ADVANCED FAULT DIAGNOSIS TECHNIQUES AND THEIR ROLE IN PREVENTING CASCADING BLACKOUTS

A Dissertation

by

NAN ZHANG

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

December 2006

Major Subject: Electrical Engineering

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Approved by:

Chair of Committee,	Mladen Kezunovic
Committee Members,	Chanan Singh
	Krishna Narayanan
	William Lively
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ABSTRACT

Advanced Fault Diagnosis Techniques and Their Role
in Preventing Cascading Blackouts. (December 2006)
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Chair of Advisory Committee: Dr. Mladen Kezunovic

This dissertation studied new transmission line fault diagnosis approaches using new technologies and proposed a scheme to apply those techniques in preventing and mitigating cascading blackouts. The new fault diagnosis approaches are based on two time-domain techniques: neural network based, and synchronized sampling based.

For a neural network based fault diagnosis approach, a specially designed fuzzy Adaptive Resonance Theory (ART) neural network algorithm was used. Several application issues were solved by coordinating multiple neural networks and improving the feature extraction method. A new boundary protection scheme was designed by using a wavelet transform and fuzzy ART neural network. By extracting the fault generated high frequency signal, the new scheme can solve the difficulty of the traditional method to differentiate the internal faults from the external using one end transmission line data only. The fault diagnosis based on synchronized sampling utilizes the Global Positioning System of satellites to synchronize data samples from the two ends of the transmission line. The effort has been made to extend the fault location scheme to a complete fault detection, classification and location scheme. Without an extra data requirement, the new approach enhances the functions of fault diagnosis and improves the performance.

Two fault diagnosis techniques using neural network and synchronized sampling are combined as an integrated real time fault analysis tool to be used as a reference of

traditional protective relay. They work with an event analysis tool based on event tree analysis (ETA) in a proposed local relay monitoring tool. An interactive monitoring and control scheme for preventing and mitigating cascading blackouts is proposed. The local relay monitoring tool was coordinated with the system-wide monitoring and control tool to enable a better understanding of the system disturbances. Case studies were presented to demonstrate the proposed scheme.

An improved simulation software using MATLAB and EMTP/ATP was developed to study the proposed fault diagnosis techniques. Comprehensive performance studies were implemented and the test results validated the enhanced performance of the proposed approaches over the traditional fault diagnosis performed by the transmission line distance relay.

To My Wife, Hong Ge, and My Parents for Their Love, Patience and Support

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TABLE OF CONTENTS

CHAPTER Page

LIST OF TABLES

LIST OF FIGURES

FIGURE Page

FIGURE Page

FIGURE Page

CHAPTER I

INTRODUCTION

A. Problem Statement

1. Power System Cascading Blackouts

Power system is one of the largest dynamic systems in the world, consisting of thousands of electrical sources, loads, transmission lines, power transformers, circuit breakers, and other equipment to provide power generation, transmission and distribution. Fig. 1 shows an example of power system including those typical components. For over a century, the power engineers have striven hard to maintain the reliable operation of the power system, transmitting the electricity uninterruptedly from the generators to the customers. With the ever-increasing load demand and the advent of the deregulated power market recently, the power systems are pushed more often to operate close to their design limits and with more uncertainty of the system operating mode. That makes the power systems face more challenges than before. As a most catastrophic result, power system large-scale blackouts, as the one that occurred on Aug 14, 2003 [1], can interrupt the power supply for a few hours, affecting millions of people and causing huge economic loss. The causes for this kind of large-scale blackout are quite involved due to the complexity of power system operations and the randomness of different system contingencies. Typical factors are inadequate system understanding, inadequate operational awareness, inadequate tree trimming, relay misbehavior, bad weather, human errors, etc. The large-scale black-

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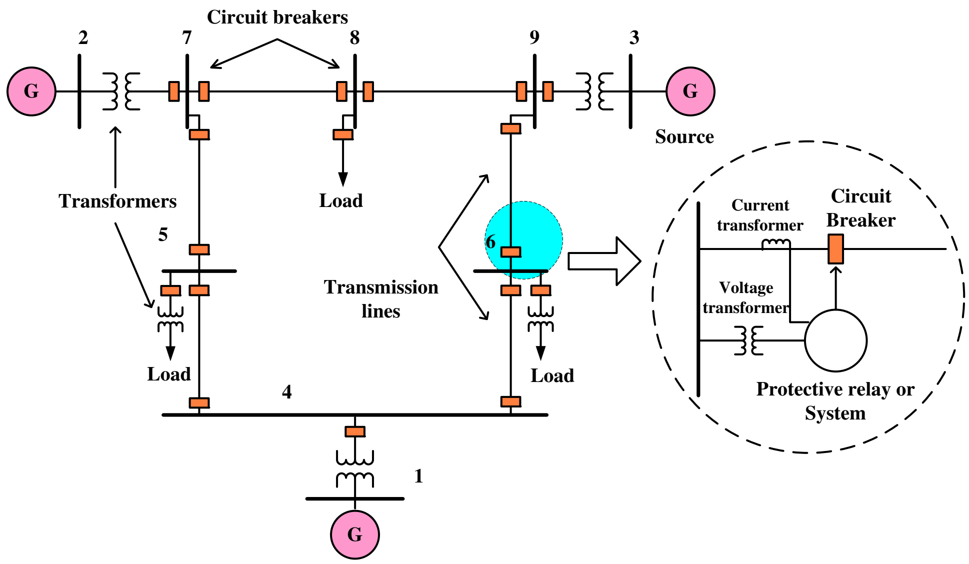


Fig. 1. Example of a power system

out usually has a cascading process which can last from a few seconds to even a few hours. No two blackouts appear identical according to the historical records [2]. But there is a common cascading process for different blackouts, which can be described as follows [3, 4]:

- System state before the blackout: Before the blackout, system parameters usually remain within their normal operating reliability ranges. At the same time, some noticeable deviations that could potentially weaken the systems, such as high electricity demands, heavy power flows, depressed voltages, and frequency variations, etc, could be observed. Some scheduled maintenances on the nearby generators and/or transmission facilities may also happen before the blackouts.

- Contingency conditions: Before the blackouts, the system may be additionally weakened by unscheduled outages, such as several transmission line, transformer and generator outages due to the faults. Those conditions lead the system to a more stressful stage.

- Initiating events: At a certain point of the blackout development, a triggering event happened. Triggering event is the point separating a period where multiple contributing but not direct factors for final blackout are accumulated, from the direct sequence of events with clear cause/effect relationships.

- Steady state progression with slow succession: The triggering event as well as the subsequent events in a blackout scenario may cause power flow surges, overloads, or voltage problems. The protection system may remove the equipment or a group of equipment from the rest of network if it detects the low voltage and high current even though there may be no faults. Some load loss may accompany this process. This can result in more power flow surges, overloads, and voltage problems, and so on. In this initial stage, the cascading process can be relatively slow.

- Transient state progression with fast succession: In this stage, the system begins to lose major parts which results in bigger power swing, overload or low voltage. The components begin to trip one by one in a very short time. Uncontrollable system separation, angle instability, and voltage collapse may occur. As a result, a significant load loss may be inflicted. Final large-scale blackout is reached in a very short period.

From the above description, one can see that the cascading blackout is a result of accumulation of a chain of contingencies and system reactions. Protective relay misoperation or unintended operation is believed to be one of the contributing factors in 70 percent of the major disturbances in North America [5]. This cause can be identified in any stage of the blackout process mentioned above. Relay misoperations or unintended operations due to overload, power swing, and relay hidden failure are the main factors contributing to the blackouts. Most of the problems are associated with relays tripping too many healthy lines. Since a relay makes the decision automatically to remove a component from the system according to its internal mechanism, the relay misoperation or unintended operation can make an effective influence on the system stability.

The associated problem with relay misoperation or unintended operation is the inadequate real time diagnostic support for verifying the correctness of relay operation. In the existing practice, the relay operation is evaluated offline to investigate a specific event and prevent future relay misbehavior. When the system operates close to its limits, every single relay operation after N-1 contingency could cause a chain of unfolding events eventually. For present power system, there are no real time monitoring tools available to verify if the relay has responded to the disturbances correctly. The system operator can only monitor an outcome of the relay decision no matter whether it is correct or not. The system operator is not able to influence the relay operation online in order to avoid system disturbances unfolding into cascading events.

As mentioned, most of the cascading blackouts have a slow pace during the initial stage, and may evolve or cascade quickly when the time elapses without effective mitigating schemes. A real time relay monitoring tool can help correct relay misoperation or unintended operation and mitigate the blackout at the initiating stage. Those kinds of schemes are not readily available today.

2. Transmission Line Protection

The protective relay system, which is shown in the zoomed area in Fig. 1, is the most important component in the power system to preserve the reliability of system operation. It detects the faults using its fault diagnosis mechanism and removes the faulted component by its associated circuit breaker action in a short time to avoid damage of the system equipment. The protection system for transmission lines is very important since the transmission lines are mostly extended across large geographic area to carry the power from sources to loads. They can easily experience a fault due to the lightning that causes loss of insulation.

The performance of protection system is measured by several criteria including reliability, selectivity, speed of operation, etc. [6, 7]. Reliability has two aspects: dependability and security [8]. Dependability is defined as "*the degree of certainty that a relay system will operate correctly when there is a fault on the system*". Security "*relates to the degree of certainty that a relay or relay system will not operate incorrectly when there is no fault on the system*" [7]. For a weakened system that already lost several components, loss of reliability due to the relay misbehavior will have a large impact on the system that may contribute to the cascading blackout. There are two kinds of relay unintended operations:

- Relay fails to operate. This situation is relative rare. But it is very harmful to the system stability when it happens. Even though the fault is cleared by the backup relays in a delayed time, there are healthy components removed from the system. This can result in more power flow surges, overloads, and voltage problems for a weakened system.

- Relay operates in an non-fault situation. This situation is more common in most of blackouts involving distance relay unintended operations. For example, the relays may observe a low voltage and a high current, at the time during the overload, power swing or low voltage. Trip of the healthy components will also result in more power flow surges, overloads, and voltage problems for a weakened system. The event may unfold and spread out.

Each transmission line protective relay has its own designated area known as primary zone, and usually it still has the opportunity to operate in overreached zones to provide backup protection for an adjacent transmission line section. To ensure the selectivity of transmission line protection systems, the relays need to be coordinated with the backup relays to operate only when the primary relay fails to clear the fault. Hence, selectivity is important to assure maximum service continuity and minimum system disconnection. The speed of operation indicates how fast the relay can isolate a faulted area. Usually for transmission line protection, the high-speed relay is one that operates in less than 20 ms. Not in all situations the very high-speed operation is preferred. The relay must have the ability to differentiate fault and other tolerable transients very well before issuing high-speed operation.

The most commonly used scheme for transmission line protection is the distance relay. The basic principle is shown in Fig. 2. The voltage and current measured through voltage transformer (VT or PT) and current transformer (CT) are the inputs for protective relays. The distance relay algorithm is trying to extract the fundamental

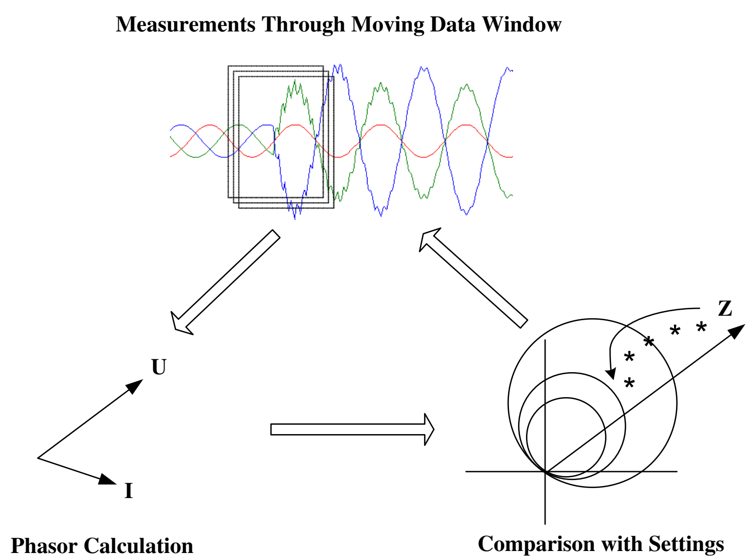


Fig. 2. Basic principle of distance relay

frequency phasor of voltage and current signals. Then through the calculation of certain nonlinear ratio of voltage and current phasors, the apparent impedance seen by the relay is obtained and compared to the preset thresholds. If the impedance falls into the protected zones, the relay will assume a fault occurred and will send a trip signal to the circuit breaker on the transmission line to disconnect the faulted line. Once triggered, the impedance calculation is continuously iterated using the moving data window. The relay algorithm is fixed by design. When the relay is installed in the system, the most important task is to determine the thresholds (settings). The settings are obtained by comprehensive short-circuit system studies in a predefined system operating condition. To ensure the protection system maintains dependability when protecting the equipment as fast as possible, a backup scheme is provided for each relay.

The distance relay principle is straightforward and usually performs reliably. That is the reason why this principle is still dominantly used in the industry, although the relay hardware has advanced through the technologies of electromechanical, solid state, and microprocessor. However, there are still some inherent problems associated with the distance relay principle:

- The transient signal during the fault is a non-stationary signal containing fundamental frequency component, DC offset with damping, harmonics, etc. When extracting the fundamental frequency component from the faulted signal, algorithms can only obtain an approximate value since the information from unused components is lost. In some extreme situations, this may result in an inaccurate representation of the faulted signal and may cause the false judgment in relays [9]. Since an approximation of steady state phasors of voltage and current are used for distance relay algorithm, other non-fault situations that can cause low voltage and high current, such as under-voltage, overload, and power swing may cause relay to misbehave. The speed of operation of distance relay is also limited by its principle since it will take some time for calculated impedance to move from pre-fault load area to a stable fault area.

- The calculation of relay settings is very important. It is usually done using certain fault parameters for a worst case system operating condition. The compromise is made to cover worst case fault and system operating conditions for N-1 contingency. When the fault condition and system condition significantly deviate from the expected ones, which may be the case for N-M contingency, the relay settings may be inadequate causing the relay to misbehave. For a large system, the calculation of settings is very complex and tedious. Correct coordination needs to be made for the settings to ensure the selectivity of each relay in the system.

- The dependability and security are conflicting criteria for distance relay. There is no perfect means to guarantee the dependability and security at the same time. The trade-off is made when setting the relays to ensure a certain level of balance of the two criteria. In the regulated power system before, dependability was of most concern since the primary task of protective relay is protecting the expensive power system equipment at all costs. Security issue was not so critical because overtripping would not cause major problems due to the redundancy of the transmission system. Falsely removing some non-faulted lines may have not interrupted many customers or even cause the catastrophic system blackouts since there was enough system redundancy at that time. After the utility industry was deregulated, the increase of power generation and power grid did not match the increase of the power demand. This caused power grid to be more stressed and there are more opportunities to operate the system closer to its transmission limit. The importance of the protective relay security has become an issue. Falsely removing non-faulted lines in the system may cause a serious problem such as triggering a cascading blackout.

As a summary for the problem statement section, the following issues are the major concern of this dissertation:

- Relay misoperation or unintended operation is one of the major contributing factors for power system cascading blackout. Approaches to reduce the relay misbehavior need to be identified .
- Real time monitoring tools to assess the relay misbehavior are needed, providing the system operator accurate information about unfolding events.
- Existing transmission line protection scheme still has drawbacks. Advanced fault analysis mechanism to enhance the system dependability and security simultaneously are desirable.

B. Existing Solutions

1. Schemes to Prevent and Mitigate Cascading Blackouts

As mentioned, cascading blackout is a result of a chain of accumulated contingencies and system reactions. The complete prevention of the power system blackout is almost impossible due to the uncertainty in system operation pattern, weather, human factors, etc. However, one can expect to mitigate the unfolding event against developing into a large area blackout by some carefully designed defensive strategies. Among those strategies, the analysis and monitoring tool for relay system operation is the first step since the relay misbehavior may be a very important factor contributing to the blackout. Some useful solutions are proposed in the literature [5, 10–16]. The relation between the relay hidden failure and power system disturbances is analyzed in [5], where the author developed a way to calculate the vulnerability index of each relay in the system to indicate which group of relays is most likely to cause a problem if and when the hidden failure exists. That provides the information which relay in the system should be careful monitored. The line protection schemes and their relation to voltage stability and transient stability is analyzed in [10], where the author provides an improvement of Zone 3 distance protection scheme to enhance the security of the protection relay operation. In [11], a wide area back-up protection expert system to prevent cascading outages is proposed. The scheme tries to precisely locate the faulted area and avoid unnecessary trip due to the hidden failure or overload. Adaptive protection schemes are introduced to coordinate the relay operations and settings with the prevailing system operating conditions [12–14]. System protection schemes proposing the idea of coordinated protection and control means to minimize the impact of a disturbance are discussed in [15, 16].

2. Improvements over Traditional Relay Principles

The new protection schemes that are better than traditional transmission line protection principles are very extensively studied in the literature. After the digital relay is introduced, the relay principle can be realized using more flexible software means [17–20]. New fault diagnosis principles for transmission line relay are proposed. The traveling waves based relay schemes, adaptive relay schemes, neural network based relay schemes, and transients based relay schemes are developed as new directions for transmission line protection [12–14, 21–40].

The traveling wave based protection for transmission line, which can be used for fast fault detection, was introduced in the late 1970s [21–27]. When the fault occurs on the transmission line, the traveling waves are generated from the faulted point and start moving towards both ends of the transmission line. The traveling wave based protection schemes are formed based on detection of the traveling wave at line ends. These relays have the advantage of: a) fast response, b) directionality, c) not being affected by power swing and CT saturation. However, the characteristics of existing widely-used instrument transformers are inadequate yet to support this type of protection scheme.

The concept of adaptive protection was introduced during the 1980s [12–14]. The concept of adaptive relaying is to make an assessment of the state of the power system first, and then automatically make adjustment to protection systems so that their settings are suitable for the prevailing conditions. The application areas of adaptive relaying could be distance protection and autoreclosing. The advantages of adaptive relaying are: improved system responses, increased reliability and reduced costs. However, the basic principles of the various existing relays cannot been easily changed to encompass the adaptive techniques.

The application of artificial intelligent techniques in protection attracted researchers since 1990s [28–33]. As an example, neural networks can be used for different applications in transmission line protection including fault detection, fault location, distance and direction detection, autoreclosing, etc. The neural networks based protection scheme arranges the voltage and current signal samples as a pattern. The fault detection issues then become the pattern recognition issues. The advantage of neural network based protection scheme is its “intelligence” to find the internal similarity of different types of disturbances. The decision is made by measuring the similarity between the unknown patterns and the trained prototypes instead of comparing the characteristics of unknown patterns to the fixed relay settings. The disadvantage is that one must train the network with a large data set, and one must select enough relevant training scenarios.

In recent years, the concept of the "Transient Based Protection" is introduced by using fault generated high frequency transients to develop new relaying principles [34–40]. The technique detects high frequency transient signals through specially designed transducers and algorithms, thereby, overcoming the bandwidth limitation of conventional transducers. There are a few applications using the fault generated transient signals in transmission line protections developed so far. Although it is still not proven that this kind of method is reliable when high frequency disturbance in the signal is introduced, it is very attractive to explore significant improvement in terms of speed and new protection principle.

Although new protection schemes have been studied for a while, the conventional transmission line relays are still widely used in practice today. At the theoretical level, the new relay principles must be superior to the traditional relays in order to be used as a substitute. At the practical level, the design of the new relay principles considers the state-of-art computer and signal processing technology. As the digital relays are more widely used, the new relay principles are expected to be applied in the future. Although a lot of new techniques proposed in previous literature can provide an overall enhancement over the traditional relay, it is still hard to find a perfect match due to the algorithm or hardware limits. A combination of different techniques might be a better solution to achieve a high performance and simplify the real time decision making.

The existing proposals and solutions for preventing cascading blackout do not propose new relay principles. Most of the schemes depend on the improvement of distance relay principles. To solve the problems in preventing cascading blackouts, one can suggest some new protection schemes to be installed in the monitoring mode as the operation verification tool for existing distance relays. The improved fault analysis and event analysis results can be communicated between the centralized system and local substation to seek a better solution to reduce the impact of that event. Currently, this kind of online application has not been implemented or even proposed. Most of fault analysis is implemented offline, which does not allow understanding the disturbances in real time.

C. Research Issues

This dissertation has the following major objectives: a) Investigate new transmission line fault diagnosis approaches using advanced technologies, b)Integrate the transmission line fault analysis tool with the traditional relays to improve the overall performance of transmission line protection system, c) Apply those techniques in preventing and mitigating cascading blackouts, d) Propose a relay monitoring tool at substation level as a local diagnostic support, e)Provide the solution that coordinates the system and local actions to prevent blackouts.

The dissertation will focus on the new techniques that are basically different from the traditional distance relay schemes. Since most of the new principles such as traveling wave, neural network, and transient based protections have their shortcomings, a different solution for dealing with the application issues must be studied when developing new techniques. A more suitable solution may be obtained by combining two or more new techniques. Previous studies show a promising benefit using neural network and synchronized sampling [41–43]. Those two techniques both use the time-domain samples as input, without requiring the phasor and relay setting computation as required for the traditional relays. In this dissertation, the fault diagnosis approaches for transmission line protection based on those two techniques are further studied, improved, and carefully evaluated to make sure they are more feasible for online use.

How to apply the new technologies in a systematic strategy to monitor relay operations and prevent cascading blackout is another focus of this dissertation. As mentioned earlier, the existing relay monitoring tool mostly depends on improvement of distance relay design. If a more accurate diagnosis result is available from new algorithms, one can refer to this result as a reference when verifying the correctness of relay operations. A straightforward monitoring tool can help the system operator to take the corrective activities in a short time. This kind of tool will be designed in this dissertation.

D. Research Approach

A breakdown of research approach in this dissertation is as follows:

- Investigate the relationship between distance relay operation and transient stability limits. The background of distance relay and its behavior during the disturbances are explored and demonstrated. A much clearer picture of the role of relay misbehavior contributing to the cascading blackouts will be drawn.

- Develop improved fault diagnosis techniques using neural network and synchronized sampling [44–48]. This study utilizes several enhancements of the prototype algorithms developed earlier.

- For the neural network based algorithm, improve the overall performance effectively when applied to a large set of random scenarios in the power system [44,47]. The method of selecting the scenarios, coordinating different neural networks and optimizing the input and output is discussed and proposed.

- Develop a new method to use the fault generated high frequency component as extracted feature to achieve advanced transmission line boundary protection [48]. That is an extension of the neural network based fault diagnosis approach.

- For synchronized sampling based algorithm, improve the previous algorithm by using it for purposes beyond just fault location [45–47]. An extended fault diagnosis scheme based on synchronized sampling is proposed and the optimization of original algorithm in term of speed and accuracy is discussed.

- In order to benefit from the advantages of both neural network and synchronized sampling, combine the two techniques as a real time fault analysis tool to be used as a reference for analyzing the traditional transmission line relay performance [47]. The possible application, hardware configuration and software implementation are described in detail.

- Design an event analysis tool using event tree analysis (ETA) for monitoring the relay operations, providing the system operator accurate information about disturbance/response from the local substation level [49]. This dissertation demonstrates the effective way to build a set of typical event trees for a relaying system and use them in online relay monitoring.

- Propose an interactive mitigation scheme to combine local and system-wide actions to prevent cascading blackout [50–52]. This dissertation suggests the way of using interactive schemes between the system-wide and local monitoring and control actions.

- Develop a comprehensive modeling, simulation and evaluation tool for assessing new fault diagnosis algorithm [53] and implement comparative studies of developed algorithms. This dissertation implements a comprehensive modeling and simulation tool using MATLAB [54] and Alternative Transients Program

(ATP) [55]. The assessment of the performance of the proposed fault diagnosis algorithms will be reported at the end.

E. Dissertation Outline

The dissertation is organized as follows. Problems with existing transmission line protection are outlined in Chapter II. Chapter III describes the fault diagnosis techniques using a specially designed fuzzy ART neural network algorithm. A new technique using neural network and wavelet transform for transmission line boundary protection is introduced in Chapter IV. Chapter V describes a complete fault diagnosis technique using a synchronized sampling based algorithm. An integrated real time fault analysis tool that combines neural network and synchronized sampling techniques is described in Chapter VI. A real time relay monitoring tool using event tree analysis method for monitoring transmission line protection system is introduced in Chapter VII. Chapter VIII demonstrates the interactive schemes for the system/local analysis to prevent and mitigate cascading blackouts. A comprehensive simulation tool using MATLAB and ATP is described in Chapter IX as a new simulation environment for design and evaluation of fault diagnosis algorithms. The simulation steps and results are shown and discussed in Chapter X. Conclusions are given in Chapter XI. References and Appendices are attached at the end.

CHAPTER II

PROBLEMS WITH TRANSMISSION LINE RELAYING

A. Introduction

The problems to be solved in this dissertation are presented briefly in the previous chapter. This chapter explores the existing transmission line relaying techniques and explains in detail the drawbacks in those principles and why they may contribute to the cascading blackouts. In Section B, the category and history of transmission line relays are reviewed. Section C demonstrates the basic principles of the commonly used distance relay for transmission line protection. The drawbacks behind the principles are exposed. The system transient stability and power swing are briefly explored in Section D and E respectively, where we can understand how relay performance is related to those issues. An overview of cascading blackouts and the role of relay misbehavior in the blackouts are given in the Section F. The problems with traditional relaying are summarized in Section G.

