,1,\cdots,m)$, then we can get $m+1$ equations

$$\frac{\partial\varphi}{\partial a_k}=2\sum_{j=1}^{n}\left(\sum_{i=0}^{m}a_i x_j^i-y_j\right)x_j^k=2\left[\sum_{j=1}^{n}\sum_{i=0}^{m}a_i x_j^{i+k}-\sum_{j=1}^{n}y_j x_j^k\right]=0 \tag{10-4}$$

Viz.

$$\sum_{i=0}^{m}\left(a_i\sum_{j=1}^{n}x_j^{i+k}\right)=\sum_{j=1}^{n}y_j x_j^k \tag{10-5}$$

For convenience, we note them as

$$\sum_{j=1}^{n}y_j x_j^k=T_k \quad \text{and} \quad \sum_{j=1}^{n}x_j^k=S_k$$

And equation (10-5) can be written as

$$\sum_{i=0}^{m}a_i s_{k+i}=T_k \quad (k=0,1,\cdots,m) \tag{10-6}$$

Equations (10-6) are also named as Normal Equations. The $m+1$-degree linear equations with unknown variables a_i can be written as the form of matrix

$$\begin{bmatrix} S_0 & S_1 & S_2 & \cdots & S_m \\ S_1 & S_2 & S_3 & \cdots & S_{m+1} \\ S_2 & S_3 & S_4 & \cdots & S_{m+2} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ S_m & S_{m+1} & S_{m+2} & \cdots & S_{m+m} \end{bmatrix}\begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ \vdots \\ a_m \end{bmatrix}=\begin{bmatrix} T_0 \\ T_1 \\ T_2 \\ \vdots \\ T_m \end{bmatrix} \tag{10-7}$$

As we see that the elements in the reverse diagonal of the coefficient matrix are equal. Therefore only the 2m+1 elements in the first and last row are acquired then the coefficient matrix can be formed. In addition, after the acquisition of m+1 T_k, the normal equations (10-6) can be formed and $a_k (k = 0,1,\cdots,m)$ is also obtained.

10.2.1.2 Channel error adjustment coefficients of k_1' and k_2' with Least-squares algorithm

Suppose the data through sampling channels are respectively y(n), y(n-1), ..., y(n-k+1), y(n-k), and after adjustments these data are transformed into x(n), x(n-1), ..., x(n-k+1). The process can be achieved by

$$k_1' y(n) + k_2' y(n-1) = x(n) \tag{10-8}$$

For $\varphi\left(k_1', k_2'\right)$, the least-squares algorithm can be utilized, then

$$\varphi\left(k_1', k_2'\right) = \sum_{l=0}^{k-1}\left[k_1' y(n-l) + k_2' y(n-l-1) - x(n-l)\right]^2 \tag{10-9}$$

To minimize $\varphi\left(k_1', k_2'\right)$ is to differentiate k_1', then

$$\frac{\partial \varphi}{\partial k_1'} = 2\sum_{l=0}^{k-1}\left[k_1' y(n-l) + k_2' y(n-l-1) - x(n-l)\right] y(n-l) = 0 \tag{10-10}$$

Viz.

$$\sum_{l=0}^{k-1}\left[k_1' y(n-l)y(n-l) + k_2' y(n-l-1)y(n-l) - x(n-l)y(n-l)\right] = 0 \tag{10-11}$$

and

$$\sum_{l=0}^{k-1}\left[k_1' y(n-l)y(n-l) + k_2' y(n-l-1)y(n-l)\right] = \sum_{l=0}^{k-1} x(n-l)y(n-l) \tag{10-12}$$

and

$$k_1' \sum_{l=0}^{k-1} y(n-l)y(n-l) + k_2' \sum_{l=0}^{k-1} y(n-l)y(n-l-1) = \sum_{l=0}^{k-1} x(n-l)y(n-l) \tag{10-13}$$

Follow to differentiate k_2', then

$$\frac{\partial \varphi}{\partial k_2'} = 2\sum_{l=0}^{k-1}\left[k_1' y(n-l) + k_2' y(n-l-1) - x(n-l)\right] y(n-l-1) = 0 \tag{10-14}$$

Viz.

$$\sum_{l=0}^{k-1}\left[k_1' y(n-l)y(n-l-1)+k_2' y(n-l-1)y(n-l-1)-x(n-l)y(n-l-1)\right]=0$$

(10-15)

and

$$k_1'\sum_{l=0}^{k-1}y(n-l)y(n-l-1)+k_2'\sum_{l=0}^{k-1}y(n-l-1)y(n-l-1)=\sum_{l=0}^{k-1}x(n-l)y(n-l-1)$$

(10-16)

Equation (10-13) and (10-16) can be written as

$$\begin{bmatrix}A_{11} & A_{12}\\ A_{21} & A_{22}\end{bmatrix}\begin{bmatrix}k_1'\\ k_2'\end{bmatrix}=\begin{bmatrix}B_1\\ B_2\end{bmatrix}$$

(10-17)

where

$$A_{11}=\sum_{l=0}^{k-1}y(n-l)y(n-l)=y(n)y(n)+y(n-1)y(n-1)+\cdots+y(n-k+1)y(n-k+1)$$

$$A_{12}=\sum_{l=0}^{k-1}y(n-l)y(n-l-1)=y(n)y(n-1)+y(n-1)y(n-2)+\cdots+y(n-k+1)y(n-k)$$

$$A_{21}=A_{12}$$

$$A_{22}=\sum_{l=0}^{k-1}y(n-l-1)y(n-l-1)=y(n-1)y(n-1)+y(n-2)y(n-2)+\cdots+y(n-k)y(n-k)$$

$$B_1=\sum_{l=0}^{k-1}x(n-l)y(n-l)=x(n)y(n)+x(n-1)y(n-1)+\cdots+x(n-k+1)y(n-k+1)$$

$$B_2=\sum_{l=0}^{k-1}x(n-l)y(n-l-1)=x(n)y(n-1)+x(n-1)y(n-2)+\cdots+x(n-k+1)y(n-k)$$

Solve the equations, and we can get

$$k_1'=(B_1A_{22}-B_2A_{12})/(A_{11}A_{22}-A_{12}A_{21})$$
$$k_2'=(B_2A_{11}-B_1A_{21})/(A_{11}A_{22}-A_{12}A_{21})$$

(10-18)

The adjustment coefficients of sampling channels can be acquired by the equation (10-18). This method ensures the coefficients to be highly accurate in theory.

10.3 Practical algorithm

Adjustment algorithm for amplitude and phase is as follows:

Consider m sampling steps and phase difference ϕ between $x(n)$ and $x(n-m)$.

$$x(n) = \sin(\omega t) \tag{10-19}$$

$$x(n-m) = \sin(\omega t - \phi) \tag{10-20}$$

Suppose k_1 and k_2 are the two specific adjustment coefficient and sequence $y(n)$ has been already adjusted. The adjustment equation is given below:

$$y(n) = k_1 x(n) + k_2 x(n-m) \tag{10-21}$$

Suppose B is the adjustment coefficient of amplitude and θ is the adjustment coefficient of phase. After the adjustment, sequence $y(n)$ becomes:

$$y(n) = B\sin(\omega t + \theta) \tag{10-22}$$

Then k_1 and k_2 can be solved out.

$$k_1 = B\sin(\phi + \theta)/\sin\phi \tag{10-23}$$

$$k_2 = -B\sin\theta/\sin\phi \tag{10-24}$$

In summary, if B and θ have already known, then k_1 and k_2 can be obtained for setting.

The above process can directly complete the adjustment of sample data during each interrupt of digital protection in software and form the new data that meet the requirements of digital protection. In theory there are absolutely no error in adjustment of amplitude and phase. The data for various protective algorithms have totally been adjusted and it facilitates the modularization of software.