B. Types of Transmission Line Relays

In general, the transmission line faults are associated with increased currents and decreased voltages. Other changes of the AC quantities in one of the following parameters may also occur: phase angles of current and voltage phasors, harmonic components, active and reactive power, frequency of the power system, etc [6]. Those parameters can be the inputs of the relays to detect the faults. The operating principles of the relays in use on transmission lines, may be classified as follows [6, 56]:

- Magnitude Relays: These relays are based on the comparison of the magnitude of one or more operating quantities to the threshold. For example, the overcurrent relay responds to the changes in the magnitude of the input current. The load-shedding relay responds to the changes of the system frequency.

- Directional Relays: These relays are based on the comparison of the phase angle between two AC inputs. The comparison can be based on current phasor and voltage phasor, and also on current phasor and another current phasor.

- Ratio Relays: These relays are based on the comparison of the ratio of two phasors to the thresholds. The ratio of two phasors are complex number, therefore the threshold should be set in a complex plane. A typical example of a ratio relay is the distance relay.

- Differential Relays: These relays are based on the algebraic sum of two or more inputs. In a general form, those inputs may be the currents entering (or leaving) a specific protection zone. According to the Kirchhoff's law, the algebraic sum should be close to zero when there is no internal fault and should be a big value when there is an internal fault.

- Pilot Relays: These relays are based on the communicated information obtained from the two ends of a transmission line. The decisions made by a local relay and by a remote end relay are combined to form the final decisions. The inside principle of each relay could be any of the four types described above.

When applied to the transmission line protection, the above principles can be further classified into two broad categories: a) non-unit protection scheme and b) unit protection scheme. The non-unit protection scheme uses data from one end of a transmission line while the unit protection scheme usually uses data from two or more ends. For non-unit schemes such as overcurrent relay and distance relay, they can not protect very accurately the entire length of the primary line because they can not differentiate the internal faults from external faults occurring around the line boundaries due to the imperfections caused by measuring errors, transformation errors, the inaccuracy of the line impedance, source and load changes, different fault parameters, etc. Backup protection needs to be introduced as a trade-off for protecting the entire length of the transmission line. Unit protection schemes such as differential relays and pilot relays can protect the entire length of the transmission line. They require a communication link to transmit the blocking or transfer tripping signals. Therefore, the reliability of the unit protection scheme highly depends on the reliability of the communication link. The cost of the communication link also needs to be taken into account.

The primary goal of transmission line protection, whatever the principle it uses, is to rapidly and precisely detect the fault and disconnect the faulted area. If possible, it should also differentiate the internal faults from external faults so that only the faulted line is removed; provide the exact fault type selection so that advanced tripping and reclosing schemes (single-pole tripping and reclosing) can be applied; locate the precise fault position on the transmission line so that the line can be repaired and restored quickly.

The earliest relay designs were electromechanical devices using plungers, balanced-beams, induction discs or cups, etc [6]. Those relays are robust but require a fairly high amount of energy to operate. Solid-state relays appeared in late 1950s. Those relays were based on electronic components such as diodes, transistors and operational amplifiers, offering a better flexibility than the electromechanical relays. Both electromechanical relays and solid-state relays are still in use today. Microprocessor based relay (or digital relay) was introduced in 1980s and has been developed extensively in the following years until today [56–58]. Compared to the electromechanical relays and solid-state relays, the size of a digital relay is very compact, and the cost is reduced. The unique benefits can be found in digital relays with their reliability and functional flexibility. It can also provide an easy way to implement adaptive relaying, system integration and digital substation automation environment.

In a digital relay, the voltage and current signals from the power system are sampled and converted to digital form by the Analog-to-Digital Converter (ADC). The data is then processed by the relaying algorithm to produce a digital output. A great many algorithms have been developed typically including sinusoidal-wave-based algorithms, Fourier analysis and Walsh function based techniques, least squares based methods, differential equation based techniques, etc. All of the algorithms try to extract the useful AC quantities to implement the different relay principles mentioned above. The details of each relay algorithms, which are out of scope in this dissertation, can be found in [56, 57] .

C. Distance Relay

Distance relay is the most common type of protection for multiterminal transmission lines [6, 58, 59]. As implied by its name, it calculates the impedance between the relay location and the fault location. The impedance is calculated through the measured voltage and current signals at the relay location. If the measured fault impedance is smaller than the line impedance, the relay will assume that an internal fault has occurred on the transmission line. Since the impedance per mile of a transmission line is a relatively constant parameter, the distance relay hence responds to the computed impedance that corresponds to the distance between the relay location and the fault location.

1. Relay Coordination Scheme

Due to the imperfections in the distance relay measurement caused by measuring errors, transformation errors, the inaccuracy of the line impedance, source and load changes, different fault parameters, etc, the distance relay may not be able to always protect the entire line length using only one end of measured data. A coordinated protection scheme using distance relays is applied today. As shown in Fig. 3, the scheme is described for the relay at position "1" (relay 1). For relay 1, the security margin of 10-15% should be selected from the remote end (Bus B) to be absolutely sure that the relay 1 will not overreach to the next line in some situations. Hence the first zone (Zone 1) of relay 1 is set to reach 85-90% of the line length A-B. If fault is found within Zone 1 of the distance relay, the trip signal will be sent to the circuit breaker instantaneously or with a very small time delay t_1. The rest of the line A-B will be covered by an overreaching zone (Zone 2). The reach of the second zone is usually set at 120-150% of the line length A-B. If the adjacent line B-C has a quite different impedance characteristics, Zone 2 can be also set as the line length of A-B plus 20-50% of the line length B-C [58]. A timer t_2, usually 0.3-0.5 seconds, should

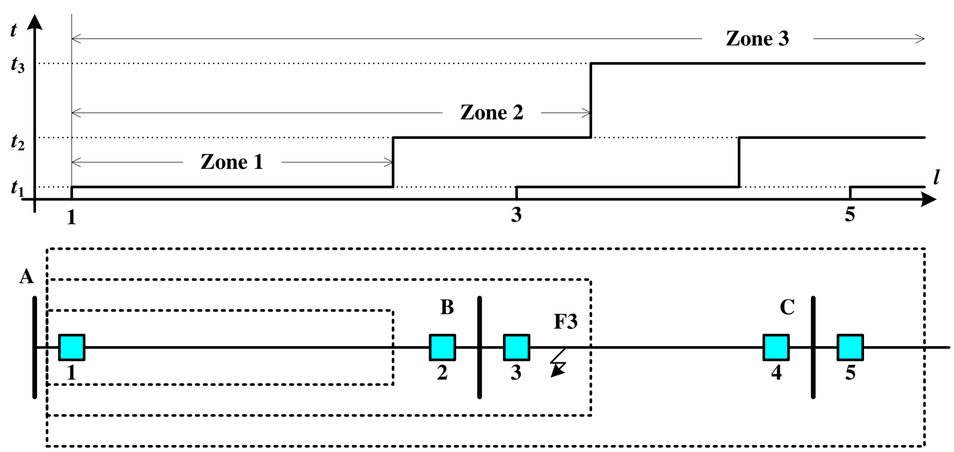


Fig. 3. Relay coordination scheme

be set for Zone 2 to ensure that relay 1 is delayed to allow relay 3 to trip the fault at F3. Relay 1 must provide enough time for relay 3 to respond the fault in its Zone 1 before relay 1 sends the trip signal. The Zone 2 of relay 1 will also provide a backup function for the relay 3 since it overreaches to the line B-C. However, it is only true for part of the line B-C because Zone 2 of relay 1 can not reach beyond Zone 1 of relay 3 to ensure the similar selectivity mentioned above. Another zone (Zone 3) is used to provide the backup function for the entire line length of line B-C. Zone 3 of relay 1 is usually extended to the 250% of the line length of line A-B and the timer t_3 for its delayed action is set for a delay in the order of 1 second.

Similarly, the step distance settings for other relays in the system will follow the same principle. It should be noted that in this example only the typical system configuration is considered. In reality, the settings must be calculated and coordinated by a comprehensive short circuit study for more complicated network structures [58]. Such a tedious work may result in incorrect settings due to the human error or improper settings due to lack of consideration of unusual system operating conditions. The relay settings may play a significant role in different stages of cascading blackouts [1, 2].

2. R-X Diagram

Since the distance relay respond to the impedance measurements, it is common to use an R-X diagram to analyze and demonstrate the behavior of the distance relay. Consider an R-X diagram matching an ideal simple system shown in Fig. 4. The origin of the R-X plane is the relay location. The axis R corresponds to the real part of the impedance Z, while the axis X corresponds to the imaginary part of the impedance Z. The apparent impedance at the relay location is calculated by the

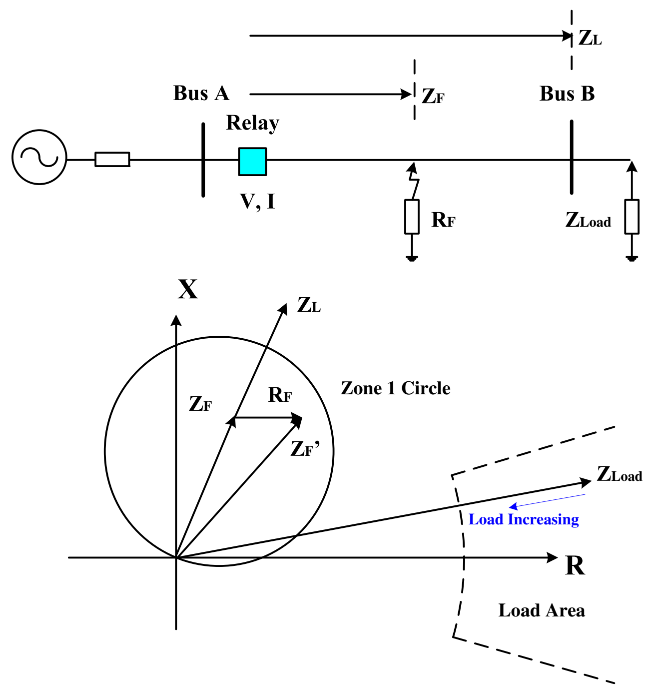


Fig. 4. R-X diagram

quotient of the measured secondary voltage and current phasors.

$$Z_a = \frac{V_s}{I_s} \tag{2.1}$$

During the normal condition, the measured apparent impedance is close to the load impedance since $Z_L \ll Z_{Load}$. The load area shown in Fig. 4 is far from the relay settings. When fault occurs, the apparent impedance seen by relay will change to $Z_f' = Z_f + R_f$, where Z_f is the line impedance from the relay location to the fault location and R_f is the fault resistance. Since $R_f \ll Z_{Load}$, the line section behind the fault location as well as the load impedance can be neglected according to the circuit theory. As shown in Fig. 2 in last chapter, the impedance during the fault will flow into the relay setting area. Due to the transient phenomenon during the fault, the impedance will not jump instantaneously from Z_{Load} to Z_f'. In R-X plane, it will move step by step to Z_f' until the transient is gone after about one cycle. From the

R-X diagram, it is not difficult to conclude that the performance of the distance relay will depend on the fault resistance. The fault resistance is a random value that may be influenced by the electrical arc between two phases of the transmission lines or between one phase and a grounded object. The magnitude varies with respect to the fault type, fault location, and fault inception time. Besides the fault resistance, the pre-fault load condition will also play a role for the distance relay performance. If the load is too high, it may float to the relay setting area, especially for the backup settings in Zone 2 and Zone 3. In that case, the relay may operate in the overload situation thinking that it is a real fault. When some of the healthy lines are removed from the system, the power flows in those lines are re-dispatched to the other lines. Similar overload situations will cause more healthy lines being tripped by the relays and unfolding cascades may start.

3. Three-phase Distance Relay

The previous illustration is based on a single phase system. On a three-phase power system, the apparent impedance can not be calculated using (2.1) directly. There are 11 different fault types in three-phase systems, which are single-phase-to-ground faults (A-G, B-G, C-G), phase-to-phase faults (A-B, B-C, C-A), phase-to-phase-to-ground faults (A-B-G, B-C-G, C-A-G), three-phase fault (ABC) and three-phase-to-ground fault (ABC-G) [6]. For different fault type, a symmetrical component analysis may be used to obtain the relationship between voltages and currents measured at the relay location [59, 60]. It is known that regardless of the fault type, distance relay is able to measure the positive sequence impedance from relay location and fault location in a three phase system [6]. Therefore, the relay settings can be calculated based on the total positive sequence impedance of the transmission line regardless of the fault type.

Consider the system shown in Fig. 4 is a three-phase system and the fault is a B-C fault. The symmetrical network connection for this fault is shown in Fig. 5, where the subscript "1" corresponds to positive network components and subscript "2" corresponds to negative network components. We can observe that

$$V_{1F} = V_{2F} = V_1 - Z_{1F} I_1 = V_2 - Z_{2F} I_2 \tag{2.2}$$

Since $Z_{1F} = Z_{2F}$ for a transmission line, we can further get

$$\frac{V_1 - V_2}{I_1 - I_2} = Z_{1F} \tag{2.3}$$

The relationship between phase value and sequence value can be expressed as:

$$a = e^{j\frac{2\pi}{3}} \tag{2.4}$$

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} \tag{2.5}$$

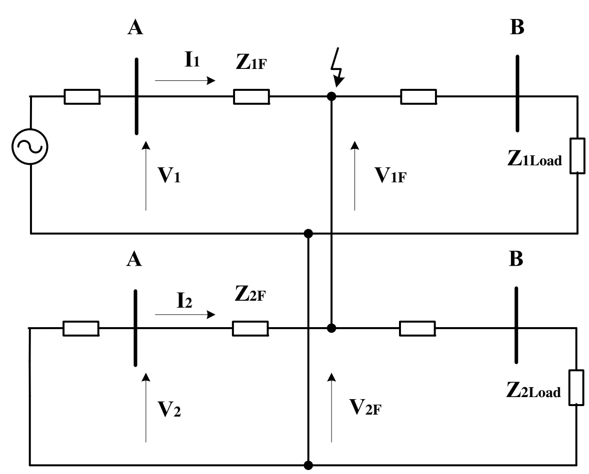


Fig. 5. Symmetrical network connection for B-C fault

Subtract the third row from the second row, we have

$$V_b - V_c = (a^2 - a)(V_1 - V_2) \tag{2.6}$$

Similarly, we can also get

$$I_b - I_c = (a^2 - a)(I_1 - I_2) \tag{2.7}$$

Substituting (2.6) and (2.7) in (2.3), we get

$$\frac{V_b - V_c}{I_b - I_c} = \frac{V_1 - V_2}{I_1 - I_2} = Z_{1F} \tag{2.8}$$

It relates the phasor measurements at relay location to the positive impedance measured from relay location to the fault location. For other fault types, we can also use different symmetrical component networks to get the voltage and current used to calculate the positive impedance. The result is shown in Table I, where it can be seen that in order to detect a three-phase fault, a pair of voltage and current may be used for phase fault detection or for ground fault detection since they are required to calculate the exact positive impedance in a three-phase fault. For traditional electromechanical relays and solid-state relays, we need six elements to respond to all eleven fault types. In a digital relay, the different voltage and current pairs shown in Table I can be organized by the relay software as long as the three-phase voltage and

Table I. The voltages and currents used to calculate apparent impedance for each fault type

	AB/ABG	**BC/BCG**	**CA/CAG**	**AG**	**BG**	**CG**	**ABC/ABCG**
V	$V_a - V_b$	$V_b - V_c$	$V_c - V_a$	V_a	V_b	V_c	Any of the six V on the left
I	$I_a - I_b$	$I_b - I_c$	$I_c - I_a$	$I_a + k_0 I_0$	$I_b + k_0 I_0$	$I_c + k_0 I_0$	Corresponding I

$*k_0 = \frac{Z_0 - Z_1}{Z_1}$

current inputs are available.

4. Specific Applications

The above introduction of distance relay principles are based on the very simple system configuration. In real practice, the distance relay need to be tuned to face specific system configurations [61, 62]. Four typical system configurations are shown in Fig. 6. For parallel lines that are on the same tower or share the same right-of-way, the mutual coupling between these lines must be taken into account for the relay schemes. For the multi-terminal lines, the infeed current from the tapped terminal plays a role in the fault detection. For a weak electrical system in which the source impedance is high, one should notice relative low values of fault current and relatively flat voltage profile along the line seen by the relay. For the series compensated line in which the the series reactor or series capacitor is installed, the relay scheme must take into account the change of the line impedance due to the on/off switching of the compensation devices.

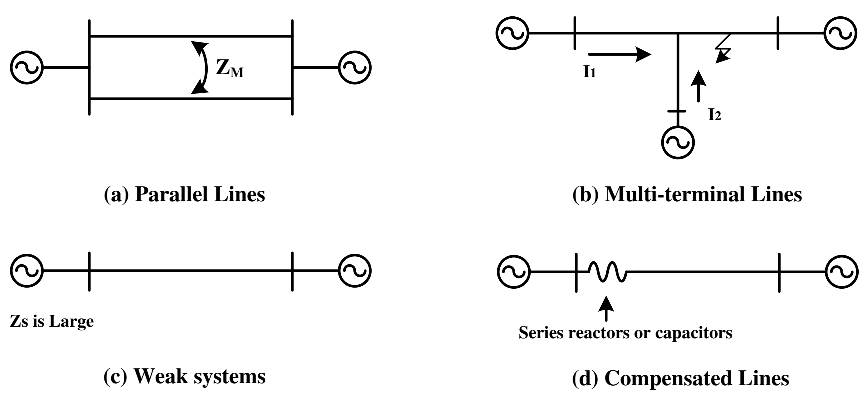


Fig. 6. Specific system configurations for distance relay application

D. Transient Stability

The real power system is a dynamic system and the normal operation condition may be altered by certain disturbances caused by faults, load rejection, line switching, and loss of excitation. Transient stability is defined as the ability of the power system to maintain synchronism when subjected to those disturbances [63, 64]. The protection system performance plays an important role to maintain the system transient stability after the fault.

The basic idea of transient stability can be demonstrated using a simple two-machine system shown in Fig. 7. For this system, if we neglect the resistance of the line, the active power P_e transferred between two generators can be expressed as,

$$P_e = \frac{E_S \cdot E_R}{X} \cdot sin\delta \tag{2.9}$$

where δ is the angle difference between the two generators and $X = X_S + X_L + X_R$.

If the E_S, E_R and X is fixed, the relationship between P_e and δ can be described using the power angle curve shown in Fig. 8, where the two power angle curves correspond to the normal state and the fault situation respectively.

The differential equation to model the motion of the generator rotor angle is known as the swing equation [63, 64]:

$$\frac{2H}{\omega_0}\frac{d^2\delta}{dt} = P_m - P_e \tag{2.10}$$

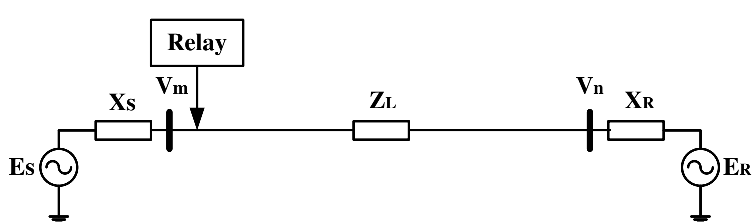


Fig. 7. A two-machine system

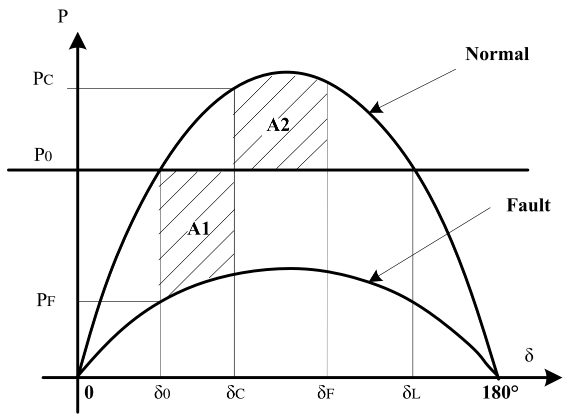


Fig. 8. The power angle curve

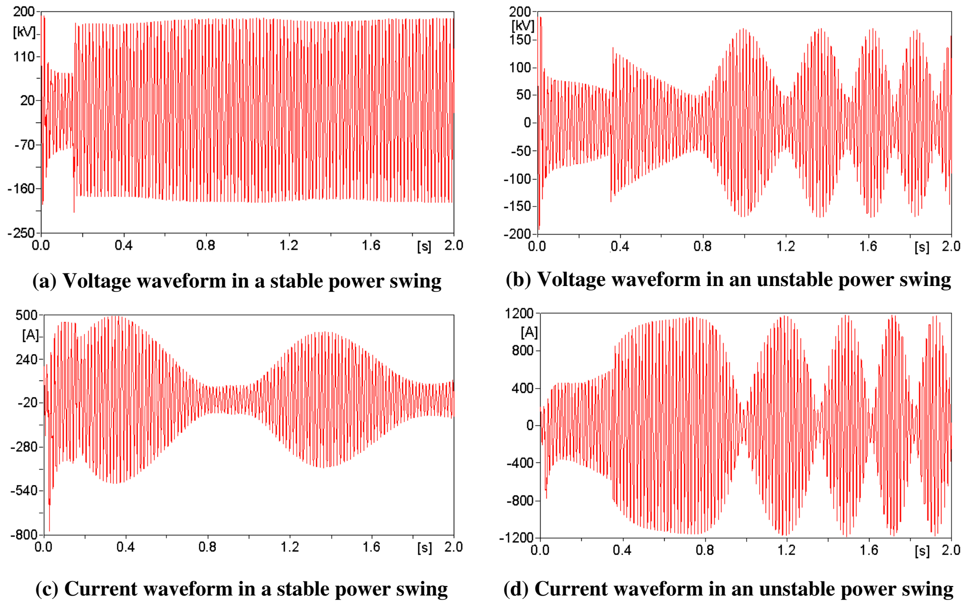
where P_m is the mechanical power input of the generator and H is the inertia constant.

As shown in Fig. 8, during the normal state, $P_m = P_e = P_0$. The generator rotor runs at a constant speed and the rotor angle difference between the generators is constant, as δ_0. When a fault occurs, the power transmission P_e is dropped to the P_F from P_0. At the same time, the mechanical power P_m of generator can not be changed at once to match the change of P_e, resulting in the rotor acceleration and δ increasing. When the fault is cleared at the time δ reaches δ_C, the power transmission P_e returns to the P_C, which is larger than mechanical power $P_m = P_0$. That causes the rotor to decelerate and δ reaches δ_F due to the inertia of the rotor system. At δ_F, the deceleration area $A2$ is equal to the acceleration area $A1$. This is known as the equal-area criterion [63, 64]. If δ_F is smaller than δ_L, δ can eventually go back to the original balance point δ_0 with sufficient damping. The system is transient stable in this case. If area $A1$ is still larger than $A2$ at the time δ reaches to δ_L, the rotor will accelerate again beyond recovery since $P_e < P_m$. The system is transient unstable and may cause big problem such as cascading blackouts. It is seen that the fault clearing time by the protection system will directly relate to the area of $A1$ and $A2$. The faster the fault is cleared, the more stable the system. Consider a large system, any disturbance such as fault, load rejection, line switching, loss of excitation, etc will cause similar behavior of each system generator as demonstrated above, resulting in the oscillation of system bus voltages and angles. That will in turn have an impact on the relay operations, which will be explained in the next section.

There are several ways to enhance system transient stability, such as high-speed fault clearing, reduction of transmission system reactance, single-pole switching, generator tripping, controlled system separation and load shedding, etc [64]. It is obvious that the fast and accurate response of transmission line protection system, which can precisely recognize the disturbances and take correct actions, is the first and most important requirement. With the informed situation about the disturbance delivered to the system control center, the system-side contingency study can be activated effectively hence the system-wide corrective control can be selected earlier to minimize the impact of the disturbances.

E. Power Swing

The associated phenomenon with the transient stability issue is power swing, which is defined as "*a variation in three phase power flow which occurs when the generator rotor angles are advancing or retarding to each other in response to changes in load magnitude and direction, line switching, loss of generation, faults and other system disturbances.* [65]" The power swing is stable if the generator does not experience pole slipping and unstable (out-of-step) if one or a group of generators experience pole slipping. A simulation example of power swing observed at relay location is shown in Fig. 9.



(a) Voltage waveform in a stable power swing
(b) Voltage waveform in an unstable power swing
(c) Current waveform in a stable power swing
(d) Current waveform in an unstable power swing

Fig. 9. A simulation example of power swing observed at relay location

Distance relay for transmission line protection is designed to isolate faults occurring within the desired zone only. It is not supposed to trip the line during the power swing caused by the disturbances outside the protected zones. Even for the out-of-step conditions, the preferred operation is to separate the system with an out-of-step tripping (OST) protection at pre-selected network locations and blocking other distance relays by out-of-step blocking (OSB) protection [65, 66].

Power swing, either stable or unstable, may have impacts on distance relay judgment. During the emergency state, such kind of relay unintended operation may cause more healthy lines removed from the system, resulting in the system becoming even more stressful. The reason is given below.