After the above process of adjustments, the error between the calculated amplitude and phase and the actual analog amplitude and phase has decrease. However, if CTs or other hardware of alternative current channels are changed, the previous adjusting coefficient should be reset to fit the new characteristics of the changed channels. In this case, coefficient k_1 and k_2 should be reset.

Suppose the previous adjusting coefficients are k_1 and k_2, the amplitude adjustment coefficient B' and the phase adjustment coefficient θ' need to calculated again and new coefficients k_1' and k_2' can be obtained.

Equations (10-23) and (10-24) become:

$$k_1' = B'\sin(\phi+\theta')/\sin\phi \tag{10-25}$$

$$k_2' = -B'\sin\theta'/\sin\phi \tag{10-26}$$

Suppose k_{new1} and k_{new2} are new coefficients, then

$$k_{new1} = \frac{(B\times B')\times\sin(\phi+\theta+\theta')}{\sin\phi} \tag{10-27}$$

$$k_{new2} = \frac{-(B\times B')\times\sin(\theta+\theta')}{\sin\phi} \tag{10-28}$$

According to Equations (10-23), (10-24), (10-25) and (10-26), we can have

$$\sin\theta = -\frac{\sin\phi}{B}k_2 \tag{10-29}$$

$$\sin\theta' = -\frac{\sin\phi}{B'}k_2' \tag{10-30}$$

$$\cos\theta = \frac{1}{B}k_1 + \frac{\cos\phi}{B}k_2 \tag{10-31}$$

$$\cos\theta' = \frac{1}{B'}k_1' + \frac{\cos\phi}{B'}k_2' \tag{10-32}$$

Corresponding to Equation (10-27), we have

$$k_{new1} = \frac{B\times B'}{\sin\phi}\left(\sin\phi\cos\theta\cos\theta' + \cos\phi\sin\theta\cos\theta' + \cos\phi\sin\theta'\cos\theta - \sin\phi\sin\theta\sin\theta'\right) \tag{10-33}$$

$$k_{new2} = -\frac{B\times B'}{\sin\phi}\left(\sin\theta\cos\theta' + \cos\theta\sin\theta'\right) \tag{10-34}$$

Substitute Equations from (10-29) to (10-32) into Equations (10-33) and (10-34), then

$$k_{new1} = k_1k_1' - k_2k_2' \tag{10-35}$$

$$k_{new2} = k_1'k_2 + k_1k_2' + 2k_2k_2'\cos\phi \tag{10-36}$$

Considering the iterative adjustment, the new coefficient k_{new1} and k_{new2} are universal. In practice, the effect is ideal and after the adjustments the parameters of channels with the error range of 0.5% approach the expected values.

10.4 Flow chart in software

The flow chart of automatic adjustment of channel parameters is shown in Fig. 10.1.

The standardization of channels, which is not introduced in the preceding sections, will be illustrated in the following paragraphs.

The aim of channel's standardization is to eliminate the effect of channel adjustment caused by the change of CT/PT ratio. The signals through the sampling channels are discreet digital data and they do not show any difference of channel properties. Therefore before starting the adjustments the effect caused by CT/PT ratio should be eliminated and the standardization of channels should process so that the adjustment will be unified in the perspective of numerical calculation. It facilitates to realize the modularization of parameter automatic adjustment.

The steps of channel' standardization are as follows:

Suppose $x(n)$, $x(n-1)$, ..., $x(n-23)$ are the reference channel sequences and $y(n)$, $y(n-1)$, ..., $y(n-23)$ are the channel sequences needed for adjustments. The ratios of CT/PT are respectively M_x and M_y.

(1) Standardization of reference channels

Standardization of amplitude

Consider $X_m^2 = x^2(n) + x^2(n-3)$, and then process the signal sequence of half wave. Thus

$$X_m^2 = \sqrt{[x(n)^2 + x(n-1)^2 + x(n-2)^2 ...... + x(n-8)^2]/6}$$

Standardization of phase

$$K_x = X_{\exp} * 1.414 / X_m * M_x$$

After the standardization, the signal sequences of reference channels become

$$x'(n) = K_x x(n), \cdots, x'(n-23) = K_x x(n-23)$$

(2) Standardization of channels needed for adjustment

$$Y_m^2 = \sqrt{[y(n)^2 + y(n-1)^2 + y(n-2)^2 ...... + y(n-8)^2]/6}$$

$$K_y = (Y_{\exp} * 1.414 / Y_m * M_y) * [(X_{\exp} * M_x) / (Y_{\exp} * M_y)]$$

Suppose the expectative value of phase is $Q_{\exp}$, then

$$y'(n) = y(n)\cos(Q\exp) - y(n-3)\sin(Q\exp)$$

After the above process, the reference channels and the channels needed for adjustment have been standardized.

The other processes in Fig. 10.1 have been already introduced in the previous sections.

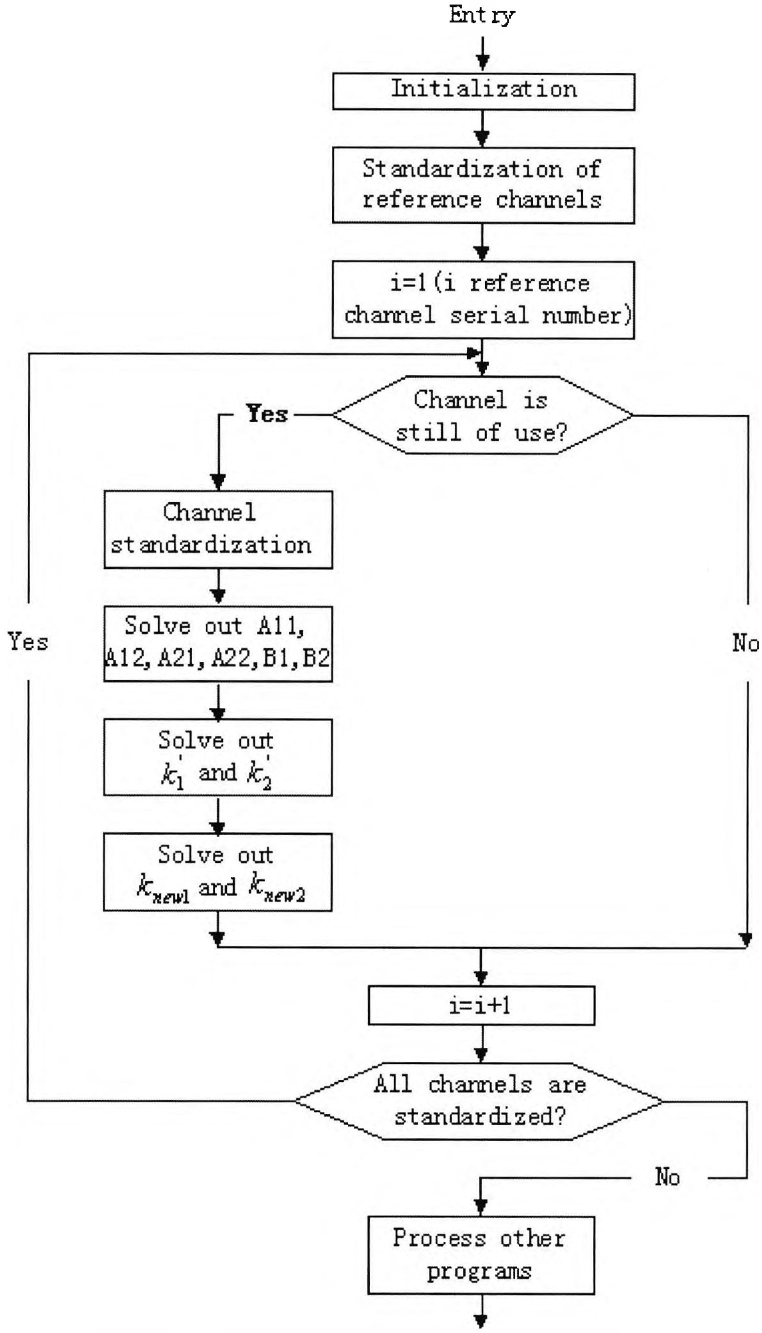


Fig. 10.1 Flow chart of automatic adjustment of channel parameters

10.5 Example analysis

In this section, current data of five channels are given to test the automatic adjustment of channel parameters. The results of tests are shown in the Table 10.1.