For the two machine system shown in Fig. 7, for steady state, assume the two sources have the terminal voltages as $E_{S0}\angle\delta_0$ and $E_{R0}\angle 0$ respectively, where the phase angle of the receiving end generator is always used as the angle reference. As for the two-machine system, the power swing appears to a relay as an oscillation of magnitudes and the angles of two generators. At certain time during the power swing, assume the voltages are $E_S\angle\delta$ and $E_R\angle 0$. Then we have

$$\dot{I} = \frac{E_S\angle\delta - E_R\angle 0}{Z} \tag{2.11}$$

where $Z = X_S + Z_L + X_R$.

From Fig. 7, we have

$$\dot{V_m} = E_S\angle\delta - jX_S \cdot \dot{I} \tag{2.12}$$

Therefore, the apparent impedance seen by the relay at bus m can be expressed as

$$Z_m = \frac{\dot{V_m}}{\dot{I}} = -jX_S + jZ\frac{E_S\angle\delta}{E_S\angle\delta - E_R} \tag{2.13}$$

The trajectory of Z_m with respect to E_S and E_R can be found in [65,66]. When the angle difference δ becomes large enough, the trajectory of Z_m will float into the relay setting area and cause relay unintended operation.

Now, let us extend the idea to regular multi-machine systems. Still look at Fig. 7. Consider the line in the middle as one of the transmission lines in the system with the terminal voltages of $V_m\angle\theta_m$ and $V_n\angle\theta_n$. The other parts outside the line represent the rest of the system.

If there is no fault on the line, the impedance seen by relay at bus m is,

$$Z_c = \frac{\dot{V_m}}{\dot{I_m}} = \frac{\dot{V_m}}{(\dot{V_m} - \dot{V_n})/Z_L} = Z_L\left(\frac{1}{1 - \left|\frac{V_n}{V_m}\right|\angle\theta_{nm}}\right) \tag{2.14}$$

According to (2.14), Z_c is only related to the magnitude ratio ($|V_n/V_m|$) and angle difference ($\theta_{nm} = \theta_n - \theta_m$) of the bus voltages at the two ends. When power swing occurs in the system, $V_m\angle\theta_m$ and $V_n\angle\theta_n$ will oscillate during the time. Assuming line impedance $Z_L = 1\angle 80^o$, we can draw the figure of Z_c trajectories in the R-X phase with respect to voltage magnitude ratios and angle differences, as shown in the left side of Fig. 10.

The conclusion is similar as in the two-machine system. If the power swing causes θ_{nm} large enough, the impedance seen by relay will reach the zone settings and relay will misoperate. The right side of Fig. 10 gives an example of typical actual impedance trajectories during a stable power swing and an unstable power swing.

F. Cascading Blackouts

Although the power system is well planed and redundancy is provided, it is still occasionally affected by large scale system blackouts. An overview of the major North America blackouts is listed in Table II [1]. We can notice that each blackout has caused a significant economical loss. With the advent of deregulation and restructuring, power systems are increasingly being operated close to their limits. When exposed

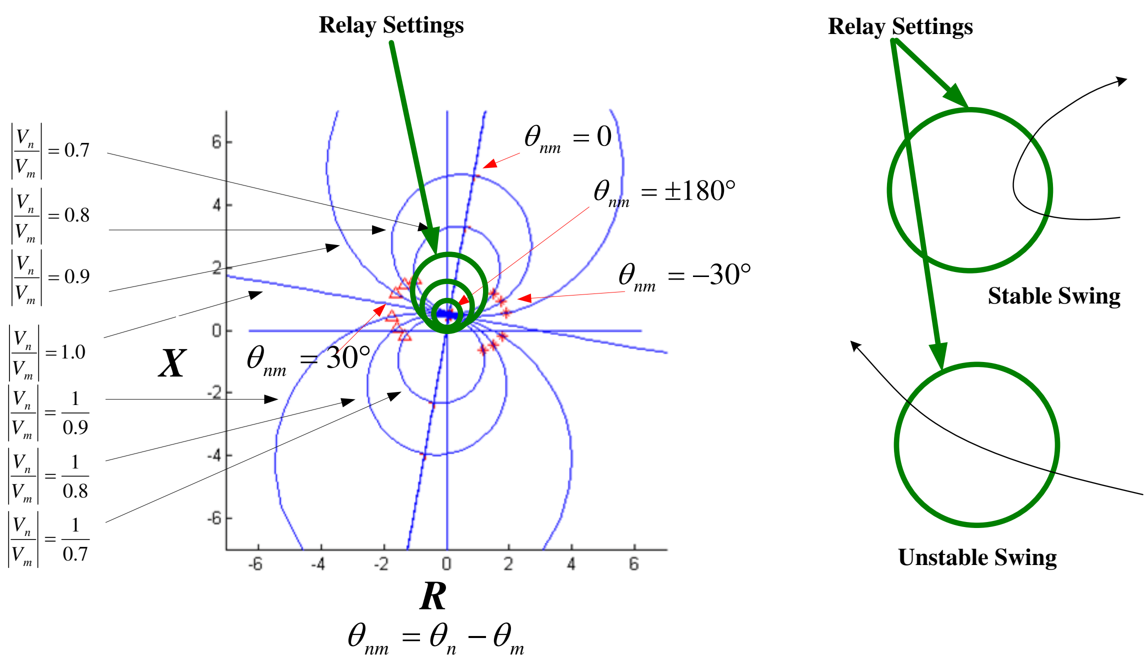


Fig. 10. Z_c trajectory in the R-X diagram in different terminal conditions

Table II. Comparison of several North America large scale blackouts

Date	Location	Lost of MW	Affected People	Collapse Time	Outage Duration
Nov. 9, 1965	Northeast	20000	30 million	13 mins	13 hrs
July 13, 1977	New York City	6000	9 million	1 hr	26 hrs
Dec. 22, 1982	West Coast	12350	5 million		
July 2-3, 1996	West Coast	11850	2 million	35 secs	a few mins to several hrs
Aug. 10, 1996	West Coast	28000	7.5 million	>6 mins	a few mins to 9 hrs
June 25, 1998	Upper Midwest	950	152000		19 hrs
Aug. 14, 2003	Northeast	61800	50 million	>1 hr	up to 4 days

to weak connections, bad weather, unexpected events, relay system failures, human errors, etc, the system may loose stability and experience catastrophic failures.

As one of the most contributing factors, the relay misoperations or unintended operations are always found in the blackout reports [1,2]. In 1965 Northeast Blackout, a backup protective relay misoperated to open one of five $230kV$ lines taking power north from a generating plant in Ontario to the Toronto area. That was the direct cause of the subsequent power swings resulting in a cascading outage that blacked out much of the Northeast. In 1977 New York City Blackout, the external $138kV$ ties to Consolidated Edison tripped in an overload situation and directly isolated the Consolidated Edison System. In July 2-3, 1996 West Coast Blackout, a protective relay on a parallel $345kV$ transmission line incorrectly detected the fault on the other line, resulting in the tripping of both parallel lines, which triggered the cascading events. In the recent August 14, 2003 Northeast Blackout, many distance relays operated on the power swing, and overload/low voltage conditions rather than faults. Although relay misbehavior was not the triggering cause, it was one of the major factors in spreading the blackout.

The common factors regarding the relay system failures in the major blackouts are the relay unintended operations due to the improper settings, inherent defects in the principles and relay hidden failures [5]. Additionally, the inability of system operators or coordinators to recognize the events either at the local level or at the entire system level was a contributing factor as well. There are several NERC recommendations regarding the relay system improvement to prevent cascading events [1], as shown in Table III. Obviously, application of new techniques and new real time tools is encouraged for better system operation.

G. Problems with the Traditional Relay

The problems with the traditional transmission line protective relay are summarized here based on the review of its background in the previous sections. Those problems are the ones we need to solve or avoid when developing new relay schemes.

- All traditional relay schemes depend on calculation of fundamental frequency phasor of measurements as well as settings. As described in Chapter I, some extreme fault and system operating conditions will cause unreliable phasor extraction and improper settings, resulting in incorrect fault diagnosis of relay.

- The most commonly used distance relay can not accurately protect the entire length of the line due to the measurement imperfections. The backup protection scheme is a necessity.

- Distance relay scheme and settings must be adjusted to cope with unusual

Table III. Several NERC recommendations to prevent future blackouts

21	"Make more effective and wider use of system protection measures."
22	"Evaluate and adopt better real-time tools for operators and reliability coordinators."
28	"Require use of time-synchronized data recorders."

system configurations. Some specific network structures need very complicated protection scheme and coordination.

- The system transient stability will be affected if distance relay has a slow or improper response to the fault due to the inaccurate fault diagnosis. That will cause power swing or even out-of-step in the system.
- The judgment of distance relay may be affected during the power swing and out-of-step situation since they may appear as a fault for the distance relay in some situation. In that case, the relay may issue an unintended command to remove the healthy transmission line.
- The relay misoperation or unintended operation may trigger or spread a cascading event that contributes to a large scale system blackout.

H. Summary

The purpose of the protective relaying is to minimize the effect of power system faults by preserving service availability and minimizing equipment damage [67]. Different types of the transmission line relays have been explored in this chapter. For the traditional principles, there is not a very sound method yet to balance the dependability and security of the protection system. The advent of the digital relay motivated development of new techniques to solve that problem. Distance relay is the most common type for the transmission line protection. The principe is straightforward while it still has some inherent drawbacks. New fault diagnosis techniques for transmission line protection are needed and new real time event analysis tool based on those techniques are highly desired. The remaining chapters will focus on the improvement of existing protection system based on the new techniques.

CHAPTER III

FAULT DIAGNOSIS USING NEURAL NETWORK*

A. Introduction

The traditional transmission line protection schemes are mostly based on the calculation of certain AC quantities and their comparison to pre-defined thresholds. This kind of method relies on a "hard" criterion. The settings require short circuit analysis to cover worst case fault conditions and coordinate the selectivity of each relay protection zone. The threshold based algorithm needs theoretical understanding and verification through the use of elaborate analysis tools.

The above issues can be improved by applying a "soft" criterion based on artificial intelligence techniques. Neural network is one of such techniques that has been studied in the power system area for quite a while [68–71]. Neural network based fault diagnosis algorithms usually use the time-domain voltage and current signals directly as patterns instead of calculated phasors. They compare the input voltage and current signals with well-trained prototypes instead of predetermined settings. Hence, the major problems in traditional relay principles described in Chapter I.A.1, which is about phasor extraction and setting coordination, are not an issue in neural network based algorithms. As mentioned in Chapter II.C.4, traditional protection schemes need to be properly set when applied to the specific system structures. In neural network based approaches, this is not an issue since they can be trained through the simulated waveforms to adapt to different kinds of system configurations.

To be used as an independent transmission line protection scheme, every tech-

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nique must take into account the detailed application issues. Some of the following issues are common for all kinds of neural network based algorithms. Those issues will be discussed in this chapter in detail.

- The transmission line fault can occur anywhere in the system with different combination of fault parameters and system operating conditions. The argument that neural network based algorithm has better performance than conventional relay is based on an assumption that the neural network has broader view of system contingencies through a comprehensive learning and training process. The neural network based algorithms thus face the issue of dealing with a large set of training data. How to train the network efficiently when taking into account the large number of system-wide scenarios is critical.

- The neural network based algorithm should be immune to the impact of non-fault situations such as overload and power swing. If the input pattern uses raw voltage and current samples, the waveforms during the overload and power swing may appear as low voltage or high current, which may be confused with fault waveforms, so neural network needs to be trained to differentiate such cases.

- Most of the neural network based algorithms implement the training using fixed post-fault data window. An assumption is made that one can identify an exact fault inception point, otherwise the real pattern is quite different from those learned and the performance of neural network will be degraded. In realistic situation, the inception point needs to be well identified to ensure the neural network based algorithm is tuned correctly.

Along with a background of neural network, this chapter will review a previously developed fuzzy Adaptive Resonance Theory (ART) neural network algorithm used for transmission line fault classification [41, 72]. The previous contribution of the proposed approach was extensively focused on the tune-up of the training and testing mechanism to achieve an effective pattern recognition scheme [41,72]. The application issues mentioned above were not fully addressed as in other neural network based approaches. In this chapter, an enhancement of the prototype fuzzy ART neural network algorithm is provided to address the mentioned application issues, so that it will be more feasible to be as a stand alone distance relay with full fault diagnosis capability.

In Section B, a brief background of neural network and its application in transmission line fault diagnosis are reviewed. Section C provides the background of fuzzy ART neural network algorithm, which was developed earlier and will be used as the major technique in this chapter and following chapters. The application issues identified in the previous neural network implementation as limitations are discussed in Section D. The solution to solve the problems and improve performance of the previous algorithm is provided in Section E.

B. Neural Network and Its Application in Transmission Line Fault Diagnosis

Neural network (NN) or artificial neural network (ANN) is introduced to solve the complex nonlinear problems which the conventional analytical methods cannot easily solve. By resembling the human brain, the neural network works as a parallel distributed processor made up of simple processing units (neurons), which have a natural capability for storing experiential knowledge and making it available for generalization [73]. The “knowledge” of the neural network is formed by a learning process and is stored by the interneuron connection strengths, or synaptic weights.

A neuron is the most fundamental information-processing unit of a neural network. Fig. 11 shows the structure of a single neuron. The three basic elements of a neuron are synaptic weights, summing junction, and the activation function. The input-output mapping of a neuron can be expressed by following two equations:

$$u_k = \sum_{j=1}^{n} w_{kj} x_j \tag{3.1}$$

and

$$y_k = \varphi(u_k + b_k) \tag{3.2}$$

The use of neural network offers several benefits over the traditional analytical methods. The typical benefits are:

- Generalizability: Through its powerful parallel distributed structure and the learning capability, a neural network can produce reasonable outputs for the inputs not participated in the learning process. It can handle imperfect or incomplete data, and has the potential to be fault tolerant. That is very useful when analyzing the practical noisy data.

- Nonlinearity: The neural network could have nonlinear structure. This is very

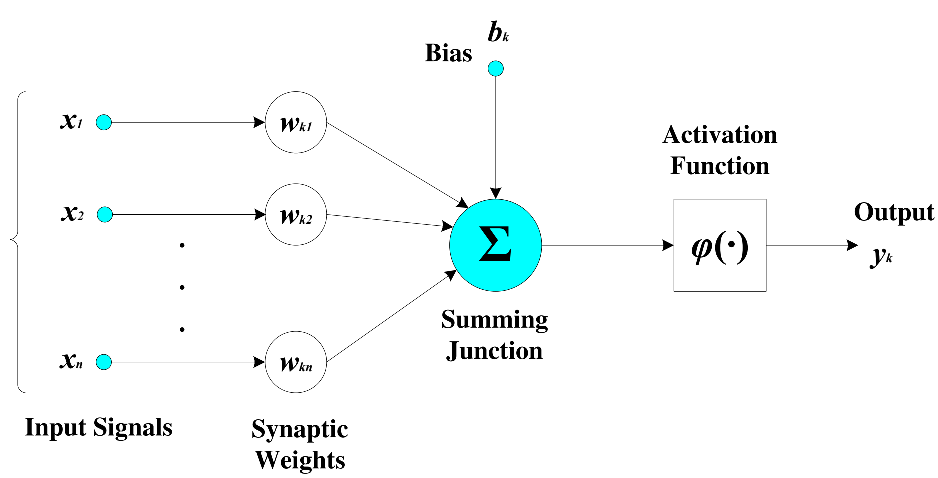

Fig. 11. A basic neuron model

useful for representing very complex large-scale systems.

- Adaptivity: The neural network has a natural capability to adapt its knowledge to changes in the applied environment. It can be retained to deal with the changes even in a nonstationary environment. That makes it a useful tool in adaptive pattern recognition, adaptive signal processing and adaptive control.

- VLSI Implementability: The massive parallel structure of neural network make it well suited for implementation using very-large-scale-integrated (VLSI) technology to achieve fast computation tasks.

From the pioneering work of neural networks by McCulloch and Pitts in 1943 [74], the theoretical and practical work of neural network has been rapidly growing until today. It has been used in such diverse applications as modeling, time series analysis, pattern recognition, signal processing, and control. Typical fields where neural networks are used are: aerospace, automotive, banking, electronics, games, medical, oil and gas, robotics, speech, telecommunications, vision, etc. Regarding the power system, it has been successfully applied in addressing the large set of problems such as load forecasting, security assessment, control, fault diagnosis, system identification, operation, planning, protection, alarm processing, etc [68]. As to the concern of this dissertation, the area of transmission line fault diagnosis also finds the neural network a useful tool in fault detection and classification [29, 31–33, 41, 75–83], fault direction discrimination [30], fault location [31, 84–89], fault analysis [90–92], autoreclosing [28, 93], high impedance fault detection [94–96], adaptive relaying [97, 98], etc.

Learning process is the most important step when applying neural networks. The learning techniques for most neural networks can be classified into two broad categories: supervised learning (or learning with a teacher) and unsupervised learning (or learning without a teacher). In supervised learning, each input signal is associated with the labeled output. The task is the input-output mapping by adjusting the synaptic weights to minimize the overall error between the entire output set and their corresponding input data set. In unsupervised learning, the categories of the outputs are not known in advance. The network is self-organized by some sort of clustering techniques to identify the mutual similarity of the input patterns. The task is to adjust the network weights until the similar inputs can produce similar outputs.

The typical supervised and unsupervised neural network techniques are shown in Fig. 12. Single Layer Perceptron (SLP) is the first model of supervised learning proposed by Rosenblatt in 1958 [99]. Due to its simplicity, the application of this model is limited. The most commonly used supervised neural networks is Multilayer Perceptron (MLP) [100]. It has a feedforward structure as shown in Fig. 13. By introducing one or more hidden layers, it can be used for learning complex nonlinear relationships between input and output data. In 1986, Rumelhart and McClelland introduced the back-propagation (BP) algorithm for training MLP networks [101],

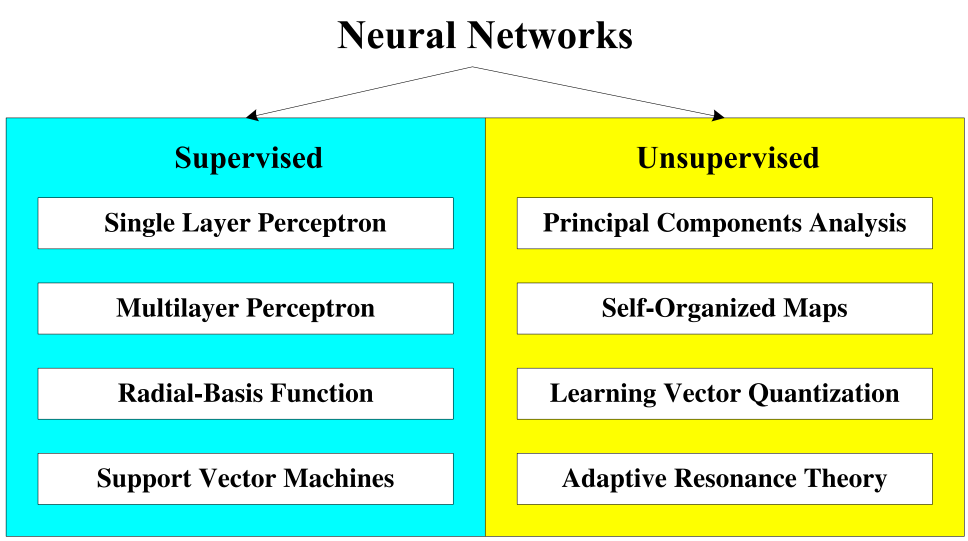

Fig. 12. The types of supervised and unsupervised neural network techniques

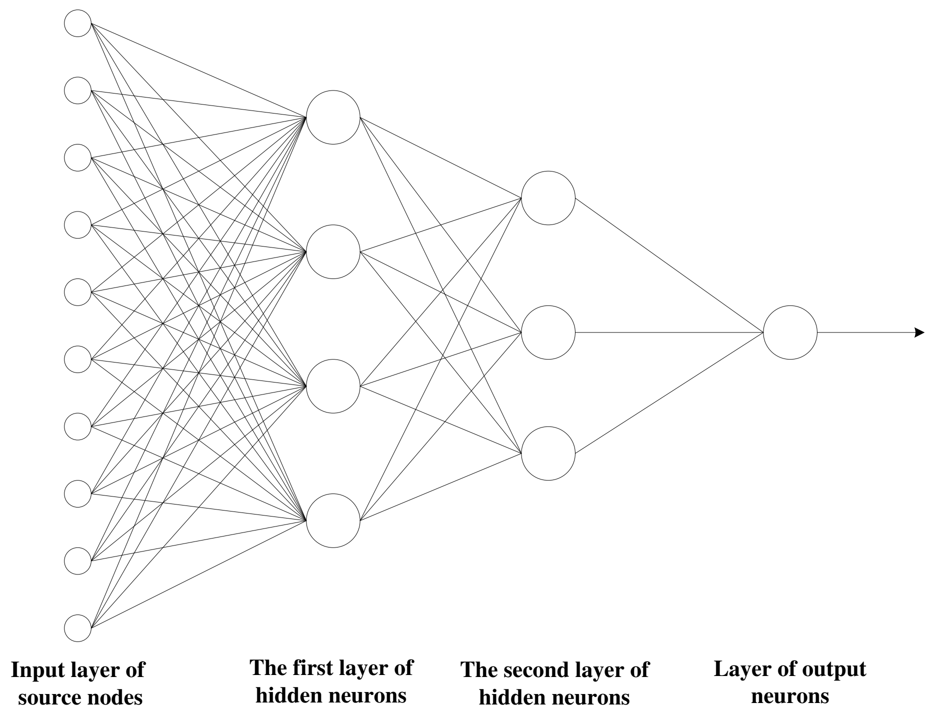

Fig. 13. The structure of Multilayer Perceptron

making MLP more popular in practical applications. Radial-basis function network is invented in 1988 [102]. The locally tuned response characteristics produce faster training than BP algorithm. Another powerful supervised learning network, support vector machine (SVM) was introduced in 1990s by Vapnik and his colleagues [103]. Unsupervised learning networks usually use the competitive learning rule, which is a clustering technique to group the data into clusters so that the patterns in a cluster have similarity with each other. The typical techniques including primary component analysis (PCA) [73], self-organized map (SOM) [104], learning vector quantization (LVQ) [105], and adaptive resonance theory (ART) [106–109]. ART networks have a unique property to solve the problem of unstable learning. It can adjust the number of clusters during the training and adapt itself to new inputs without affecting the results of the previous training.

Except for the simplest SLP neural network, the mentioned neural network techniques have all been used in the transmission line fault diagnosis. MLP neural networks with BP algorithm have been dominantly used [28–31,77,78,81,84–87,90,92–94, 97,98]. Since BP is the basis of the modern neural network algorithm, it can be used as a good start to solve the fault diagnosis problem. Recently, the following problems of those kinds of neural network algorithms have been recognized in the literature: time consuming training, uncertainty in selecting the number of hidden neurons, selection of the proper learning rate, and convergence issues. New approaches using other type of neural networks has been reported, including RBF [82,91], SVM [88,89], SOM [79], LVQ [33], PCA [95, 96] and ART [41, 75, 76, 80, 83]. Supervised learning techniques have similar issues in the MLP networks. Unsupervised techniques, because of the self-organized property, can solve most of the mentioned problems. But this property needs to be combined with other classifier to implement the pattern recognition and classification tasks.

Neural network based on combined unsupervised/supervised training scheme is proved to be more capable of handling large data sets of random fault scenarios than solely using supervised training schemes [41, 79]. In this and next chapters, a specially designed, fuzzy ART neural network algorithm, is used to deal with transmission line fault diagnosis issues in traditional line protection scheme and boundary protection scheme.

C. Background of Fuzzy ART Neural Network Algorithm

1. Overall Scheme

The fuzzy ART neural network algorithm for fault classification was described in its original form in [75, 76]. Further enhancements are introduced regarding: a)

Preprocessing of input data; b) Refining supervised training; c) Applying fuzzy decision rule; and d) Taking into account complex system conditions. The latest version of the algorithm is described in [41, 72].