Table 10.1 Results of adjustment coefficient experiments

Given testing current	Phase Name	Before adjustment		Expected value		After adjustment		K1	K2
		Amplit -ude (A)	Phase (°)	Amplit -ude (A)	Phase (°)	Amplit -ude (A)	Phase (°)		
1A	A	0.878	0	1	0	1.003	0	1.1406	0
	B	0.864	240.4	1	-120	1.001	240.4	1.1065	0.0445
	C	0.851	119.2	1	120	0.989	120.4	1.1927	-0.0278
2A	A	1.759	0	2	0	2.004	0	1.1361	0
	B	1.770	241.3	2	-120	1.994	240.5	1.0914	0.0417
	C	1.715	120.1	2	120	2.002	120.2	1.1787	-0.0157
3A	A	2.626	0	3	0	2.995	0	1.1375	0
	B	2.650	240.9	3	-120	3.020	240.1	1.0959	0.0437
	C	2.565	119.4	3	120	3.004	120.3	1.1836	-0.0156
4A	A	3.512	0	4	0	4.000	0	1.137	0
	B	3.541	240.9	4	-120	4.010	240.2	1.0941	0.0437
	C	3.432	119.7	4	120	3.993	120.4	1.1782	-0.0129
5A	A	4.398	0	5	0	5.002	0	1.1364	0
	B	4.437	241.4	5	-120	4.999	239.7	1.0858	0.05
	C	4.281	119.6	5	120	4.996	119.9	1.1733	-0.0065

It has been seen from Chart 10.1 that the amplitude and phase within the error range of 0.5% reach or approach the expected values after the first automatic adjustment using coefficients of k_1 and k_2.

10.6 Adjustment of differential protection channel's parameters

Differential protection sometimes demands for current data more than ten channels. The signals through these channels should be of the same characteristic of amplitude and phase so that the normal biased current of differential protection will decrease to least. However, software generally cannot once adjust the data of all channels. On one hand, the efficiency of this action will not be high; On the other hand, in the laboratory there are not enough testing instruments simultaneously provided for so many current channels. Consequently, digital differential protection generally selects three channels to adjust simultaneously.

Because the data of all channels cannot be adjusted at once, it is necessary to firstly select one channel as the reference channel to adjust phase, and other channels process the adjustments according to the phase of the reference channel. In consideration of least-squares algorithm providing high accuracy of adjustments, adjusting coefficients of each channel for differential protection still meet the requirement of accuracy and will not bring inherited error.

10.7 Conclusions

According to the features of digital protection, the algorithm of automatic adjustment of channel parameters, least-squares algorithm, is presented in this chapter. This method uses short data window to set the expected values of amplitude and phase of channels so as to realize the automatic adjustment of channel parameters. This method can also automatically eliminate the memorial characteristic of adjusting coefficients and realize iterative adjustments on the basics of the original adjustments (which means that the variable resistance already adjusted is during the transition of adjustments).

Automatic adjustments in software can make the amplitude and phase of signals meet the requirements of differential protection through sampling channels.

Chapter 11 Prospect of Modern Digital Differential Protection

The Chapter will illuminate the future trends of digital differential protection and the possible available technology.

11.1 Introduction

After about 20 year's development, digital protection is largely different from the post. It has integrated much more complicated functions to digital protection by changing from the former PC protection in main charge of protection function to the present digital protection with data acquisition, correspondence, wave record and protection function as well, which precludes from more mistakes or hidden trouble caused by man-made factor and improve digital protection reliability to a larger extent.