The block diagram of fuzzy ART neural network algorithm used for fault diagnosis is demonstrated in Fig. 14. The two major components of the algorithm are ART neural network training and fuzzy K-NN classification. The theoretical background of these two approaches can be found in [107, 110]. By using those techniques, the fault detection and classification becomes a pattern recognition approach instead of phasor computation and comparison. Without calculating the phasor, the voltage and current signals from the local measurement are formed as patterns using time-domain data samples, which can retain the original information in the waveforms. Without need to specify settings, the setting coordination work can be avoided. Thousands of patterns obtained from power system simulation or substation database of field recordings are used to train the neural network offline and then the pattern prototypes are used to detect the real faults online by using the fuzzy K-nearest neighbor

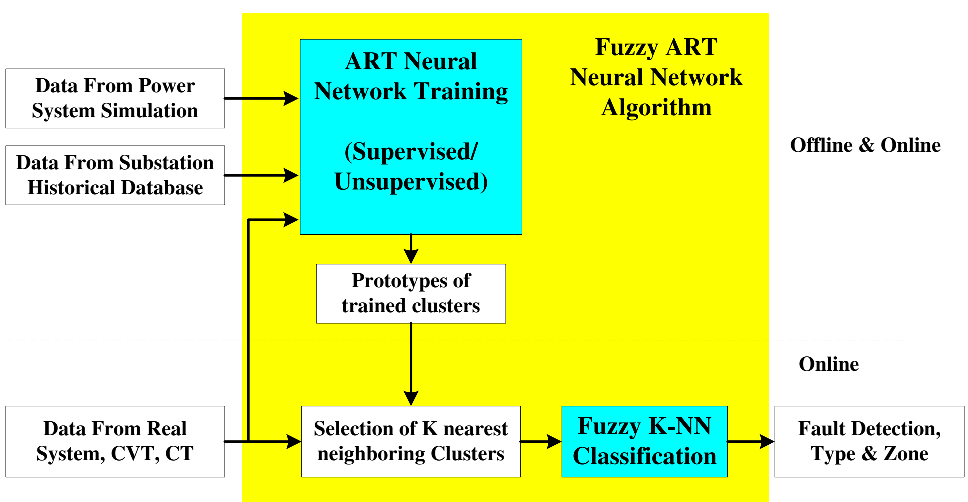

Fig. 14. Fuzzy ART neural network algorithm for fault diagnosis

(K-NN) classifier. The ART neural network is also capable of online training aimed at updating the pattern prototypes. Using the prototypes of trained clusters, fuzzy K-NN classifier can realize online analysis of unknown patterns for fault detection and classification. The fuzzy K-NN classifier takes into account both the effect of weighted distances and the size of neighboring clusters for distinguishing new patterns. From the simulation results in [41], it is shown that fuzzy K-NN classifier has better performance than a common K-NN classifier. A graphic view of the status of input patterns at each step during training and testing process is shown in Fig. 15 [41].

2. Training

The procedures of training and testing the fuzzy ART neural network, which were developed in [41], are reviewed in this and next sections using graphic demonstrations. The neural network training process is shown in Fig. 16. Unsupervised learning is

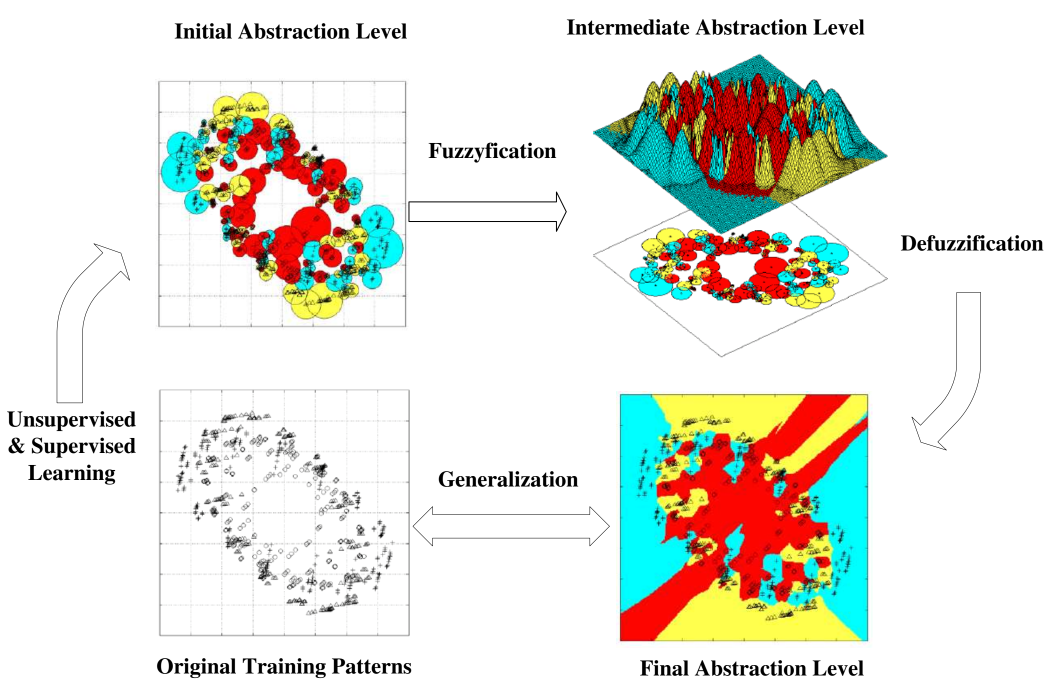

Fig. 15. Entire procedure of training and testing

the first stage to process the initial data set, containing all the patterns. During this stage, the category of each pattern is not presented in advance. The input patterns are grouped by themselves according to some sort of similarity. Neither the initial guess of the number of cluster nor their position is specified in advance.

Unsupervised learning consists of two steps: initialization and stabilization. In initialization phase, the entire pattern set is presented only once to establish initial cluster structure based on similarity between patterns. As shown in Fig. 17, the first cluster is formed with only the first input pattern assigned. From the second pattern being presented, new clusters are formed incrementally if the shortest Euclidean distance d_p between a new pattern and all existing prototypes is larger than the predetermined threshold, or radius ρ. Otherwise the pattern is allocated to the "nearest" existing cluster, which will then update its center and radius with the new pattern. The initialization stage of the unsupervised learning will follow one of the routes shown in Fig. 17 until all of the n input patterns are presented. By the end of this phase, the output is an initial set of unstable clusters, since the clusters keep changing their positions while new pattern comes in. The past patterns are not allowed to change their clusters during this phase. In stabilization phase, the entire pattern set is being presented numerous times and the process is similar to that in the initialization phase. By measuring the Euclidean distance to each existing cluster, a pattern

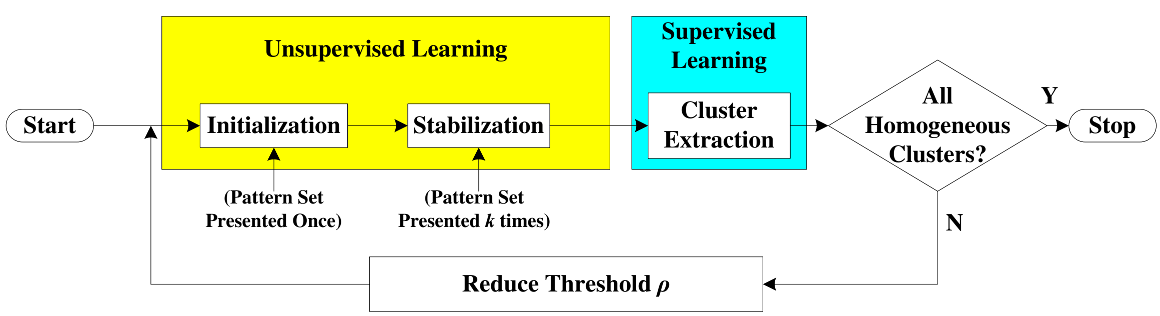

Fig. 16. Flowchart of neural network training

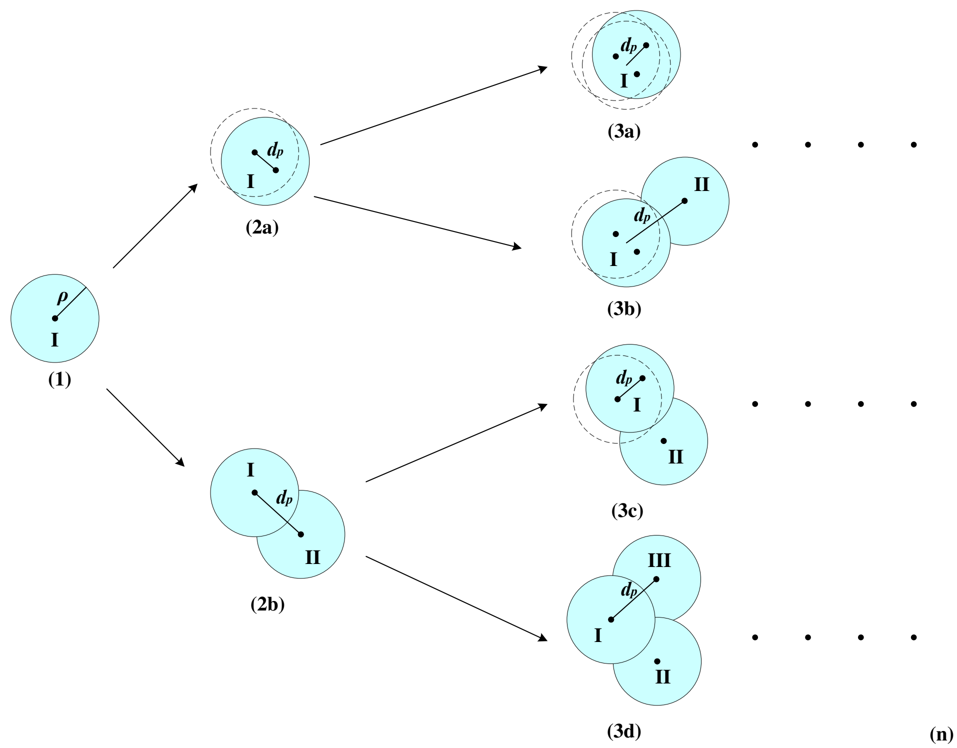

Fig. 17. Graphic demonstration of initialization stage

either remains unchanged from previous cluster or will be allocated to a new "nearest" cluster. The iterations will not end until the initial unstable cluster structure becomes stable and no patterns change clusters after single iteration. Unsupervised learning produces a set of stable clusters, including homogenous clusters containing patterns from same category, and non-homogenous clusters containing patterns from other categories.

In supervised learning process, as demonstrated in Fig. 18, class label is associated with each input pattern allowing separation of homogenous and non-homogenous clusters produced in unsupervised learning. For homogeneous clusters, their position, size, and category are stored to the memory and the patterns from those clusters are removed from initial training pattern set. The remaining patterns, presented in non-homogenous clusters are left for new learning iterations. When all clusters are

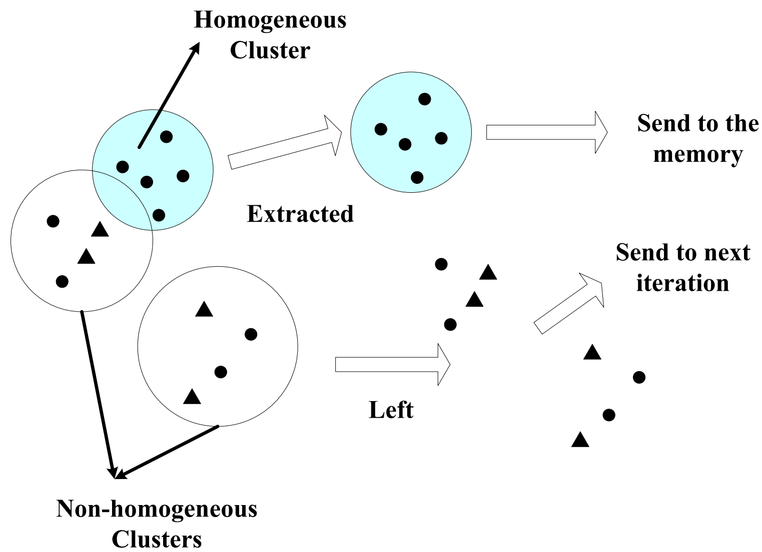

Fig. 18. Graphic demonstration of supervised learning stage

examined, the new data set is sent to next unsupervised/supervised learning iterations with reduced threshold parameter ρ, as shown in Fig. 16. The entire learning process is completed when all the patterns are grouped into homogeneous clusters with predefined class labels.

3. Testing

The prototypes (clusters) are obtained during the training process to represent the characteristics of the input pattern. When classifying the unknown pattern that is not presented in the training process, we will face two situations. When the new pattern falls into one of the trained clusters, it is easy to assign the category of the cluster to the unknown pattern. While when the new pattern falls into the unclaimed space, the fuzzy K-NN algorithm is used to classify the unknown patterns according to their similarity to the neighboring clusters, as shown in Fig. 19 [41]. The membership

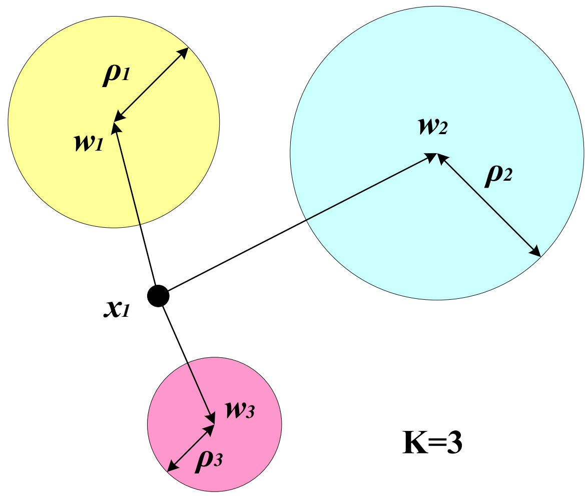

Fig. 19. Graphic demonstration of fuzzy K-NN algorithm

degree of a new pattern x_i belonging to a category c is calculated by

$$\mu_c(x_i) = \frac{\sum_{k=1}^{K} [\mu_c(w_k)/d_k(x_i)]}{\sum_{k=1}^{K}[\rho_k/d_k(x_i)]} \tag{3.3}$$

where K is the predefined number of nearest neighbors. Compared with the regular K-NN classifier, fuzzy K-NN classifier takes into account both the effect of weighted distances and cluster size of the neighboring clusters to the tested new pattern. In (3.3), distance $d_k(x_i)$ is usually selected to be the weighted Euclidean distance between pattern x_i and prototype w_k

$$d_k(x_i) = \|x_i - w_k\|^{\frac{2}{m-1}} \tag{3.4}$$

where parameter m is fuzzyfication variable and determines how heavily the distance is weighted when calculating each neighbor's contribution to the pattern class membership.

In (3.3), $\mu_c(w_k)$ is the membership degree of cluster k belonging to category c.

In fuzzy K-NN algorithm, $\mu_c(w_k)$ is defined to reflect the relative size of the cluster k

$$\mu_c(w_k) = \begin{cases} \rho_k & \text{if cluster } k \text{ belongs to category } c \\ 0 & \text{Otherwise} \end{cases} \tag{3.5}$$

where ρ_k is a membership degree value that is proportional to the radius of cluster k.

When the membership degree of pattern x_i belonging to each category is calculated by (3.3), the most representative category is assigned to the pattern

$$g(x_i) = max_c[\mu_c(x_i)] \tag{3.6}$$

D. Application Issues

The previous research contribution to fuzzy ART neural network algorithm [41] was focused on the inside tune-up of the algorithm to achieve an effective training and testing mechanism. Its application for classifying transmission line fault is also reported [41, 72].

The previous implementation of the fuzzy ART neural network algorithms uses one neural network to implement both fault detection and classification tasks [41,72]. Although the ART algorithm has better solutions to handle the convergence issue when dealing with the large data set, it is still time-consuming and inefficient when considering thousands of system-wide fault scenarios. The previous approach does not require feature extraction. The input pattern is directly arranged using raw samples of three-phase voltage and current waveforms. Although that simplifies the implementation, it may fail to distinguish the snapshot of a fault from that of the power swing or overload situation. As shown in Fig. 9, the power swing can present low voltage and high current at certain time, which is very similar to the waveform observed during a fault. The approach also can not differentiate two-phase fault from two-phase-to-ground fault very well. Fig. 20 shows that the two fault scenarios present similar waveforms when other fault parameters are identical. At last, the previous approach is lacking a method to locate the fault inception point, which may limit it for the on line use. A new fault detection and classification scheme is proposed below to solve the mentioned issues.

E. New Fault Detection and Classification Scheme

1. Use of Multiple Fuzzy ART Networks

To deal with the system-wide disturbances effectively, the task of fault detection and classification is improved by defining and training two neural networks. The scheme is demonstrated using a system with specific configuration shown in Fig. 21.

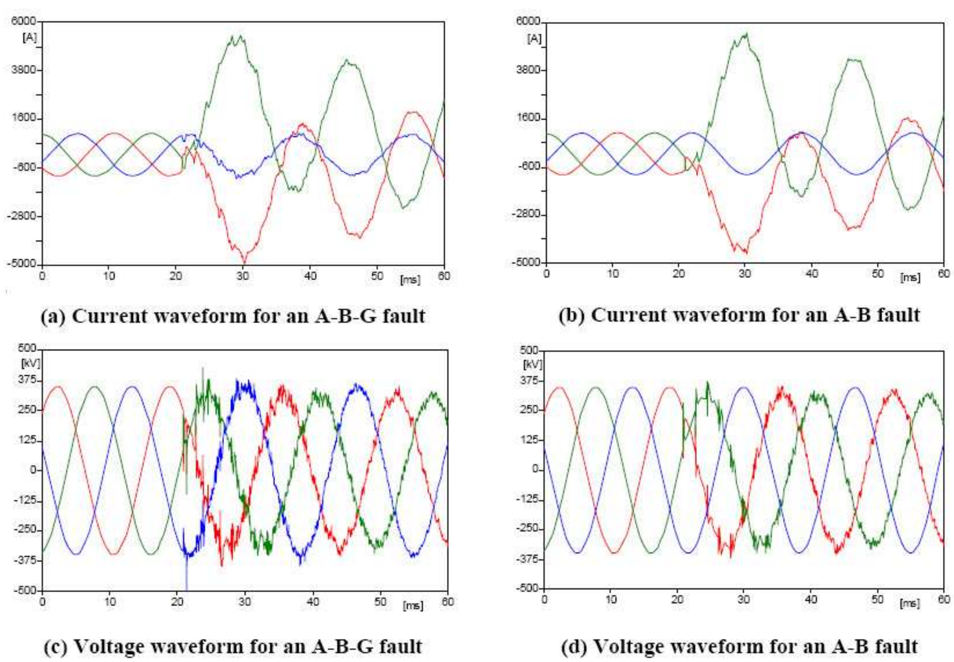

Fig. 20. Waveform comparison for an A-B-G fault and A-B fault

To protect the line of interest in Fig. 21, the first neural network (NN1) makes a crude differentiation of the disturbances occurring within and around the line of interest (the highlighted area) from those occurring outside that area. The training of NN1 will take into account as many faults as possible throughout the entire system that may affect the desired fault detection and classification. The training process is not significantly involved since there are only two outputs, "fault" and "no fault". The second neural network (NN2) refines the classification within the highlighted area. It is well trained by a comprehensive scenario set including many fault parameters and system operating conditions. More scenarios are obtained around the boundaries of the protection zone to achieve more accurate conclusions. The output of NN2 is the combination of all 11 fault types (including "normal") and 2 fault zones. The final conclusion is drawn by taking into account the outputs from NN1 and NN2 simultaneously. The advantage of coordinating the two neural networks is distributing the large input set into different neural networks to reduce the burden of training and testing. NN1 has large number of inputs but fewer outputs, providing an initial crude conclusion where the faults may be located. NN2 takes more patterns from limited areas to refine the classification. By coordinating the two neural networks, the training process achieves great efficiency when dealing with system-wide events

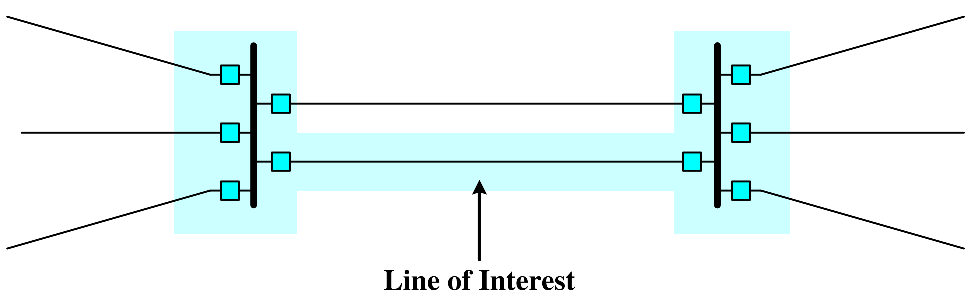

Fig. 21. A specific system configuration

and hence the online performance will be greatly improved.

2. Feature Extraction

The pattern arrangement for the neural networks is shown in Fig. 22. The pattern is arranged using the post-fault samples of three phase voltage and current signals. Typically, the data window length in each phase is one cycle or half a cycle. The zero sequence values of voltage $3v_0 = v_a + v_b + v_c$ and current $3i_0 = i_a + i_b + i_c$ are also included to precisely detect ground faults. In this case, all fault types can be differentiated very well.

For each element as shown in Fig. 22, we define:

$$u(k) = u(k) + 2u(k - \frac{N}{2}) + u(k - N) \tag{3.7}$$

where u represents the signals of related voltage or current phases, k is the present sampling point, and N is the number of sampling points in a cycle.

Such method of pattern arrangement uses only the fault generated superimposed voltage and current waveforms as the major feature. If there is no significant variation of the original waveforms during one cycle, which happens in most cases in overload and power swing conditions, the pattern will appear as very low value close to the

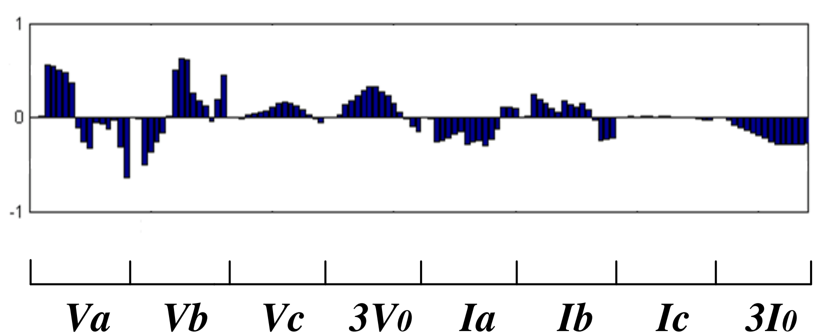

Fig. 22. Pattern arrangement for proposed neural network algorithm

normal system situations. The effect is shown in Fig. 23. From Fig. 23 (a) and (b), we can see that the preprocessed signal during the power swing is very close to zero. From Fig. 23 (c) and (d), we can see that the prefault steady state signal is eliminated after preprocessing while the fault signal is clearly presented after preprocessing. Such a preprocessing step makes the appearance of the power swing close to the normal situation, and not the fault situation. The input pattern is finally normalized into the space of $[-1, 1]$ before used for training and testing.

Equation (3.7) can be modified as the criterion to locate the fault inception point:

$$\left| i(k) + 2i(k - \frac{N}{2}) + i(k - N) \right| \geq T \tag{3.8}$$

where i is the current sample in any of the three phases, threshold T is set to take into account the model and measurement imperfection.

From Fig. 23 (d), we can see that the fault inception point can easily be located using this approach. If (3.8) is satisfied in any of the three phases for a successive cycle, the first sample point is considered as the inception time to trigger the neural

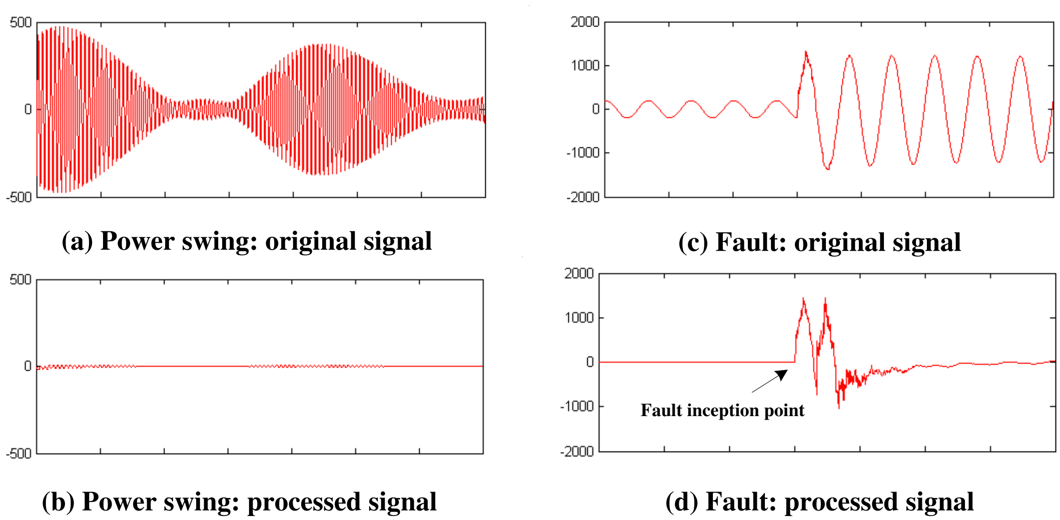

Fig. 23. Comparison of original signals and preprocessed signals

network based fault diagnosis.

3. Implementation of the New Scheme

The proposed scheme uses one-end data to perform transmission line fault detection and classification. The block diagram is shown in Fig. 24. It takes the same input and output as distance relay and can be used as independent protection scheme. The training and testing process of the two neural networks are the same as in the previously mentioned scheme shown in Fig. 14.

4. Advantages of Proposed Fault Diagnosis Scheme

The advantages of the proposed fault diagnosis scheme are summarized as follows:

- The applied fuzzy ART neural network uses time-domain data and elaborate training to get away from traditional phasor and relay setting concept.

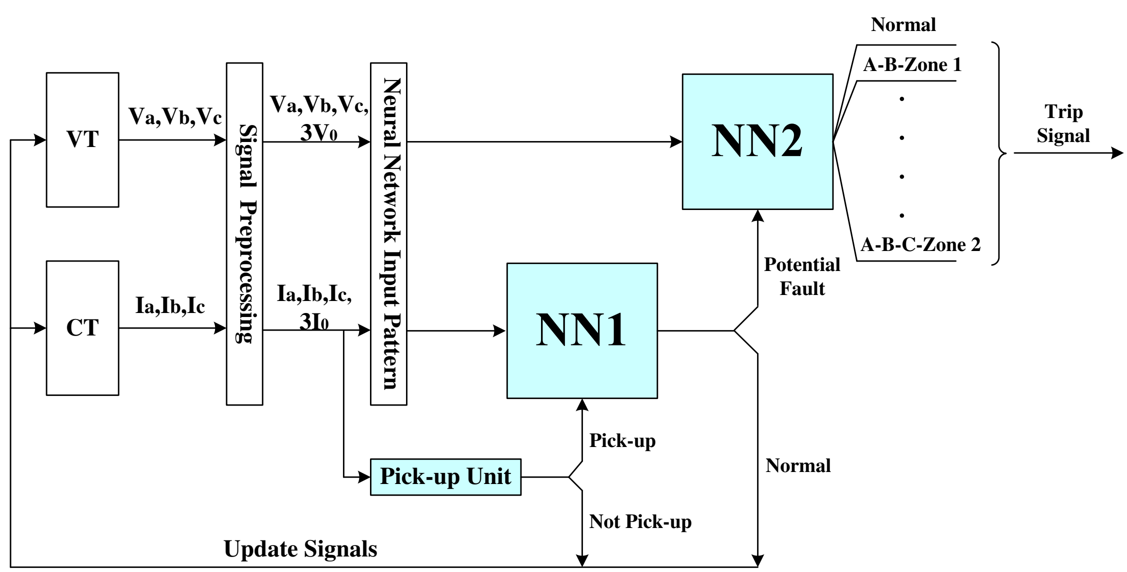

Fig. 24. The block diagram of proposed fault diagnosis scheme

- Task allocation of the two neural networks provides an effective approach in handling the large input data set.
- Feature extraction method helps to precisely locate the fault inception point and eliminates the impact from power swing and pre-fault loading condition.

F. Summary

The background of neural network is reviewed in this chapter. It was proven to be a useful tool to solve the complex nonlinear problems which are the obstacles for the traditional methods. The theory of the neural network itself is still being improved. Its application in transmission line protection has been extensively studied. The idea of the previous research of the fuzzy ART neural network algorithm is explored and the application limits in handling the large input data set, removing the impact from power swing and overload, and locating the fault inception point are discussed. The newly proposed scheme uses coordinated neural networks and enhanced feature extraction approach to solve the mentioned problems. The performance study of the proposed scheme will be reported in Chapter X. ART based neural network has a better scheme to train the large data set. Since this type of neural network is a pattern recognition technique, it can not be used as a fault location scheme since the fault location is a continuous variable which will produce infinite categories in the sense of pattern recognition. In this sense, the feed-forward neural network which is good at input-output mapping could be one of the choices for fault location problems. Some solutions can be found in [31, 84–89].

CHAPTER IV

BOUNDARY PROTECTION USING NEURAL NETWORK AND WAVELET TRANSFORM*

A. Introduction

A perfect transmission line protection scheme is expected to differentiate the internal faults from external using one-end measurements only. That can not be realized by the traditional non-unit protection schemes, which are mostly based on the fundamental frequency components of fault signals. They can not protect the entire length of the primary line because they can not differentiate the internal faults from external occurring around the multi-zone boundaries. As introduced in Chapter II, time-step backup protection is therefore introduced as a trade-off scheme for protecting the entire length of the transmission line. As mentioned earlier, unintended operation of backup protection is the most troublesome factor in the power system blackouts because the extended zone settings in backup protection may be too close to the relay apparent impedance during power swing and overload in some extreme conditions.

Recently, new techniques using high frequency components of the fault generated transient signals were studied and some useful solutions were obtained [34,39,40,111]. An approach called "boundary protection" for solving the disadvantages of conventional non-unit protection schemes was proposed [39,112]. This approach introduces a possibility of precisely differentiating the internal faults from external using measurements from one end only. In this case, the relay at one end can protect the entire line length with no intentional time delay.

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This chapter proposes a new approach based on wavelet transform and the previously introduced fuzzy ART neural network to realize accurate boundary protection and fault type classification using one end measurements from a transmission line. The new method retains both low frequency and high frequency components of the fault signal to achieve high reliability and selectivity of the protection scheme. It inherits many advantages from different techniques it utilizes. The proposed approach in this chapter is an extension of neural network based fault diagnosis scheme introduced in the last chapter. If this approach can be realized with the available hardware, one can expect to use one-end measurements of a transmission line to realize accurate unit protection scheme. This kind of scheme is very attractive both in theoretical analysis and practical deployment.

In Section B, the background of boundary protection is reviewed. Brief introduction of wavelet transform is then provided in Section C. Section D describes the entire design procedure of the new protection scheme.

B. Background of Boundary Protection

The principle of boundary protection is studied in [39]. The previous work is explored in this section to provide background of the new approach introduced in this dissertation. The system shown in Fig. 25 is a typical multi-line system. We assume the relay is installed at the bus 2 to protect the line $2-3$ shown in the figure. A fault on the lines will generate wideband transient voltage and current signals. The signals will travel in both directions with reflections and refractions at the discontinuity points, which are usually the busbars and faults. The busbar of the power system is always connected to many power system apparatus and they usually represent the capacitance at high frequency. This effect is shown in Fig. 25. For an

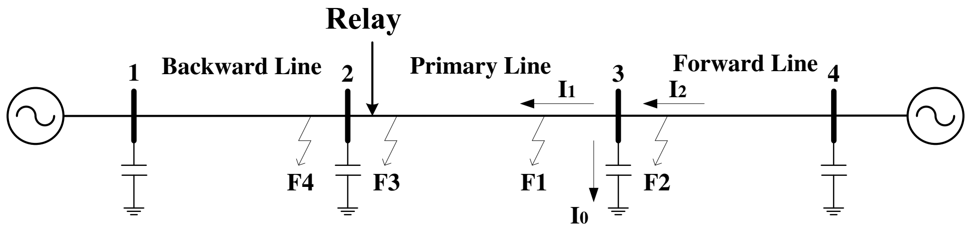

Fig. 25. An example of multi-line system

external fault $F2$ close to the bus 3, the high frequency portion of the fault current signal I_2 will be shunted to earth (in I_0) significantly due to the busbar capacitance. The higher the frequency, the more significant portion of the current signal will be shunted. From the viewpoint of the relay, the magnitude of high frequency portion of the fault current signal I_1 is reduced. In contrast, for the internal fault $F1$ close to the bus 3, the fault current of the entire frequency band can be seen by the relay. That means, if other fault conditions (fault type, fault resistance, fault angle) are identical, we can differentiate the internal fault $F1$ from the external fault $F2$ by comparing the high frequency portions of their signals. Similarly, the same method can be used to differentiate the faults at $F3$ and $F4$. Using the voltage signals, we can still differentiate faults at $F1$ and $F2$ but can not differentiate faults at $F3$ and $F4$ because the voltage measurements of the relay are obtained from bus 2.

The feature differences of the faults on different line sections seen by the relay at bus 2 in Fig. 25 can be summarized as follows:

- For faults on the primary line, the energy of high frequency portion of the voltage and current signals will be seen as “big” values.
- For faults on the backward line, the energy of high frequency portion of the voltage signals will be seen as “big” values while the energy of high frequency portion of the current signals will be seen as “small” values.

- For faults on the forward line, the energy of high frequency portion of the voltage and current signals will be seen as "small" values.

It should be emphasized that the above statements are based on the assumption that all other fault parameters are the same and the "big" and "small" values are indicating relative numbers. The absolute values are dependent on fault type, fault resistance, fault angle, etc.

In [39], the author uses a specially designed multi-channel filter to extract the transient current signals for two signal outputs I_{f1}, I_{f2} with center frequency at $80kHz$ and $1kHz$ respectively. Then the ratio of the energy spectrum for I_{f1}, I_{f2} is calculated and compared to a threshold to find out whether the fault is internal or external. The advantage of this method is justified by the result from a performance study.

Still some issues are remaining in this method: a) The direction of the external faults can not be distinguished since only the current signal is used. The method also has no phase selection function available; b) The theoretical basis for selection of the center frequency of the extracted features and selection of the thresholds is not apparent; c) The reliability of the method is unknown since only high frequency signal is used. It may be affected by the disturbance from noise, switching, lightning, etc; d) There are no extensive studies provided for the performance evaluation under various fault conditions. As mentioned earlier, the boundary condition are highly dependent on fault type, fault resistance, fault angle, etc.

This chapter provides a new boundary protection scheme aimed at solving those issues. First of all, the voltage and current signal will both be used; this can provide more information about the direction of the fault point. The new scheme uses wavelet transform as the feature extraction tool thus there is no need to design extra filters.

Wavelet transform has a strong capability of extracting the signal component under different frequency bands while retaining the time domain information. Secondly, the extracted features will be handled using the fuzzy ART neural network introduced in last chapter. With its strong capability of generalization and training mechanism, it can be used as an alternative solution when theoretical basis for dealing with the fault generated high frequency signal components is not well defined. The fault classification scheme mentioned in last chapter can also be further improved if the faulted line section is indicated in advance. Only the scenarios for the internal faults are considered. The inputs for training the neural network are reduced significantly and the accuracy of classification will be improved. Finally, the new scheme will use both the low and high frequency components of the fault signal to eliminate impact from non-fault disturbances. The reliability and robustness of the method will be verified by an extensive study for various kinds of faults.

C. Wavelet Transform

Wavelet analysis is a relatively new signal processing tool and is applied recently by many researchers in power systems due to its strong capability of time and frequency domain analysis [113, 114]. The two areas with most applications are power quality analysis and power system protection [115–117].

The definition of continuous wavelet transform (CWT) for a given signal $x(t)$ with respect to a mother wavelet $\psi(t)$ is:

$$CWT(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} x(t)\psi\left(\frac{t-b}{a}\right) dt \tag{4.1}$$

where a is the scale factor and b is the translation factor.

For CWT, t, a, b are all continuous. Unlike Fourier transform, the wavelet transform requires selection of a mother wavelet for different applications. One of the most popular mother wavelets for power system transient analysis found in the literature is Daubechies's wavelet family. In the new scheme, the $db5$ wavelet is selected as the mother wavelet for detecting the short duration, fast decaying fault generated transient signals.

The application of wavelet transform in engineering areas usually requires discrete wavelet transform (DWT), which implies the discrete form of t, a, b in (4.1). The representation of DWT can be written as:

$$DWT(m,n) = \frac{1}{\sqrt{a_0}^m} \sum_k x(k)\psi\left(\frac{k - nb_0 a_0^m}{a_0^m}\right) \tag{4.2}$$

where original a and b parameters in (4.1) are changed to be the functions of integers m, n. k is an integer variable and it refers to a sample number in an input signal.

A very useful implementation of DWT, called multi-resolution analysis, is demonstrated in Fig. 26. The original sampled signal $x(n)$ is passed through a highpass filter $h(n)$ and a lowpass filter $l(n)$. Then the outputs from both filters are decimated by 2 to obtain the detail coefficients and the approximation coefficients at level 1 ($D1$ and $A1$). The approximation coefficients are then sent to the second stage to repeat the procedure. Finally, the signal is decomposed at the expected level. In the case shown

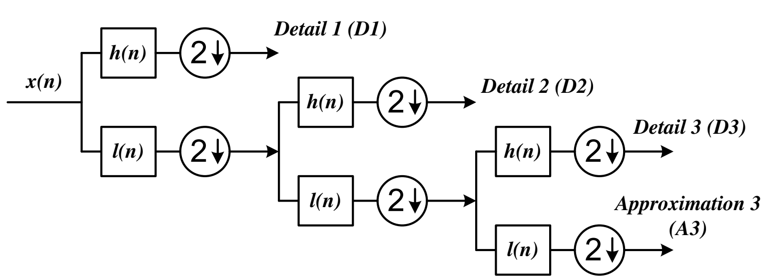

Fig. 26. The idea of wavelet multi-resolution analysis

in Fig. 26, if the original sampling frequency is F, the signal information captured by $D1$ is between $F/4$ and $F/2$ of the frequency band. $D2$ captures the information between $F/8$ and $F/4$. $D3$ captures the information between $F/16$ and $F/8$, and $A3$ retains the rest of the information of original signal between 0 and $F/16$. By such means, we can easily extract useful information from the original signal into different frequency bands and at the same time the information is matched to the related time period. An example, given in Fig. 27, illustrates the procedure. The original signal is one cycle of a post-fault current signal, as shown in Fig. 27 (a). We use $db5$ wavelet to make a 5 level decomposition. The reconstructed versions of each detail and the approximation are shown in Fig. 27 (b). The information of original signal is clearly represented at each frequency band. The original signal can be reconstructed by adding up those wavelet signals at the same sample point. The wavelet toolbox in MATLAB provides a lot of useful techniques for wavelet analysis [118].

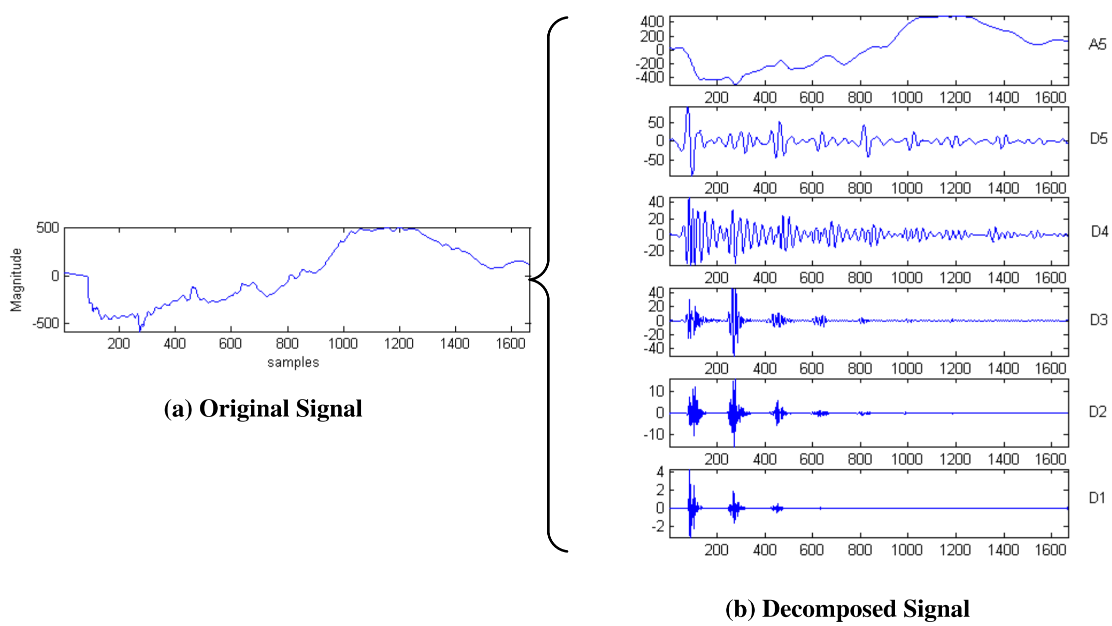

Fig. 27. Wavelet multi-resolution analysis for a fault signal

D. Design of the New Protection Scheme

1. Overview of the Scheme

The framework of the entire protection scheme is shown in Fig. 28. The goal is to implement boundary protection and at the same time provide the fault type classification using one end transmission line data. We assume that standard design of an intelligent electronic device (IED) can be adjusted to meet the requirement of the proposed scheme.

The three-phase secondary voltage and current signals shown in Fig. 28 are obtained at the sampling rate of $200kHz$. The zero-sequence voltage and current are obtained by adding up the phase values. Through the signal preprocessing stage, the pre-fault steady state component is removed from each signal. Then the wavelet multi-resolution analysis is used for decomposing each signal into low frequency approximation and high frequency details. The information is used for extracting the

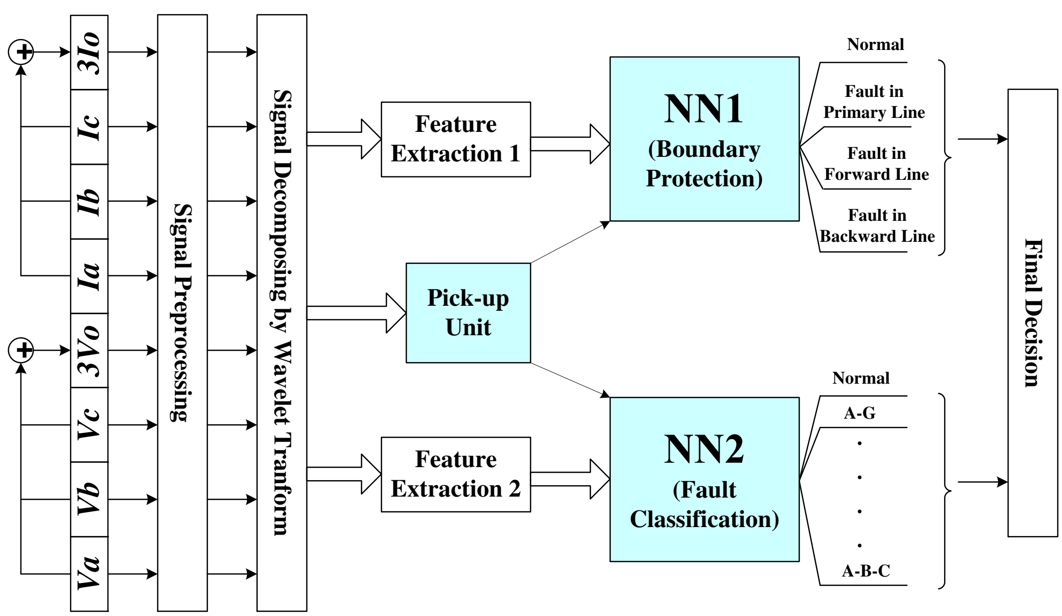

Fig. 28. Block diagram of proposed boundary protection scheme

features and forming the patterns for neural network algorithm. Two neural networks are trained to handle the boundary protection and fault classification respectively. The final conclusion can be made by simultaneously combining the conclusions of the two neural networks and then appropriate actions should be issued by the relay. A pick-up unit is introduced in front of the neural network algorithms as a threshold to screen the non-fault disturbances in low frequency band (such as overload, power swing, etc.) and in high frequency band (such as noise, switching, lightning, etc.).

2. Feature Extraction

The obtained voltage and current samples are preprocessed using (3.7) in last chapter to reduce the impact from the pre-fault load and non-fault disturbances such as overload and power swing. Only the post-fault superimposed voltage and current waveforms are presented in the selected features.

The features used as inputs of the neural network are extracted from samples in a half cycle sliding window. At every time step after preprocessing stage, the eight-channel signals are sent to the wavelet transform stage. Using the scheme shown in Fig. 26, the signals are decomposed using $db5$ wavelet to level 5. Since the sampling rate is $200kHz$, the obtained coefficients $A5$, $D5$, $D4$, $D3$, $D2$ and $D1$ match the frequency band of $0-3.125kHz, 3.125-6.25kHz, 6.25-12.5kHz, 12.5-25kHz, 25-50kHz, 50-100kHz$ respectively. Those values are used for feature extraction in the pick-up unit and in the neural networks.

For the pick-up unit, the purpose is to avoid the non-fault disturbances. The method is flexible and easy to realize. For instance, we can compare the energy spectrum of the approximation $A5$ and detail $D3$ of three-phase currents with the pre-defined thresholds, as shown in (4.3). If the condition is met in any phase, the boundary detection and fault classification are activated.

$$[E\left(A_5\right) > Threshold_1] \,\&\, [E\left(D_3\right) > Threshold_2] \tag{4.3}$$

where

$$E\left(A_5\right) = \sum_{k=1}^{n} I^2_{p-app-A5}(k)\triangle t; \qquad p = a, b, c$$
$$E\left(D_3\right) = \sum_{k=1}^{n} I^2_{p-det-D3}(k)\triangle t; \qquad p = a, b, c$$

$I_{p-app-A5}$ and $I_{p-det-D3}$ represent the wavelet signals at $A5$ and $D3$ respectively, as shown in Fig. 27.

$\triangle t$ is the time step for the samples. n is the number of total samples in a data window.

The pattern arranged for boundary protection is shown in Fig. 29 (a). For that pattern, there are four features obtained for one of the phase voltages and currents. Therefore the pattern dimension is 24×1. The four features in each phase are defined as follows:

$$\begin{aligned} x_1 &= \log\left[E\left(D_1\right)/E\left(D_5\right)\right] \\ x_2 &= \log\left[E\left(D_1\right)/E\left(D_4\right)\right] \\ x_3 &= \log\left[E\left(D_2\right)/E\left(D_5\right)\right] \\ x_4 &= \log\left[E\left(D_2\right)/E\left(D_4\right)\right] \end{aligned} \tag{4.4}$$

where $E(D_x)$ is the energy spectrum at detail x and the definition is the same as in (4.3).

The reason for this arrangement is explained next. As mentioned in Section B, the main feature differences between the external faults and internal faults are preserved in their high frequency components. The higher is the frequency, the more

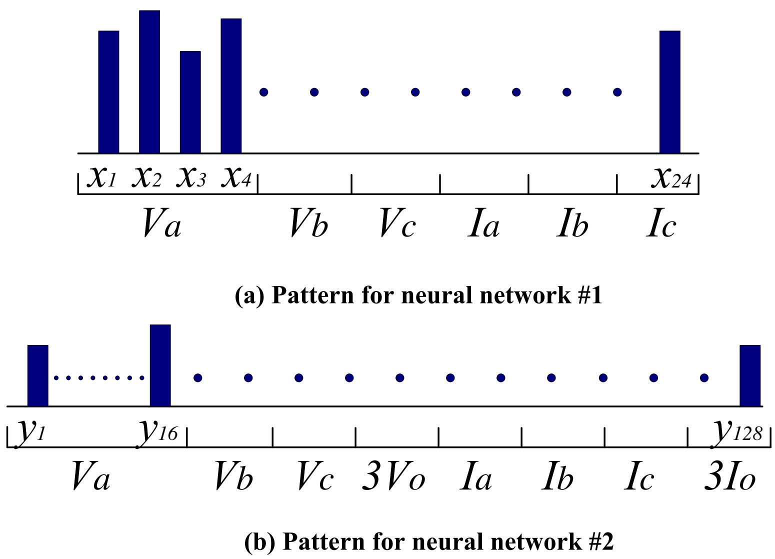

Fig. 29. Pattern arrangement for two neural networks

prominent the feature difference. Therefore, the energy spectra of higher frequency details are taken as the main features. The absolute values of the energy spectra of higher frequency details are strongly dependent on different fault type, fault resistance and fault angles, etc. To reduce that influence, the energy spectra of the lower frequency details are taken as the reference. If only one high frequency detail and one low frequency detail are used, it is easy to lose the robustness and the redundant information obtained by wavelet transform is wasted. Therefore, as shown in (4.4), we take the two highest frequency details as main features and the two lowest frequency details as references.

The pattern arranged for fault classification is shown in Fig. 29 (b). For that pattern, there are 16 features per phase obtained in one cycle of voltage or current signals. The zero-sequence voltage and current are also taken into account for indicating whether the ground is involved during the fault. The entire input pattern dimension is 128×1. The features are the samples decimated through the approximation coefficients:

$$(y_1, \ldots, y_{16}) = Decimated[Coef(A_5)] \tag{4.5}$$

3. Neural Network Training and Testing

The final stage of this approach is to train and test the two neural networks using simulation and field data. Thousands of fault scenarios could be generated taking into account the different fault types, locations, resistances and inception angles. For a single scenario, two corresponding patterns as shown in Fig. 29 are formed for the two neural networks respectively. Both of the networks form their pattern prototypes (clusters) during the training. The neural networks are then tested by another data set. If the performance is acceptable, it can be used online.

It should be noted that the patterns shown in Fig. 29 (a) and Fig. 29 (b) need to be normalized into the range of $[-1, 1]$ before the training and testing process. A general equation is defined as:

$$p = 2 \times [p - min(p)]/[max(p) - min(p)] - 1 \tag{4.6}$$

where $min(p)$ and $max(p)$ are the minimum and maximum values of the entire input space of feature p.

For neural network #1, the $min(p)$ and $max(p)$ must be found individually for each feature, and they are defined as:

$$\begin{aligned} min(x_i) &= min[x_{1i}, \ldots, x_{ki}]; \\ max(x_i) &= max[x_{1i}, \ldots, x_{ki}] \end{aligned} \tag{4.7}$$

where k represents the number of the training patterns.