11.2 Furthermore enhancing cognition of digital protection

11.2.1 Sampling frequency and calculation precision

It is universally believed that more sampling frequency can achieve more calculation precision. However it is incorrect as a matter of fact. There is no directive relation between them. If you take more sampling frequency while keeping the same data window, the precision will not be higher but lower.

As illustrated in Fig.11.1, there exist two sampling frequencies, fs1 = 600 and fs2 = 2400. Suppose sampling a 50Hz signal with these two frequencies, wave magnitude will be calculated through two adjacent points. In order to observe more conveniently, wave is displayed in equal width abscissa.

As seen from the figure below, the sampling values of adjacent points with higher frequency is quite approximate. Therefore, it is necessary for protection arithmetic to filter directive current, which will screen lots of effective information and increase sampling error.

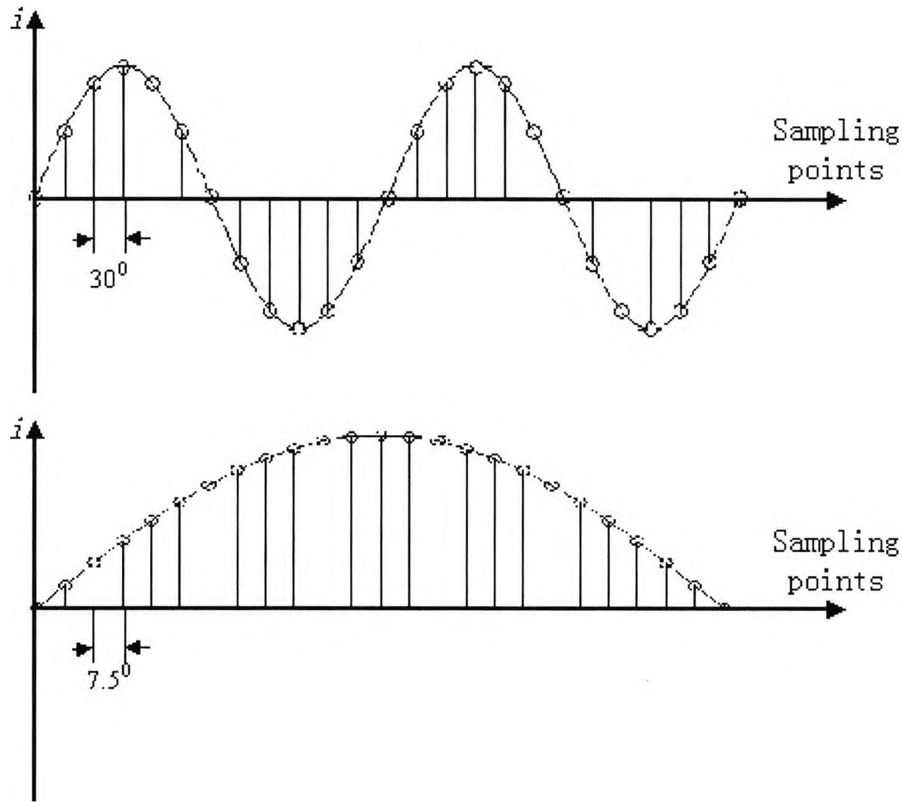


Fig. 11.1 Comparison of waveforms with two sampling frequencies

11.2.2 Sampling frequency and protection speediness

The higher sampling frequency, the faster is the protection. However, protection calculation error will increase with higher sampling rate. When the rate arrives at some speed, calculation error will not be allowed by protection and thus the two terms should be comprehensively considered.

11.2.2.1 Sampling precision of A/D

In series AD with the same model, precision of that with more digits is higher. Nevertheless, sampling precision of protection includes not only sampling precision of AD but also a serial of segments such as wave filtering, CT and PT. Actually, precision depends on section with the lowest precision.