For neural network #2, only four $min(p)$ and $max(p)$ are needed. Equation (4.8) gives the pairs for features of phase voltages $y_i(V_a, V_b, V_c)$. The values for $y_i(3V_0)$, $y_i(I_a, I_b, I_c)$ and $y_i(3I_0)$ are calculated in a similar way.

$$min[y_i(V_a, V_b, V_c)] = min \begin{bmatrix} y_{1,1}(V_a), & \ldots, & y_{k,16}(V_a) \\ y_{1,1}(V_b), & \ldots, & y_{k,16}(V_b) \\ y_{1,1}(V_c), & \ldots, & y_{k,16}(V_c) \end{bmatrix}$$

$$max[y_i(V_a, V_b, V_c)] = max \begin{bmatrix} y_{1,1}(V_a), & \ldots, & y_{k,16}(V_a) \\ y_{1,1}(V_b), & \ldots, & y_{k,16}(V_b) \\ y_{1,1}(V_c), & \ldots, & y_{k,16}(V_c) \end{bmatrix} \tag{4.8}$$

4. Advantages of Proposed Boundary Protection Scheme

The advantages of the proposed boundary protection scheme are summarized as follows:

- The wavelet transform provides an efficient way to extract signal components at different frequency bands.
- The protection tasks are distributed into two neural networks so that each neural network has different task.
- The signal preprocessing stage eliminates most of the influences from pre-fault loads, system conditions and power swings.
- Both high frequency details and low frequency approximations are being used in the proposed method and that can avoid confusing faults with other kinds of non-fault disturbances.
- Both neural networks take half cycle data window, therefore the protection speed is satisfied.

E. Summary

A new approach is introduced aiming at solving the problem of differentiating the internal faults from external using local measurements from one end of transmission line and providing the exact fault type at the same time. The proposed approach is an extension of the neural network based fault diagnosis introduced in last chapter. The design of the new approach is more attractive in its application. It utilizes advanced signal processing and artificial intelligence techniques to realize accurate boundary protection. It should be pointed out that the implementation of the proposed method needs to take into account the capability of existing instrument transformers and IEDs to provide the required input signals. With the fast development of computer hardware, optical instrument transformer, signal processing techniques, the implementation of the proposed approach could be realized in the near future. The main shortcoming of existing non-unit transmission line protection scheme, which is inability to protect the entire length of the transmission line, will be greatly improved. In Chapter VI, an integrated real time fault analysis tool combining neural network and synchronized sampling based approaches will be introduced. In order to make the integrated analysis tool feasible based on the existing available equipment in the industry, the neural network based fault diagnosis approach introduced in the last chapter is used. From the performance study to be shown in Chapter X, the neural network based approach still has difficulties detecting faults occurring around the line boundaries. When the required hardware is available, the approach introduced in this chapter can substitute the neural network part of the integrated analysis tool to achieve very accurate fault diagnosis, even for the faults occurring around line boundaries. The proposed protection scheme in this chapter will be verified by the transient simulation program, and its performance will be reported in Chapter X.

CHAPTER V

FAULT DIAGNOSIS USING SYNCHRONIZED SAMPLING *

A. Introduction

As mentioned in Chapter II.B, the fault diagnosis schemes for transmission line protection can be classified into two categories: (a) non-unit protection using measurements from one transmission line end, and (b) unit protection using measurements from two ends. When using measurements from one end the algorithm usually needs to have assumptions about fault resistance, source impedance, remote end infeed, etc. When the relay settings are calculated to cover certain system condition, the performance of relay maybe degraded when the system conditions are quite different from expected. The methods based on the neural networks as described in the last two chapters could improve the performance against those problems by elaborate training and enhanced feature extraction. When using measurements from two ends the algorithms are more accurate because the required information to derive explicit fault characteristics is available. That is more important when developing accurate fault location schemes. Currently, the approaches using two ends data become more feasible since the new techniques such as Global Positioning System (GPS), Phasor Measurement Unit (PMU), Fiber Optics and high-speed Ethernet are further developed and applied in power system [15, 119, 120].

In this chapter, an fault diagnosis technique using synchronized sampling [42, 43, 121] is enhanced to achieve very accurate fault analysis scheme using measurements from two ends of a transmission line. A complete fault diagnosis scheme including

*Part of the material in this chapter is reprinted from "Complete fault analysis for long transmission line using synchronized sampling" by Nan Zhang and Mladen Kezunovic, *Presented in IFAC Symposium on Power Plants and Power Systems Control*, Kananaskis, Canada, June 2006, ©2006 IFAC.

fault detection, classification and location is designed based on the previously developed fault location algorithms described in [42, 43, 121]. A review of the background of synchronized sampling algorithm is presented in Section B, and it is followed by the description of new fault diagnosis scheme in Section C.

B. Background of Synchronized Sampling Algorithm

The synchronized sampling algorithm was originally developed for the fault location techniques [43, 121–123]. The implementation of fault location for short line model and lossless long line model is described in [43]. The modified version to take into account the series losses in the line is developed in [121].

The theoretical principle of the synchronized sampling algorithm is demonstrated using Fig. 30, which shows a section of three-phase transmission line that is simplified using a one-line diagram. The inputs of the algorithm are raw samples of voltage and current synchronously taken from two ends of the transmission line. The synchronized samples are obtained with the help of Global Positioning System (GPS) and the data will be communicated from one end of transmission line to another.

For a healthy transmission line, the line parameters are homogeneous. The voltage and current at one point of the line can be expressed using the voltage and current at any other point along the line by certain linear relationship:

$$v_p = L^v\left(v_q, i_q, d^{'}\right); \quad i_p = L^i\left(v_q, i_q, d^{'}\right) \tag{5.1}$$

where $d^{'}$ is the distance between the point p and q.

With this idea, the voltage and current at any point of the line can be expressed using sending end voltage and current samples and receiving end samples at the same time by such linear relationship as in (5.1):

When the fault is incepted, the transmission line is broken up into two homogeneous sections, as shown in Fig. 30. In this case, the above statement is true only at the fault location [43].

$$v_F = L^v\left(v_S, i_S, d_S\right); \quad v_F = L^v\left(v_R, i_R, d_R\right) \tag{5.2}$$

A universal equation for the fault location can be derived as (5.3).

$$L^v\left(v_S, i_S, d_S\right) - L^v\left(v_R, i_R, d_R\right) = 0 \tag{5.3}$$

Since $d_S + d_R$ equals to ling length d, the only unknown variable in (5.3) will be fault location d_S. That is the basic idea of how to derive fault location algorithms [43]. Different algorithms use different linear relationship L^v to find fault location.

For transmission line, the voltage and current along the line are functions of the

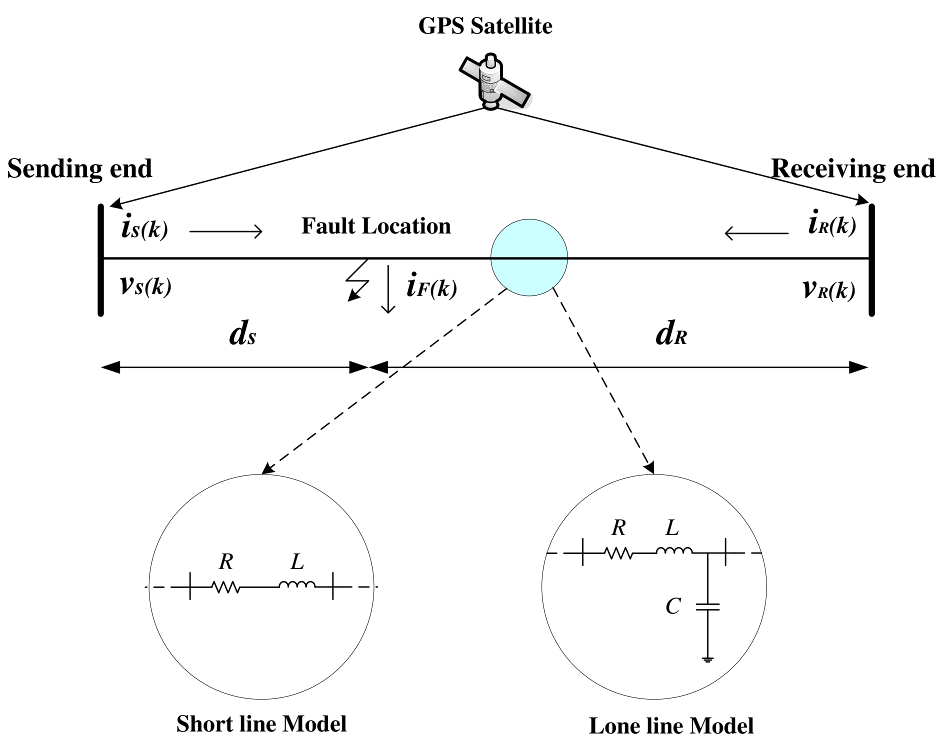

Fig. 30. A hypothetical three-phase transmission line

distance x and the time t,

$$\begin{aligned} \frac{\partial v(x,t)}{\partial x} &= -Ri(x,t) - L\frac{\partial i(x,t)}{\partial t} \\ \frac{\partial i(x,t)}{\partial x} &= -Gv(x,t) - C\frac{\partial v(x,t)}{\partial t} \end{aligned} \tag{5.4}$$

where R, L, G, C are per-unit-length resistance, inductance, conductance and capacitance respectively.

For short transmission line model that can be represented using lumped parameters, G, C in (5.4) can be neglected. The fault location can be calculated directly by solving the differential equations. The explicit form of fault location can be represented using least square estimate method for a three-phase system [43].

$$d_S = \frac{-\sum_{m=a,b,c}\sum_{k=1}^{N} P_m(k)Q_m(k)}{\sum_{m=a,b,c}\sum_{k=1}^{N} Q_m^2(k)} \tag{5.5}$$

where

$$\begin{aligned} P_m(k) &= v_{mR}(k) - v_{mS}(k) - d\sum_{p=a,b,c}\left[\left(R_{mp} + \frac{L_{mp}}{\triangle t}\right)i_{pR}(k) - \frac{L_{mp}}{\triangle t}i_{pR}(k-1)\right] \\ m &= a,b,c \end{aligned} \tag{5.6}$$

$$\begin{aligned} Q_m(k) &= \sum_{p=a,b,c}\left\{\left(R_{mp} + \frac{L_{mp}}{\triangle t}\right)[i_{pR}(k) + i_{pS}(k)] - \frac{L_{mp}}{\triangle t}[i_{pR}(k-1) + i_{pS}(k-1)]\right\} \\ m &= a,b,c \end{aligned} \tag{5.7}$$

where k is the present sample point; $\triangle t$ is the time period with respect to the sampling frequency; subscripts S and R stand for the values at sending end and receiving end respectively.

For long line model represented by distributed parameters, the C can not be neglected in (5.4). A pair of recursive equations are obtained [121]. *

* The original reference [121] has a typo for a sign in (5.8)

$$\begin{aligned} v_j(k) =& \frac{1}{2}\left[v_{j-1}(k-1)+v_{j-1}(k+1)\right]+\frac{Z_c}{2}\left[i_{j-1}(k-1)-i_{j-1}(k+1)\right] \\ &-\frac{R\triangle x}{4}\left[i_{j-1}(k-1)+i_{j-1}(k+1)\right]-\frac{R\triangle x}{2}i_j(k) \end{aligned} \tag{5.8}$$

$$\begin{aligned} i_j(k) =& \frac{1}{2Z_c}\left[v_{j-1}(k-1)-v_{j-1}(k+1)\right]+\frac{1}{2}\left[i_{j-1}(k-1)+i_{j-1}(k+1)\right] \\ &+\frac{R\triangle x}{4Z_c}\left[i_{j-1}(k+1)-i_{j-1}(k-1)\right] \end{aligned} \tag{5.9}$$

where $\triangle x = \triangle t/\sqrt{LC}$ is the distance that the wave travels with a sampling time step $\triangle t$; $Z_c = \sqrt{L/C}$ is the surge impedance. Subscript j is the position of the discretized point of the line and k is the sample point.

Since the explicit form of fault location can not be obtained, an indirect approach is used to calculate the final fault location [121]. The scheme is demonstrated using Fig. 31.

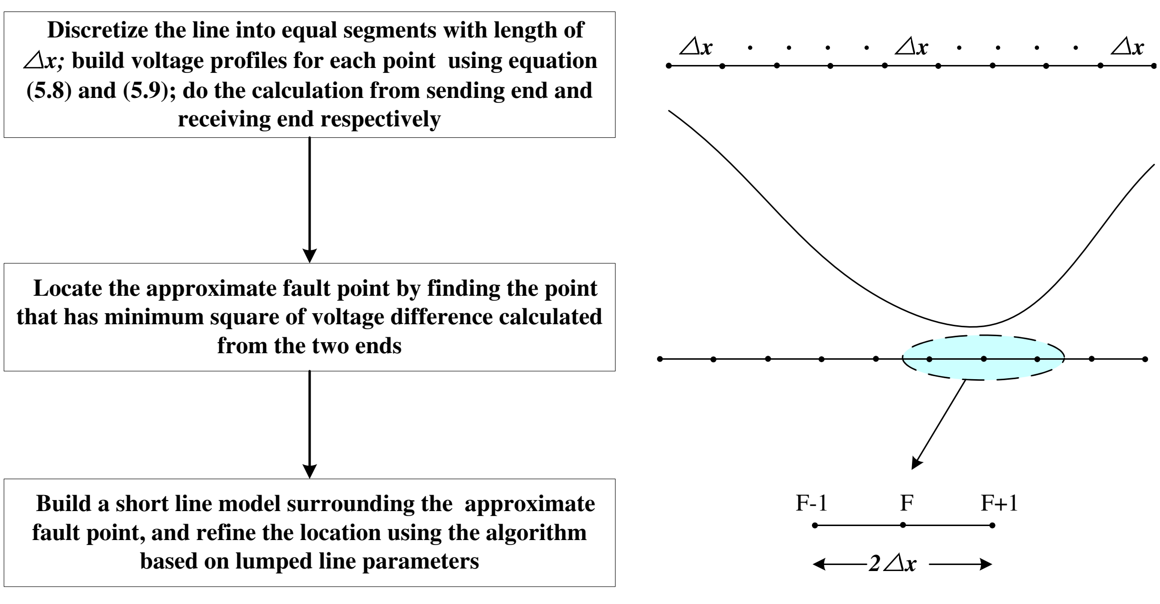

Fig. 31. Procedure of fault location

C. Design of the Complete Fault Diagnosis Scheme

As an extension of previously developed fault location scheme [42, 43, 121], a complete fault diagnosis tool will be developed in this section. Fault detection and classification part will be added and the improvement of the fault location part will be provided. The previous approach, especially for the long line model, requires transmission of large data-set and a very complex calculation procedure. Those issues make it too slow for online application. Since the information obtained from fault detection and classification may be used for fault location, the calculation only needs to be performed using post-fault value in the faulted phase. The accuracy will be improved and calculation time will be reduced.

1. Theoretical Basis for Fault Detection and Classification

For short line model, define

$$i_d(k) = i_S(k) + i_R(k) \tag{5.10}$$

As shown in Fig. 30, when there is no fault on the transmission line, $i_d(k)$ equals to zero at any data sample. When there is an fault on the line, $i_d(k)$ equals to the fault current $i_F(k)$. Since the current samples are synchronized at both ends of the transmission line, $i_d(k)$ can be obtained at every sample to detect if there is an internal fault. It is used as the main feature for the short line model in the following fault diagnosis scheme.

For long line model, the two equations (5.8) and (5.9) define the relation of voltage and current samples between two points on the transmission line with the distance of $\triangle x$, as shown in Fig. 32. Combining (5.8) and (5.9) to eliminate $v_{j-1}(k+1)$ and

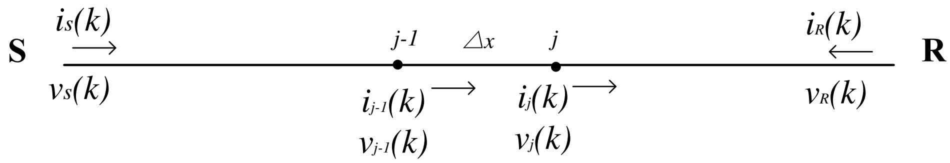

Fig. 32. A homogeneous transmission line

$i_{j-1}(k+1)$, we get

$$i_j(k)\left[1+\frac{R\triangle x}{2Z_c}\right]+\frac{v_j(k)}{Z_c}=\frac{v_{j-1}(k-1)}{Z_c}+i_{j-1}(k-1)\left[1-\frac{R\triangle x}{2Z_c}\right] \tag{5.11}$$

When there is no internal fault on the line, which means the line parameters are homogeneous, equation (5.11) can be expressed as the relation between the sending end and receiving end samples. Substitute $j-1$ with S and j with R and note the direction of I_R . Equation (5.11) is changed to

$$-i_R(k)\left[1+\frac{Rd}{2Z_c}\right]+\frac{v_R(k)}{Z_c}=\frac{v_S(k-P)}{Z_c}+i_S(k-P)\left[1-\frac{Rd}{2Z_c}\right] \tag{5.12}$$

where d is the length of the transmission line, P is the sample difference if the wave travels from the sending end to the receiving end with the time of $P\triangle t$.

Define

$$i_{d1}(k)=i_S(k-P)\left[1-\frac{Rd}{2Z_c}\right]+i_R(k)\left[1+\frac{Rd}{2Z_c}\right]+\frac{v_S(k-P)}{Z_c}-\frac{v_R(k)}{Z_c} \tag{5.13}$$

Similarly, we can get another form of (5.12) as

$$-i_S(k)\left[1+\frac{Rd}{2Z_c}\right]+\frac{v_S(k)}{Z_c}=\frac{v_R(k-P)}{Z_c}+i_R(k-P)\left[1-\frac{Rd}{2Z_c}\right] \tag{5.14}$$

And define

$$i_{d2}(k)=i_R(k-P)\left[1-\frac{Rd}{2Z_c}\right]+i_S(k)\left[1+\frac{Rd}{2Z_c}\right]+\frac{v_R(k-P)}{Z_c}-\frac{v_S(k)}{Z_c} \tag{5.15}$$

When there is no internal fault on the line, obviously $i_{d1}(k)$ and $i_{d2}(k)$ should equal to zero.

Now consider the situation of an internal fault. As shown in Fig. 33, at a certain time, the fault current and voltage at the fault point can be expressed as the signals from sending end and receiving end:

$$\begin{aligned} i_F(k) &= i_{FS}(k) + i_{FR}(k) \\ v_F(k) &= v_{FS}(k) = v_{FR}(k) \end{aligned} \tag{5.16}$$

Note that for long transmission line with distributed line parameters, $i_S(k) \neq i_{FS}(k)$ and $i_R(k) \neq i_{FR}(k)$ since there is a time delay for the wave traveling from one point to another. According to (5.12), if we note the current direction for each current signal shown in Fig. 33, we have

$$\frac{v_S(k-P_S)}{Z_c} + i_S(k-P_S)\left[1 - \frac{Rd_S}{2Z_c}\right] = i_{FS}(k)\left[1 + \frac{Rd_S}{2Z_c}\right] + \frac{v_{FS}(k)}{Z_c} \tag{5.17}$$

$$-i_R(k)\left[1 + \frac{Rd_R}{2Z_c}\right] + \frac{v_R(k)}{Z_c} = \frac{v_{FR}(k-P_R)}{Z_c} - i_{FR}(k-P_R)\left[1 - \frac{Rd_R}{2Z_c}\right] \tag{5.18}$$

where P_S and P_R are the sample differences if the wave travels from the fault point to the sending end with the time of $P_S \triangle t$ and to the receiving end with the time of $P_R \triangle t$ respectively. d_S and d_R are the distances from the fault point to the sending end and to the receiving end respectively.

Substitute k with $k - P_R$ in (5.17), and minus (5.18) to eliminate $v_F(k - P_R)$.

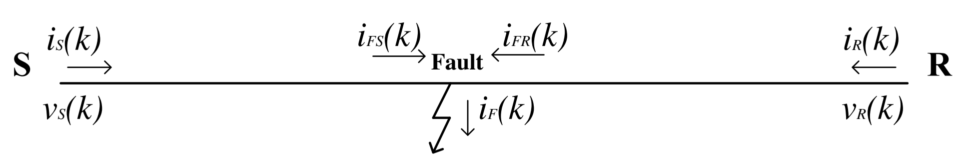

Fig. 33. A faulted transmission line

Note that $P = P_S + P_R$ and $d = d_S + d_R$, then the left-hand side is changed to

$$\begin{aligned} i_S(k-P)\left[1-\frac{Rd}{2Z_c}\right] + i_R(k)\left[1+\frac{Rd}{2Z_c}\right] + \frac{v_S(k-P)}{Z_c} - \frac{v_R(k)}{Z_c} \\ + i_S(k-P)\frac{Rd_R}{2Z_c} - i_R(k)\frac{Rd_S}{2Z_c} \\ = i_{d1}(k) + i_S(k-P)\frac{Rd_R}{2Z_c} - i_R(k)\frac{Rd_S}{2Z_c} \end{aligned} \tag{5.19}$$

And the right-hand side is changed to

$$\begin{aligned} i_{FS}(k-P_R)\left[1+\frac{Rd_S}{2Z_c}\right] + i_{FR}(k-P_R)\left[1-\frac{Rd_R}{2Z_c}\right] \\ = i_F(k-P_R) + i_{FS}(k-P_R)\frac{Rd_S}{2Z_c} - i_{FR}(k-P_R)\frac{Rd_R}{2Z_c} \end{aligned} \tag{5.20}$$

For realistic transmission line, $\frac{Rd_S}{2Z_c} \ll 1$ and $\frac{Rd_R}{2Z_c} \ll 1$, then

$$i_{d1}(k) \approx i_F(k-P_R) \tag{5.21}$$

Similarly, if we start from (5.14), we can get

$$i_{d2}(k) \approx i_F(k-P_S) \tag{5.22}$$

With the help of synchronized sampling, the current and voltage samples used for calculating $i_{d1}(k)$ or $i_{d2}(k)$ are available from the both ends of transmission line. In our fault diagnosis scheme, $i_{d1}(k)$ is used as the main feature for long line model in fault detection and classification. The equations (5.8) and (5.9) are the recursive equations used for fault location.

For a three-phase system, all the line parameters and the measured voltage and current signals should be transformed into modal domain first to get the decoupled systems and the derivation in previous section is still fulfilled for each modal component.

We use Clarke transformation matrix T to transfer the line parameters and the measured phase values into the modal domain,

$$T = \frac{1}{\sqrt{3}} \begin{bmatrix} 1 & \sqrt{2} & 0 \\ 1 & -1/\sqrt{2} & \sqrt{3}/\sqrt{2} \\ 1 & -1/\sqrt{2} & -\sqrt{3}/\sqrt{2} \end{bmatrix} \tag{5.23}$$

$$inv(T) = \frac{1}{\sqrt{3}} \begin{bmatrix} 1 & 1 & 1 \\ \sqrt{2} & -1/\sqrt{2} & -1/\sqrt{2} \\ 0 & \sqrt{3}/\sqrt{2} & -\sqrt{3}/\sqrt{2} \end{bmatrix} \tag{5.24}$$

$$[Z, Y]_{0,1,2} = inv(T)[Z, Y]_{a,b,c}T \tag{5.25}$$

$$[v(k), i(k)]_{a-0,1,2} = inv(T) \begin{bmatrix} [v(k), i(k)]_a \\ [v(k), i(k)]_b \\ [v(k), i(k)]_c \end{bmatrix} \tag{5.26}$$

It is noted that the transformation matrix T and its inverse matrix have the unsymmetrical form. From (5.26), we can get the modal components with respect to the reference phase “a”. Similarly, we can get the modal components with respect to the phases “b” and “c” by rotation. Note that the 0-mode has the same form irrespective what the reference phase is. We can get seven sets of modal components:

$$[v(k), i(k)]_0; \quad [v(k), i(k)]_{a-1,2}; \quad [v(k), i(k)]_{b-1,2}; \quad [v(k), i(k)]_{c-1,2} \tag{5.27}$$

Those components will be selected for the uses in fault detection, classification and location. From the sequence network analysis, we can find the availability of each modal component to detect the different fault type, as shown in Table IV. It is noted that there is no unique modal component that can be used to detect all the

Table IV. Availability of different modal components to correctly detect the different fault type

	AG	BG	CG	AB	BC	CA	ABG	BCG	CAG	ABC
0	√	√	√	×	×	×	√	√	√	×
$a-1$	√	√	√	√	×	√	√	√	√	√
$a-2$	×	√	√	√	√	√	√	√	√	√
$b-1$	√	√	√	√	√	×	√	√	√	√
$b-2$	√	×	√	√	√	√	√	√	√	√
$c-1$	√	√	√	×	√	√	√	√	√	√
$c-2$	√	√	×	√	√	√	√	√	√	√

fault types. That should be noted when designing the fault diagnosis algorithms.

2. Fault Detection

In the following two sections, the fault detection and classification schemes are described for long line model. For the short line model, we just need to substitute the feature of long line model i_{d1} with the feature of short line model i_d.

Define

$$I_{d1-m} = \frac{\sum_j |i_{d1}(j)|_m}{N}; \qquad j = k-N+1, k-N+2, \ldots, k \tag{5.28}$$

where m is the related modal component, N is the number of samples in one cycle. The criterion for detecting an internal fault is given as

$$max[I_{d1-a-1}, I_{d1-b-1}, I_{d1-c-1}] \geq T_1 \tag{5.29}$$

In (5.29), a threshold is set to tolerate the model and measurement imperfection. The average value of $i_{d1}(k)$ in one cycle is compared to that threshold. The calculation is carried out using “a-1”, “b-1” and “c-1” modal components.

3. Fault Classification

Through sequence network analysis with different boundary conditions, we can find the features for classifying the fault type using different modal components [124], as shown in Table V. The entries in the table are the modal fault current components at the fault point. As derived in (5.21), $i_{d1}(k)$ is directly related to the fault current with several samples delay. Therefore, we can use $i_{d1}(k)$ to design the fault classification scheme according to the Table V.

The flowchart of fault classification is shown in Fig. 34, where i_{d1-m} has identical definition as (5.28). The thresholds T_2 and T_3 are set to tolerate the model and measurement imperfection, as well as the algorithm approximation.

4. Fault Location

For short line model, the fault location is calculated using (5.5). Since the fault type is obtained from the fault classification, the calculation is only involved in the faulted phase.

For long line model, the fault location calculation follows the methods shown in

Table V. Features for classification of different fault types

Fault Type	**Features (Phasors)**
AG	$I_{F-0} \neq 0; \quad I_{F-a-2} = 0$
BG	$I_{F-0} \neq 0; \quad I_{F-b-2} = 0$
CG	$I_{F-0} \neq 0; \quad I_{F-c-2} = 0$
AB	$I_{F-0} = 0; \quad I_{F-c-1} = 0$
BC	$I_{F-0} = 0; \quad I_{F-a-1} = 0$
CA	$I_{F-0} = 0; \quad I_{F-b-1} = 0$
ABG	$I_{F-0} \neq 0; \quad I_{F_0} + I_{F-c-1} = 0$
BCG	$I_{F-0} \neq 0; \quad I_{F_0} + I_{F-a-1} = 0$
CAG	$I_{F-0} \neq 0; \quad I_{F_0} + I_{F-b-1} = 0$
ABC	$I_{F-0} = 0; I_{F-a-1} \neq 0; I_{F-b-1} \neq 0; I_{F-c-1} \neq 0$

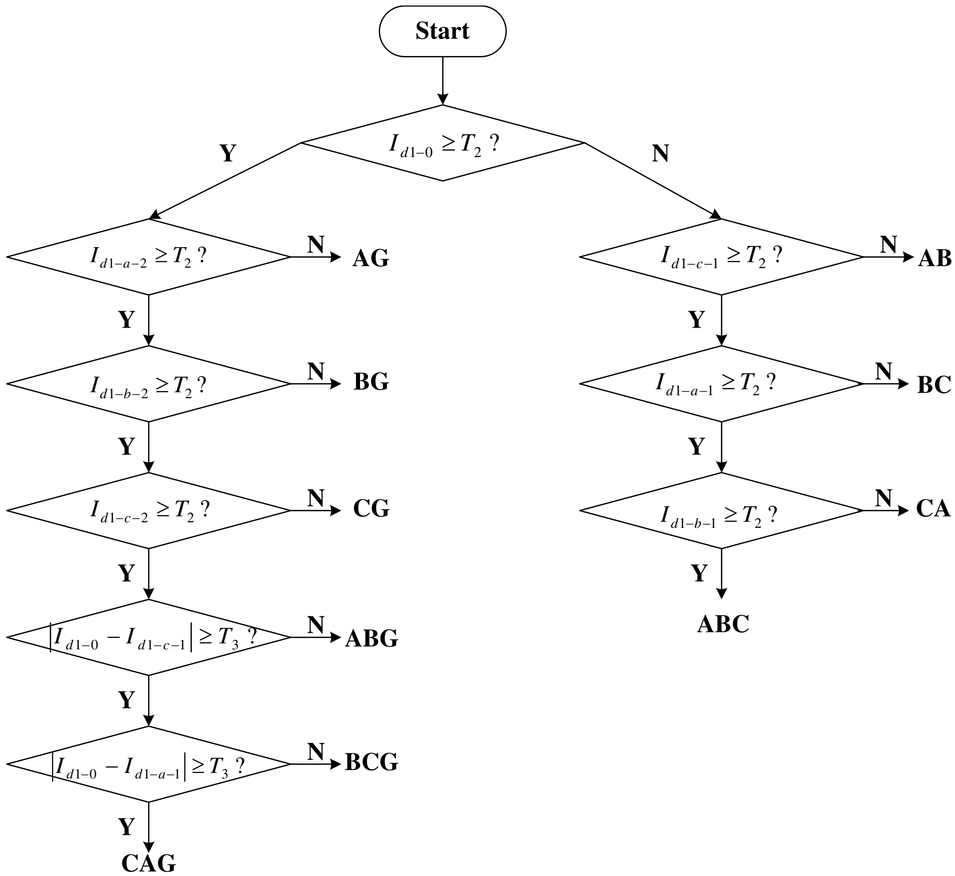

Fig. 34. Flowchart of fault classification

Fig 31. According to the fault type, the calculation will based on the selection of the prominent modal components to achieve an accurate result. The selection scheme is as follows:

- For ground fault (AG, BG, CG, ABG, BCG, CAG), the calculation is implemented using “mode 0” components. The obtained fault location is the final one.
- For AB fault, the calculation is implemented using “a-1” and “b-1” modal components. The final fault location is the average of the two results.
- For BC fault, the calculation is implemented using “b-1” and “c-1” modal com-

ponents. The final fault location is the average of the two results.

- For CA fault, the calculation is implemented using "c-1" and "a-1" modal components. The final fault location is the average of the two results.

- For three-phase fault, the calculation is implemented using "a-1", "b-1" and "c-1" modal components. The final fault location is the average of the three results.

5. Implementation of Entire Fault Diagnosis Scheme

The entire synchronized sampling based fault diagnosis including fault detection, classification and location can be implemented in the same software package. The flowchart is shown in Fig. 35. The data window used for calculation is one cycle, and the data window is moving forward with selected time step $\triangle t$. The fault is detected if the (5.29) is fulfilled for a successive cycle. Then the post-fault values are used for fault classification and fault location, using the methods demonstrated in the previous sections.

6. Advantages of Proposed Fault Diagnosis Scheme

The advantages of the proposed fault diagnosis scheme are summarized as follows:

- The proposed scheme provides a complete solution of fault detection, classification, and fault location that can be used as an independent fault analysis tool or transmission line protection scheme.

- Only time-domain data measurements are used in the calculation, and no phasor computation or relay setting issues will be involved.

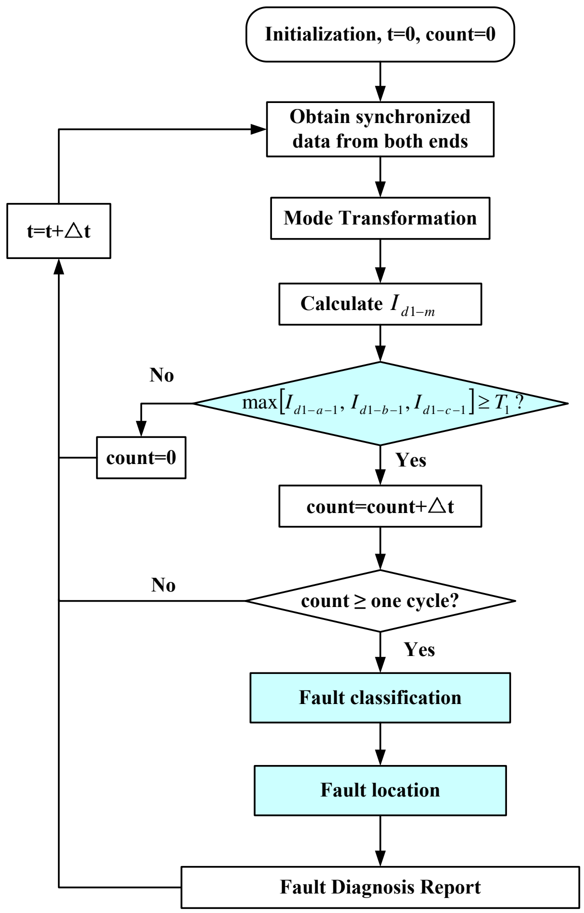

Fig. 35. Flowchart of fault diagnosis scheme using synchronized sampling

- Since synchronized sampling provides enough information for fault diagnosis, there are no assumptions about fault parameters and system conditions. The algorithm will not be affected by power swing, overload, and other non-fault situations.

D. Summary

As the previous two chapters improved the one-end measurements based protection schemes by using neural network, this chapter improves the unit protection scheme by using synchronized data samples measured at two ends of a transmission line. The traditional unit protection relies on coordinating the decisions from the non-unit protection schemes at the two ends of the transmission line, such as directional relay and distance relay. Therefore the performance will be affected by the non-unit relays. The proposed fault diagnosis scheme in this chapter collects the samples from two ends of transmission line and performs fault diagnosis using elaborate time-domain approach. The accuracy will be very high since the characteristics to describe the fault are sufficient. During the derivation of the entire scheme, there are no assumptions about the fault parameters and system conditions, therefore it is less affected by those factors. The proposed algorithm will not misoperate during the power swing since the line parameters are still homogeneous as in the normal situation. Having the accurate information from the fault detection, classification and location, one can quickly conclude whether the fault is inside of the protected line and where exactly the fault is. It will help to decide the expected operation of the relay system and correct the false trip of the healthy part of the system. The performance study of proposed approach will be reported in Chapter X.

CHAPTER VI

REAL TIME FAULT ANALYSIS TOOL INTEGRATED WITH NEURAL NETWORK AND SYNCHRONIZED SAMPLING*

A. Introduction

As mentioned in Chapter II, relay misbehavior has been a most contributing factor in power system blackouts according to the historical record [2]. To reduce the risk of a large-scale blackout, the traditional transmission line protection systems, especially those at the vulnerable areas, need to be closely monitored [125, 126]. An advanced fault analysis tool that can provide accurate and detailed fault information such as fault detection, fault type classification, internal/external fault differentiation, fault location, etc could be used as a reference to monitor traditional relays.

Different new techniques have been used as the fault analysis tools in the past. An expert system based approach is described in [127] and a phasor measurement unit (PMU) based approach is described in [128]. Those approaches still depend on the phasor calculation. A neural network based fault analysis tool is developed in [129], but it is hard to obtain a precise fault location since neural network is not good at precisely classifying the continuous variables. A synchronized sampling based fault analysis is introduced in [42], but the application is limited to short lines.

When used online as a relay monitoring reference, the fault analysis tool must be very fast and accurate, providing comprehensive information for system operator to better understand the disturbances and hence issue a correct response to reduce the impact from the disturbances. It is still hard to find a perfect and unique technique so

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far to provide a superior protection scheme due to the algorithm and hardware limits. A combination of different new techniques might be a better solution to achieve a high performance and simplify the real time decision making.

Chapter III to Chapter V introduced new fault diagnosis approaches using neural networks and synchronized sampling. They can be successfully implemented as independent relays or referent solutions in a fault analysis tool including the functions of fault detection, classification and location. They can be integrated as a powerful real time fault analysis tool since both of the techniques use time-domain signals directly and are derived using the principles that are much more accurate than the traditional transmission line relays.

This chapter proposes a new integrated fault analysis tool for transmission lines using mentioned two techniques. An overall consideration of the application of the fault analysis tool is discussed in Section B. The functions of fault analysis tool are provided in Section C. Section D and E outline the detailed hardware configuration and software implementation respectively. Section F summaries the benefits of the proposed fault analysis tool.

B. Overall Considerations

The objective of the automated fault analysis tool proposed in this chapter is to work in parallel with traditional relay and to be a relay monitoring tool which uses more accurate fault detection, fault type classification and fault location. The new fault analysis tool should have the capability to confirm if the relay operation is correct. Such a fault analysis tool can be used as one of the following three schemes:

Localized scheme: By this scheme, the fault analysis tool is installed in the substation and used as real time relay monitoring tool. If authorized, it can correct the relay operations when it confirms that the relay has made a wrong decision and misoperated. Only the fault analysis result is sent to the control center.

Centralized scheme: By this scheme, the fault analysis tool is installed in the control center and performs the analysis for all relays that detect the disturbance. The tool will not correct the relay operations directly but will serve as a reference for the system operator. The system operator will coordinate the system and control means to make a better decision to mitigate the disturbance.

Hybrid scheme: By this scheme, part of the fault analysis tool such as fault detection and classification can be installed in local substation to monitor the traditional relays. If different results are obtained between fault analysis tool and traditional relay, an alarm signal is sent to the control center. Then another part of the tool such as fault location confirms the outcome and the system operator will take the corrective controls.

The combination of neural network algorithm and synchronized sampling algorithm can realize any of the above schemes. This chapter will focus on the fault analysis tool design aimed at a localized scheme since the local monitoring tool is the major concern of this dissertation. The design can also be used in the other two schemes with minor changes in hardware and software. Chapter III and Chapter IV described two kinds of neural network based fault diagnosis scheme. The former one is based on simple preprocess of the raw samples and the latter one requires the wavelet transform of high-sample-rate data. The scheme incorporating the former neural network approach is the focus since it can be realized using the existing technology available in the industry. When high-speed sampling unit and optical transformers are commonly used in the near future, the developed boundary protection scheme in Chapter IV can be used along with the synchronized sampling scheme to achieve a much better fault analysis tool since the neural network based approach can also distinguish the internal faults from the external in this case.

C. Functions of Integrated Fault Analysis Tool

The functions of the integrated fault analysis tool are taken from the fault diagnosis schemes from the previous chapters. The major components of the integrated analysis tool are introduced here and their role in the entire scheme will be demonstrated in Section E.

Pick-up Unit: Equation (3.8) in Chapter III is used for pick-up function. As mentioned earlier, it is effective in locating the exact fault inception point, which is important for both neural network based and synchronized sampling based approaches since both approaches use the post-fault values in calculation.

Neural Network based Fault Detection and Classification (NNFDC): Neural network based approach as shown in Fig. 24 is used for fault detection and classification. It is also make an initial estimate of the fault zone. Since it uses one-end measurements, it can detect the fault as fast as distance relay. If necessary, a first comparison could be made between the result of NNFDC and distance relay.

Synchronized Sampling based Fault Detection and Classification (SSFD, SSFC): Synchronized sampling based fault detection and classification introduced in Chapter V are used in the proposed fault analysis tool. Since it uses two-end measurement, it can verify whether the fault is internal or external, which is very helpful in eliminating the unnecessary removal of healthy lines. SSFC also provides a verification of the result of NNFDC. Since SSFD and SSFC do not require high-sampling-rate data, the delay in data communication is moderate.

Synchronized Sampling based Fault Location(SSFL): Synchronized sampling based fault location algorithm mentioned in Chapter V are used here. It is the last step in verifying the previous conclusion and finding the exact fault location for fast restoration of the system. It requires relatively high-sampling-rate data, but it can still complete the computation in the range of seconds.

D. Hardware Configuration

A potential hardware configuration of proposed fault analysis scheme is shown in Fig. 36. GPS receiver, high-speed communication link and high-speed sampling unit are required for SSFL to achieve a high accuracy of fault location. The communication can be through fiber-optic links or high-speed Ethernet. The sampling unit can be phasor measurement unit (PMU) or digital fault recorder (DFR) as long as synchronized samples are made available. Unlike traveling wave based algorithms which typically require the sampling rate in the order of $300kHz$, the fault location algorithm in this fault analysis tool typically needs $20kHz$ for long transmission line and lower sampling rate (such as 32 points per cycle) for short line. Such a sampling rate can be reached by existing PMU [130], DFR [131], or other devices. The other

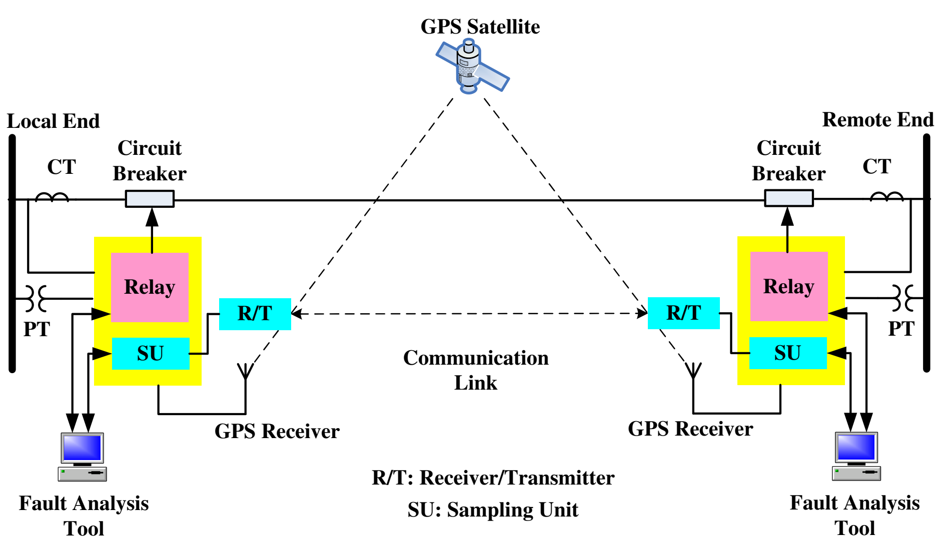

Fig. 36. Hardware configuration of real time fault analysis tool

components in the fault analysis tool, PU, NNFDC, SSFD and SSFC, just need the data with low sampling rate. As long as the hardware requirements are satisfied for the SSFL, the measured data may be obtained by software decimation from the original sampled data set obtained with higher sampling rate.

E. Software Implementation

The flowchart of the integrated fault analysis tool is demonstrated using Fig. 37 and described as follows:

Step 1. Initialization. $count = 0$.

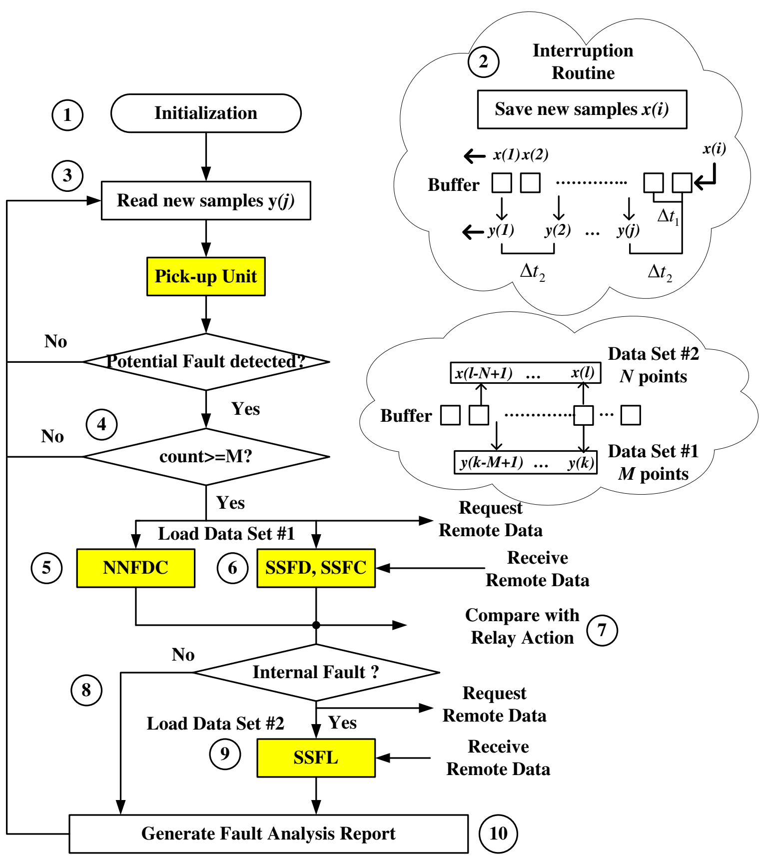

Fig. 37. Flowchart of the real time fault analysis tool

Step 2. Interruption routine. At every $\triangle t_1$, save the new data sample set $x(i)$ from the high-speed sampling unit to the buffer. $\triangle t_1$ is the time step of the high-speed sampling unit.

Step 3. At $\triangle t_2$, read the newest data $y(j)$ from the buffer. $\triangle t_2$ is the time step used in PU, NNFDC, SSFD and SSFC. Use equation (3.8) to calculate if the potential fault is detected. If yes, $count = count + 1$. Otherwise, $count = 0$, go to step 3.

Step 4. If $count \geq M$ (M is the number of samples in one cycle with respect to time step $\triangle t_2$), record the present sample point k, load one cycle of decimated post-fault data $y(k - M + 1), \ldots, y(k)$ to NNFDC, SSFD and SSFC, and request the related data from remote end. Otherwise, go to step 3.

Step 5. Run fault detection and fault classification using NNFDC.

Step 6. Receive measured data from the remote end. Confirm whether there is an internal fault using SSFD. Run fault fault classification using SSFC.

Step 7. Compare the fault analysis result with relay action. Correct the relay unintended operation if necessary.

Step 8. If an internal fault is confirmed, load one cycle of post-fault data $x(l - N + 1), \ldots, x(l)$ with high sampling rate to SSFL, and request related data from remote end. Note that $x(l) = y(k)$ and N is the number of samples in one cycle with respect to time step $\triangle t_1$. Otherwise, go to step 10.

Step 9. Receive measured data from the remote end. According to the fault type concluded by NNFDC and SSFC, select the mode to locate the fault precisely using SSFL.

Step 10. Generate the fault analysis report and send to control center. $count = 0$. Go to step 3.

The time delay for the data transmission from one end of transmission line to the other end can be crudely estimated as:

$$T = \frac{\text{size of data}}{\text{baud rate}} \tag{6.1}$$

When transmitting a data package of one cycle of three-phase voltage and current samples using a baud rate of $1Mb/s$, the time delays for the SSFD and SSFL are $0.012s$ and $0.128s$ respectively. Note that the sampling rates are 32 points per cycle for SSFD and 333 points per cycle for SSFL and assume the data set of the sample is *doubled* ($64bits$).

F. Benefits of Proposed Fault Analysis Tool

The benefits of the proposed fault analysis tool are summarized as follows:

- Both techniques use time-domain measurements. It is easy to share the data internally and get away from the phasor calculation.
- The integrated solution inherits the advantages from both techniques. It preserves the strength of neural network algorithm in fault classification and that of synchronized sampling algorithm in fault location.
- Using two different techniques, it is easy to check the consistency of decisions made by each technique to get a more convincible fault analysis result.
- The speed of the algorithm can be guaranteed for real time application.

G. Summary

An integrated real time transmission line fault analysis tool that can offer accurate fault detection, classification, internal/external fault differentiation, and fault location is proposed. Based on the advantages described in this chapter, the fault analysis tool may be used as online reference for traditional distance relay and is a major part of local relay monitoring tool, which will be introduced in Chapter VIII. The two techniques used in the fault analysis tool complement each other to achieve complete fault analysis functions and provide self-confirmation. The integrated tool uses time-domain data as inputs. The data processing errors in calculating phasors are avoided. The relay setting and coordination work when applying traditional relays is also avoided. As mentioned in Chapter I, the phasor calculation error and improper relay setting during the extreme system conditions may be a potential factor contributing to a cascading blackout. The integrated tool gets away from those issues and hence it is immune from triggering cascading blackouts in that sense. The performance study of the proposed scheme is compared to the traditional distance relay, as shown in Chapter X.

CHAPTER VII

REAL TIME RELAY MONITORING TOOL USING EVENT TREE ANALYSIS

A. Introduction

Last chapter proposed a powerful real time fault analysis tool, which can be used in parallel with distance relay to provide a fault diagnosis reference. In order to effectively use the proposed fault analysis tool to monitor relay actions and provide a local diagnostic support to the system operator, a handy tool for monitoring relay operation is needed.

Event tree analysis (ETA) is a commonly used technique for analyzing the reliability of an event-response system [132–134]. It was first applied in the risk assessments for the nuclear industry but is now utilized by a lot of other industries such as chemical processing, gas production and transportation. It is also been used recently in protection system reliability analysis and dynamic analysis in power system [135–138]. The Event Tree Analysis, as indicated by its name, has a structure of forward (tree-like) symbolic logic modeling technique. This technique explores system responses to an initial "challenge" and enables assessment of the probability of an unfavorable or favorable outcome [132]. It fits our need for real time relay monitoring, whose objective is to explore the relay actions following the initial event of a disturbance. Thus ETA is selected and modified as our event analysis tool for monitoring relay operations.

In Section B, the original structure of ETA is outlined. A modified structure to fit relay monitoring purpose is provided in Section C. A prototype design of the different event trees for relay is given in Section D. Section E describes the application procedures when using the event trees in the field. A case study is demonstrated in

Section F. Section G summarizes the benefits of the proposed relay monitoring tool.

B. Original Structure

The original structure of the event tree is demonstrated using an example of a gas leak protection system of an offshore platform. The system includes a gas detection device and two isolation valves. The event tree for this system is shown in Fig. 38. It has a forward structure with initiating contingency of the gas leak. The binary branches of the event tree consider the success (S) and failure (F) of the gas protection system according to the sequence of its actions. The outcome determined by the end-point of each event tree branch identifies all the possible consequence following the initiating event. The probability of each outcome can be evaluated if we know the individual probability of each node passing along the branches.

C. Modified Structure

The original structure is a flat design for analyzing the system reliability or performing risk assessment. In order to be more user-friendly and self-understandable for real time relay monitoring purpose, the original structure is modified, as shown

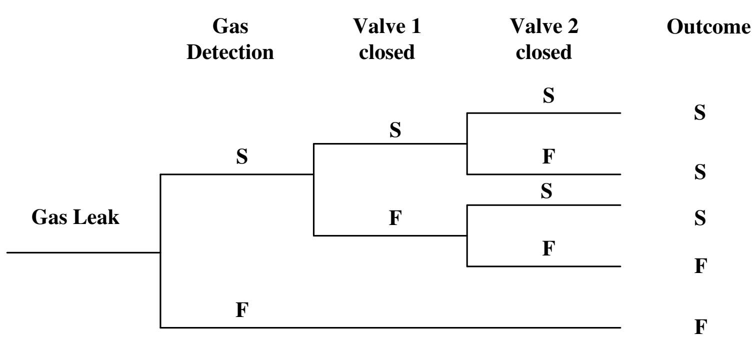

Fig. 38. An example of event tree for gas leak protection system

in Fig. 39. By using different color and shapes, the user can easily find the problem in the system. A table should be associated with the event tree to explain the event at each node and provide the reference corrective actions. That will be shown in the following section.