11.2.2.2 Sampling precision of A/D and arithmetic

If more sampling precision of AD (such as 16 digits AD) is selected, all calculation software, even those addition or subtraction, shall be changed from 16 digits to 32 digits. It is possible for some to calculate in 64 digits. For the same CPU system, calculation efficiency will be multifold lowered

11.3 Determining excellent or inferior protection

The determination will no longer be current simple care. For example, how many digits CPU chip is used, how many digits AD is chosen, how many sampling frequency, and whether DSP chip is be used. Much more attention should be put on those aspects tightly related with consumers such as protection performance, ancillary function, product quality and appearance.

11.4 Application of new technology

Application of digital protection extends and improves its technical and theoretical levels.

Since generator and transformer are important components of power systems, their protection performance improvement is vital to enhance power system performance. Therefore it is necessary to develop reliable advanced protection principle, such as new differential protection principle with resisting CT saturation. Present differential protection utilizes ratio trigging principle and mark-integral trigging principle. With the development of intelligent theory, some differential protection, such as new ones based on ANN, those based on wavelet theory, and those with more self-adaptable principle to overcome inrush current, will be popularized.

Many new theory and fresh methods are not mature. Some are still on the stage of experiment in laboratory and not be popularized and applied. The situation are caused by various reasons, for examples, the required quantity cannot be available in engineering field, or protection cannot be achieved by hardware, or it is difficult to set so as not to popularize. However, with the continuous advancing of technology, it is certain that some protection will come out.

The whole performance and function will be largely improved, while keeping developing new protection principle. Because of the powerful memory capacity of digital protection, it can integrate many functions such as protection, data acquisition, and waveform record of fault. With the development of network technology, it can supply some data to superior machine through interface of protection, and to dispatching center by dispatching telecommunication. Those data includes protection data, fault wave record, and protection event.

The future protection equipment will be fault tolerant and free from maintenance. Fault tolerant means that hardware design should take redundancy into account, and software should sufficiently consider capability to handle mistake and bad data. If there is no warning in equipment itself, protection will certainly fulfill the corresponding protection function.

Comprehensive intelligent protection integrates multi-variables and multi principles. Since digital protection has acquired and can acquire sufficient data, it is possible to reflect multi-variable and multi-character when fault occurs.

Protection configuration will be easier. Presently, the configuration mostly follows conventional idea. Actually, it can be simplified entirely. For example, for the former some capacity generator protection, there was no differential protection, because it was relatively expensive then. Nowadays, the price of digital protection is mainly on hardware. For the hardware of low-voltage overcurrent and differential protection is completely same, their cost is also identical. Therefore, protection configuration can be simplified while enhancing function performance.

Plug and play. Modularization and more powerful integration will improve protection hardware and software continuously.

11.5 Solve the hot problem

Quickness of protection is identical with system stability.

It is commonly believed that fastening action speed of protection can improve system reliability. According to research, fault on every line within system will not cause instability accident. Only few important lines affect system stability largely. For these lines, it will be extraordinary effective to improve system stability by fastening protection action speed. For those lines having little relationship with system stability, prolonging action time will enormously the reliability of protection equipment. Thus the future protection will be possibly designed to the protected device.

It is necessary to furthermore consummate transformer differential protection principle.

Presently transformer manufacturing technology is advancing very quickly. Hereby it is necessary to put forward new protection principle to meet the requirement of evolving primary equipments.

Startup current of differential protection will be more reasonable. The accuracy of transformer differential protection in engineering field is low. In order to improve reliability, operation department increases startup current of differential protection. However it lowers sensibility of inner slight fault. Actually, startup current, inflexion current and slope of differential protection all restrict sensibility to a large extent. Startup current will be more reasonable.

The development of grid will change conception. The former grid was weak. Protection operation was mostly based on guarding system safety. Single element puts less and less effect on system stability. In the future, the safety of equipment will become more and more important.

Network. Advanced digital protection will use open interface and plat and distributed database, and share and upload protected data through optic fiber cable. Protection can be operated and managed through network.

11.6 Conclusions

The chapter discusses that differential protection will change for those with new principle, powerful module and operation through network. At the same time, A/D precision of rapid protection, sampling frequency and action speed should be designed within a reasonable range so as to theoretically guarantee protection remaining optimal condition. Blindly pursuing one side of direction will be just the opposite of what you wish.

Chapter 12 CONCLUSIONS AND FUTURE WORK

An advanced differential principle is developed in this chapter in order to meet the requirement to protect large generator and transformer unit. Productive and valuable conclusions will be obtained below

12.1 Conclusions

A new ANN based generator-transformer differential principle is put forward. It is the best scheme to integrate ANN technique to protection principles. To some extent, it can eliminate both ANN and conventional principles' weakness, Such as a high reliable, high stable and high sensitive relay could be achieved. At the same time, a new scalar product differential principle has been promoted. It will be more sensitive than conventional differential principle.

As compared to conventional differential principles, ANN based protection theory has many advantages include having high security and reliability. It makes BP network converge to an expected range easily. It can optimize settings coordination between different principles and algorithms.

Multi-condition inrush restrain principle is presented to distinguish magnetizing inrush current and fault current with the introduction of breaker switching state and transformer voltages. The relay will correctly protect a transformer that provides the correct signals derived from, for example, inrush currents, short-circuit current, fault-recovery inrush current, sympathetic inrush current, transient current induced by switching on an unenergized faulted transformer, fault right after switching on an unenergized transformer state. This principle overcomes the shortcoming from conventional harmonic restraint, which when applie to modern large transformers, will meet some difficulties to distinguish short circuit and inrush. It points out over-excitation restraint function for transformer differential protection is unnecessary, especially in power plants.

Since blocking differential protection under CT broken is a regulation in China. A new restraint criterion based on current sudden change in negative direction is presented to meet the regulation. It makes great improvements on the conventional criterion for CT secondary circuits break detection, since it does not neglect the effect due to arc current.

It analyzed relationships between CT saturation and the performance of digital differential protection. It points out that in the dynamic process of CT transient saturation combining with the transient of digital filter algorithm, relay will work under transient condition for a long time, and reply locus could enter the tripping zone, but it will not stay long, that is, in the region of few ms. It is an useful phenomenon to develop a new mechanism to prevent mal-operation during CT saturation.

According to the characteristic of CT saturation, speed control approach, the trap approach and the decelerating approach against CT saturation are presented. Because all kinds of methods and approaches have their own characteristic, different theory against CT saturation should be rationally determined according to the different occasions and requirements. These measures and approaches have already been applied successfully. The concept of CT non-saturation transient and corresponding solution strategy is obtained in this thesis.

This thesis also put forward a new method to adjust channel and A/D errors automatically with least-squares algorithm. This method uses short data window to set the expected values of amplitude and phase of channels, so as to realize the automatic adjustment of channel parameters. This method can also automatically eliminate the memorial characteristic of adjusting coefficients and realize iterative adjustments on the basics of the original adjustments.

The thesis discussed A/D, sampling frequency's impact on differential relay. It can be said that they should be designed within a reasonable range of accuracy, cost and speed. so as to guarantee protection optimal condition. Unilaterally pursuing one performance may result negative influence on differential relay in spite of high cost.

A standard hardware desktop has been developed according to the principle of this thesis. Good performance, high stablility and high reliability have been confirmed through real-time dynamic testing and one-year site experience in power system.

12.2 Future work

It is important to find a productive way to further train ANN based differential principle with real recording fault data in order to find out potential problems. Since it is difficulty to get training data coverage in all aspects of fault, better performance would be obtained through further training. It will be efficient if we can develop a train mechanism to train BP network automatically as soon as fault data are available.

From the results of our research work, scalar product differential principle is sensitive to current angle. The advantage is that high sensitivity can be obtained. However, it should be noticed that mal-operation might occur due to transients in power system. Special mechanism should be considered to overcome this weakness and Further studies should be performed in the future.

High performance prototype will improve the connection to each other or to local network or even through the internet. As such, it opens a lot of research work in terms of security too.

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