D. Design of the Event Trees for Protective Relaying System

The forward, tree-like structure of the event tree provides a useful tool that can be effectively used for monitoring protective relay operations with respect to a triggering disturbance. However, there must be a smart way to design the event trees to ensure they can be simply and generally applied to thousands of different relays in ta large-scale power system.

To utilize the event tree analysis more efficiently, the initial event and the consequences must be foreseen. By doing this, all of the possible events and actions can be covered by the event tree analysis. Regarding the transmission line protection system, if the event tree is built at the centralized system level, the initial events and possible relay actions would be infinite since there are thousands of transmission lines

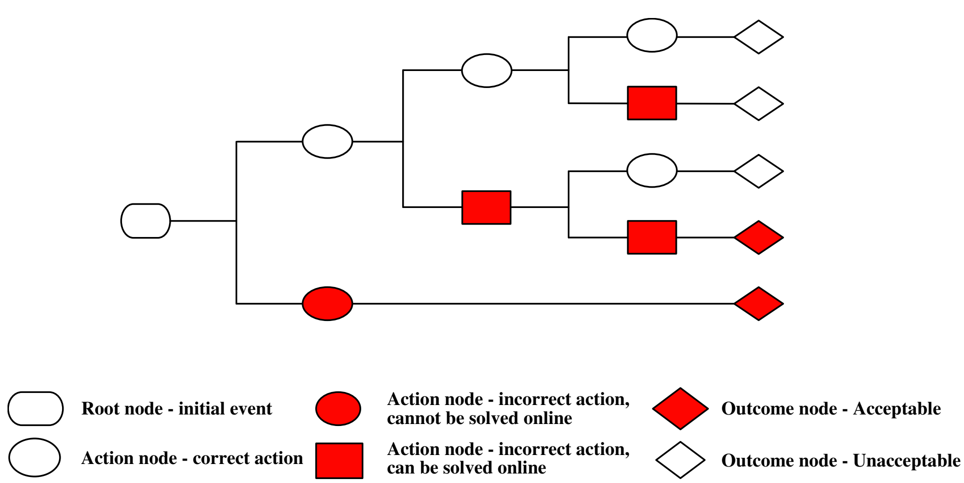

Fig. 39. The modified structure of event tree

and associated relays. An efficient way is to distribute the event tree design to each single relay.

Considering a typical transmission line protection system, which consists of a distance relay, its associated circuit breaker and communication equipment, the possible contingencies are finite and can be foreseen. In spite of the differences in relay settings and system configurations, the functions of transmission line protective relays are mostly identical. We can design the event trees starting from a typical relay as a guide. The other relays with different applications can be modified from the prototype design.

Assume we have a regular distance relay that uses a pilot protection scheme. The distance relay device is used for detecting the fault. Circuit breaker receives the relay trip signal to open the line. It also can trip the line if it receives the command from the transfer trip signal sent by a relay at remote end or if it receives manual trip signal by local command. The circuit breaker can be blocked the same way. The relay is also associated with the breaker failure protection. If the breaker has an interior defect and can not open the line, the breaker failure protection is activated to open all other circuit breakers on the same bus.

In a common situation, the transmission line protection system will face three kinds of initial events: (a) No fault in preset zones; (b) Fault occurring in the primary zone; and (c) Fault occurring in backup zones. The third condition can be separated further into the Zone 2, Zone 3, and reverse zone if the logic has significant differences. In this section, we just assume the backup protections have similar configuration and logic. The event trees for the three initial events are shown in Fig. 40 through Fig. 42. The associate node explanation and reference actions are list in Table VI through Table VIII.

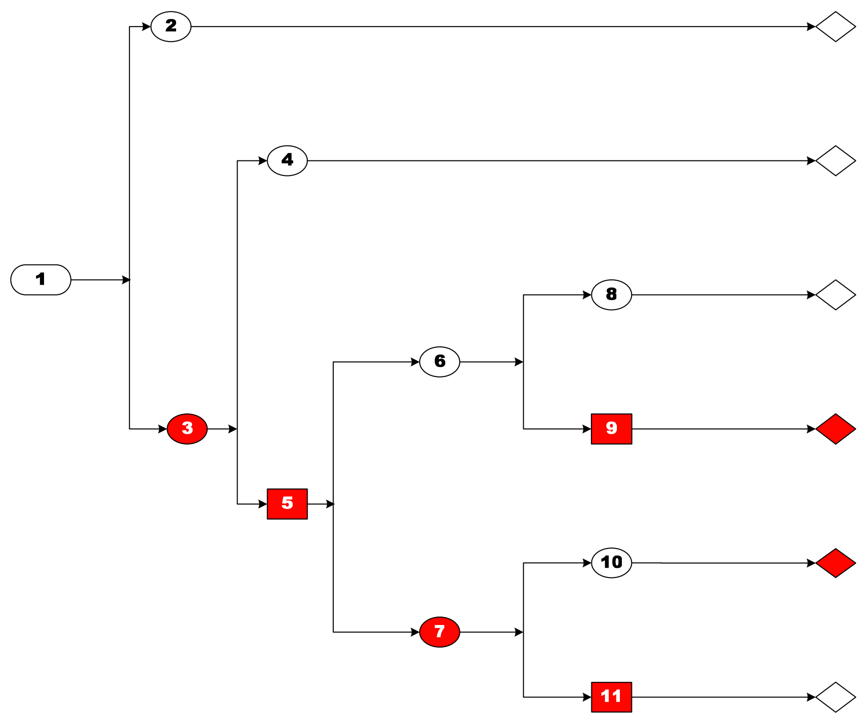

Fig. 40. Event tree #1: no fault

Table VI. The scenarios and reference actions for the nodes of event tree #1

Node	**Status**	**Reference Action**
1	No fault in any protection zone	
2	Relay dose not detect a fault	
3	Relay detects a fault and initiates a trip signal	Check relay settings and hardware
4	Trip signal is blocked by other devices	
5	Trip signal fails to be blocked	Send blocking Signal, check communication channel
6	Circuit breaker opens the line	
7	Circuit breaker fails to open the line	Check the breaker circuit
8	Autoreclosing succeeds to restore the line	
9	Autoreclosing fails	Send reclosing signal to the breaker
10	Breaker failure protection trips all the breakers	
11	Breaker failure protection does not work	Check the circuit of the breaker failure protection

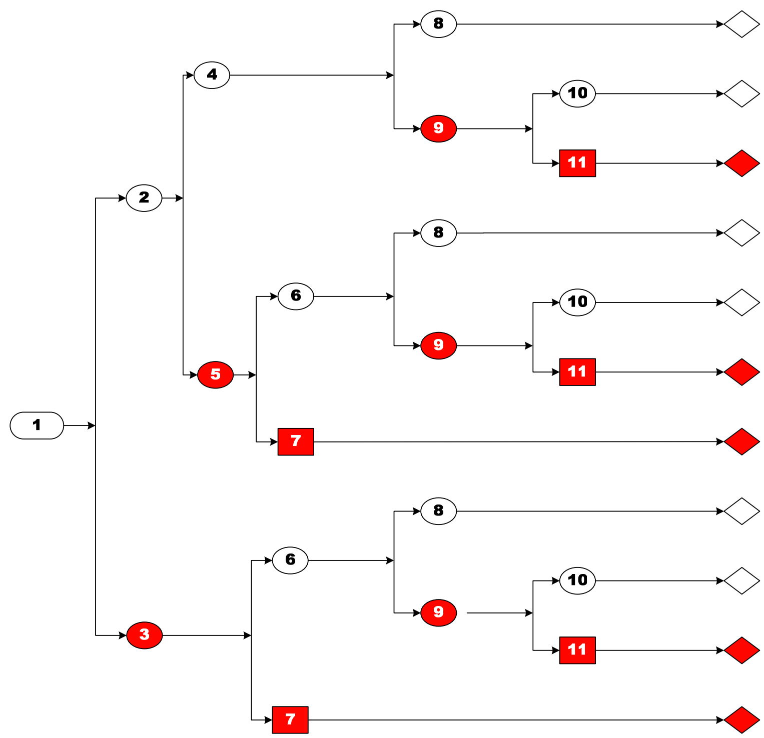

Fig. 41. Event tree #2: fault in primary zone

Table VII. The scenarios and reference actions for the nodes of event tree #2

Node	**Status**	**Reference Action**
1	Fault occurs in primary zone	
2	Relay detects the fault	
3	Relay does not detect the fault	Check relay settings and hardware
4	Relay detects the fault in a correct zone	
5	Relay detects the fault in an incorrect zone	Check relay settings and hardware
6	Transfer trip signal is received	
7	Transfer trip signal is not received	Send trip signal manually, Check communication channel
8	Circuit breaker opens the line	
9	Circuit breaker fails to open the line	Check the breaker circuit
10	Breaker failure protection trips all the breakers	
11	Breaker failure protection does not work	Check the circuit of the breaker failure protection

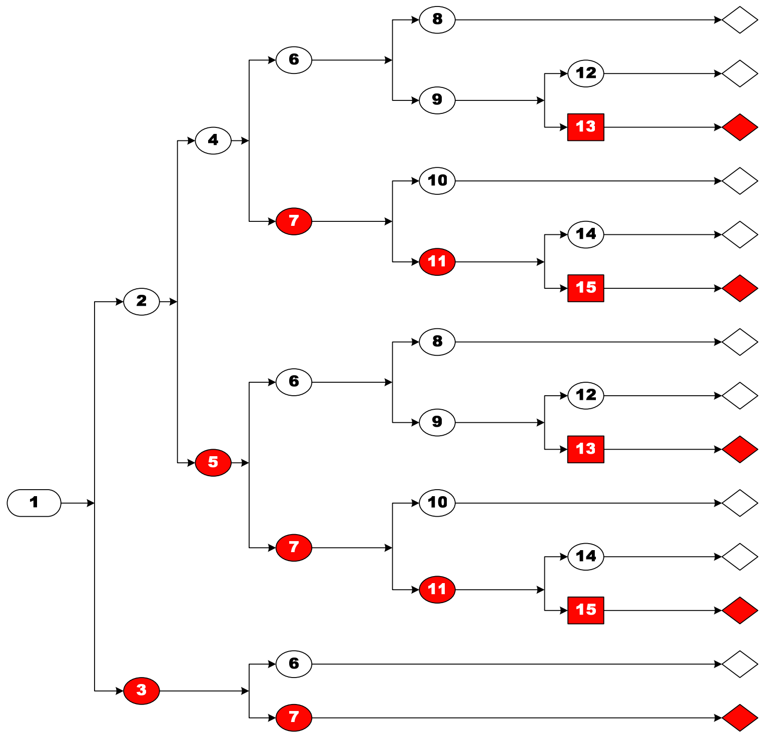

Fig. 42. Event tree #3: fault in backup zone

Table VIII. The scenarios and reference actions for the nodes of event tree #3

Node	Status	Reference Action
1	Fault occurs in backup zone	
2	Relay detects the fault	
3	Relay does not detect the fault	Check relay settings and hardware
4	Relay detects the fault in a correct zone	
5	Relay detects the fault in an incorrect zone	Check relay settings and hardware
6	Primary relay clears the fault successfully	
7	Primary relay does not clear the fault successfully	Correct the primary relay, Restore the line
8	Backup function is reset or blocked	
9	Backup function is not reset or blocked	
10	Relay trips the breaker in backup zone	
11	Circuit breaker fails to open the line	Check the breaker circuit
12	No unnecessary trips	
13	Unnecessary trip occurs	Reclose the line
14	Breaker failure protection trips all the breakers	
15	Breaker failure protection does not work	Check the circuit of the breaker failure protection

E. Use of the Event Trees

This section discusses the method for online event analysis using previously designed event trees. The event trees should be built in advance for each relay that needs to be monitored. The design of each event tree should reflect the specific system configuration and relay settings and should be able to explore all the required relay activities useful for a system view. After the event trees at local level are built, they should be stored at the system level as an event tree database, as the example shown in Fig. 43 suggests. During the disturbances, the system collects the local diagnostic information for a graphic view of the event analysis by activating the related event trees.

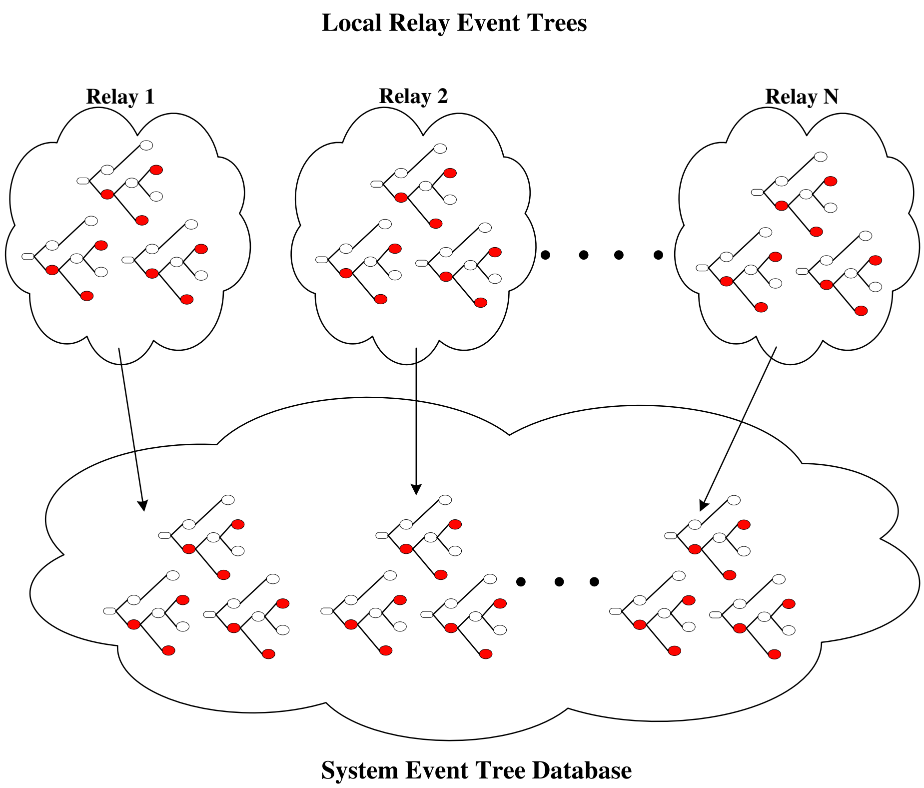

Fig. 43. Event tree database

When used online, the integrated fault analysis tool introduced in the last chapter works in parallel with the traditional relays as a real time comparison reference for traditional relays to provide accurate fault analysis. When either the fault analysis tool or traditional relay detects a fault, the event tree analysis is triggered. For each corresponding relay that operates upon a fault, one of the three event trees is selected according to the fault analysis result. The criterion is that the root node of the selected event tree should meet the conclusion of the fault analysis tool (no fault, fault in primary zone or fault in backup zone). In the related event tree, the expected relay operation branch is the very top one including only "white" nodes. When there is an incorrect operation, the branch will be changed. If the relay operation branch contains a "dark" node, corrective action needs to be taken to reach the "white" outcome node. A correction of the relay misoperation and unintended operation is first attempted locally. The detailed event analysis report of each relay will be sent to the control center shortly so that it is easier for system operator to understand what has happened in the system and more efficient control operation can be taken before the disturbance evolves into a cascading event.

F. Case Study

In order to illustrate the procedure of event tree analysis, a case study is demonstrated in this section. For the example system shown in Fig. 44, assume all the relays are distance relays which have four-zone protection scheme. For convenience, assume all the transmission lines in the system have the same length and relay settings. For each relay, Zone 1, Zone 2 and Zone 3 are set in the forward direction and reach 80%, 120% and 200% of the line length respectively. Zone 4 is in the reverse direction and reaches 20% of line length. Pilot scheme is used to speed up the fault clearing in Zone

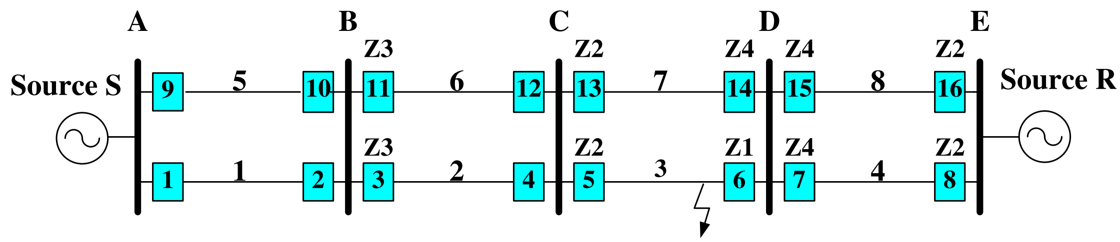

Fig. 44. A multi-bus system for demonstrating event tree analysis

1. The fault scenario of this example is the Phase A-to-ground fault on line 3, fault location is 15% of line 3 away from bus D, as shown in Fig. 44.

Assume all the relays have the mentioned fault analysis tools and they can successfully provide correct fault information. The expected fault zones for the corresponding relays are marked in Fig. 44. Assume two contingencies in two of the relays: a) Relay 5 failed to detect the fault in line 3 because of a DC battery defect in relay hardware. The transfer trip signal is not obtained by this relay as a result. b) Relay 9 falsely detects the fault as a Zone 2 fault. Because of these two contingencies, the circuit breakers associated with relay 3, 11, 13 open at line 2, 6, 7 to remove the Zone 2 fault. The autoreclosing fails because the breaker for relay 5 still has not opened. The circuit breakers associated with relay 9 also falsely open the line 5. The autoreclosing fails because the synchronism check is not passed. The monitored relay operation is shown in Table IX.

The relay operation information in Table IX will be collected by the system

Table IX. The result of event tree analysis

Relay	Event Tree	Expected Actions	Actual Actions
5	2	$1 \rightarrow 2 \rightarrow 4 \rightarrow 8 \rightarrow$ *white*	$1 \rightarrow 3 \rightarrow 7 \rightarrow$ *dark*
9	1	$1 \rightarrow 2 \rightarrow$ *white*	$1 \rightarrow 3 \rightarrow 5 \rightarrow 6 \rightarrow 9 \rightarrow$ *dark*
3, 11, 13	3	$1 \rightarrow 2 \rightarrow 4 \rightarrow 6 \rightarrow 8 \rightarrow$ *white*	$1 \rightarrow 2 \rightarrow 4 \rightarrow 7 \rightarrow 10 \rightarrow$ *white*

operator to issue corrective actions. Relay 5 and relay 9 have the higher priority since they correspond to the primary and unrelated protection respectively. For relay 5, the latest incorrect operation is at node 7. According to the reference action list in Table VII at node 7, first a trip signal will be sent manually to open the breaker for relay 5. Similarly for relay 9, a reclosing signal will be sent according to Table VI. Then consider the other three relays corresponding to the backup protection. For relay 3, 11 and 13, although the final outcome is a "white" node, which means it is acceptable, there is still a "dark" node 7 in their operation routes. After the faulted line 3 is corrected, the line 2, 6, 7 should be restored according to Table VIII.

G. Benefits of the Proposed Relay Monitoring Tool

The benefits of the proposed relay monitoring tool are summarized as follows:

- The modified event tree analysis provides a self-explainable, easy-to-use tool for real time monitoring of relay operations.
- The design of event trees predefines a remedial action in the case of the relay misoperation or unintended operation.
- The generic design of event trees is distributed to each single relay (for each relay, there are three types of events: no fault, fault in primary zone, fault in backup zone). The number of event trees is finite and the design is feasible.

H. Summary

Based on the widely used event tree analysis tool in reliability and risk assessment, this chapter proposed an event analysis approach for monitoring operation of protective relays, aimed at providing the system operator an accurate information about the relay operations under a disturbance. The structure of the original event tree has been modified to be more user-friendly and self-understandable for use in online monitoring purpose. Three event trees have been designed for a typical relay. The use of the event trees is discussed and demonstrated by a case study. The proposed approach can be extended for offline risk assessment of the relay operation if the probability of each action node is known. It can be implemented with Fault Tree Analysis (FTA) [139] to identify the causes of the intermediate subsystem failures. Some of the solutions of combined ETA/FTA can be found in [134, 140].

CHAPTER VIII

INTERACTIVE SCHEME TO PREVENT AND MITIGATE CASCADING BLACKOUTS

A. Introduction

As mentioned in Chapter I, consequences of power system blackouts may be catastrophic. Prevention of the blackout is a complex task due to its multiple potential causes. In the final report of August 14, 2003 blackout, NERC proposed 46 recommendations to enhance the system performance to prevent future large-scale blackouts [1]. Several research efforts in the literature are dedicated to understanding the blackouts [141–144] and proposing the solutions to prevent the future blackouts [4, 11, 125, 126, 137, 145–148]. A systematic defensive approach for online prevention, detection, and mitigation of the cascading blackouts is proposed recently [51, 149, 150]. By such means, the cascading blackout could be prevented or mitigated at different stages by three coordinated steps, including: a) Detection of major disturbances and protective relay operations leading to cascading events, b) Wide area measurement based remedial action, and c) Adaptive islanding with selective underfrequency load shedding. Among these, the first step is most important since the blackouts, whether involving the relay misoperation or unintended operation or not, usually start in some small area where one or more components are removed from the system. This chapter will introduce the role of the previously introduced techniques in the first step, namely in detecting the cascading blackouts.

In Section B, the structure of a local relay monitoring tool is presented. A system monitoring and control tool is briefly reviewed in Section C. The interactive scheme of system and local monitoring and control is described in Section D. A case study based on the IEEE 39-bus system is demonstrated in Section E. Section G summaries the benefits of the proposed interactive scheme.

B. Local Relay Monitoring Tool

The local relay monitoring tool is intended for installation at local substations. As shown in Fig. 45, it consists of the previously introduced real time fault analysis tool using neural network and synchronized sampling, as well as relay operation monitoring tool using event tree analysis. The real time fault analysis tool takes the inputs from a traditional relay including the measurements from the instrument transformers, the relay detection signals from the digital outputs of relay device, and the contact status from the circuit breaker. It also provides outputs to relay and circuit breaker to issue necessary control commands such as blocking and tripping signals. The real time fault analysis tool, primarily based on neural network (NN) and synchronized sampling (SS), works in parallel with traditional relays to detect the fault. For a specific relay, once the fault is detected by relay itself or the real time fault analysis

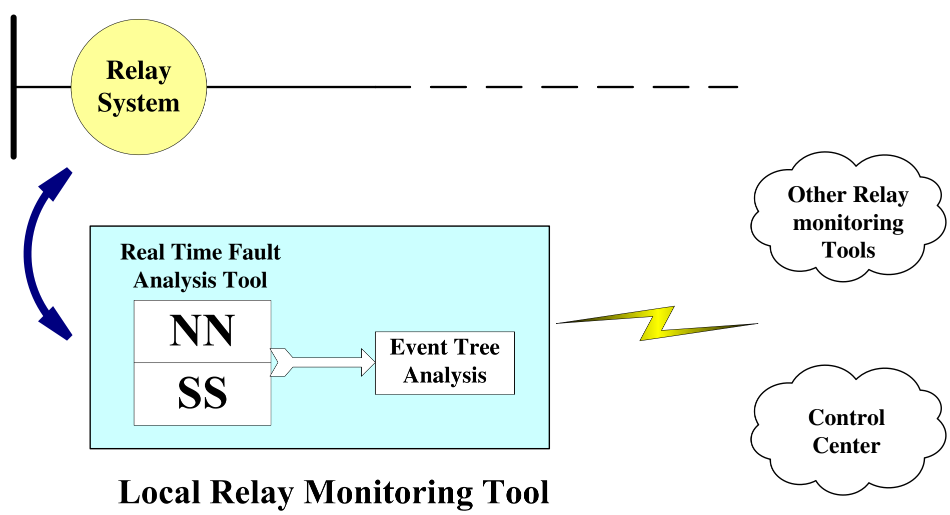

Fig. 45. Local relay monitoring tool

tool, the event tree analysis will be triggered and the monitored information will be shared with the local monitoring tools for neighboring relays as well as the system operator in the control center. The steps for real time fault analysis and event tree analysis have been described in Chapter VI and VII respectively.

C. System Monitoring and Control Tool

Besides the local relay monitoring tool at the substation level, the system level monitoring and control scheme for use at the control center plays an important role in preventing and mitigating the blackout since it is expected to help operator keep the system security and stability based on the collected system-wide data. The system-wide monitoring and control tool should have routine security analysis and event based security analysis [50].

Routine security analysis runs in regular periods to perform the contingency analysis. For the contingencies that can lead to overload, voltage dip, voltage and transient instability, the candidate corrective control means should be identified and saved. The vulnerable area by those contingencies should also be identified. The related relay should be marked for close monitoring.

Event-based security analysis is triggered when a disturbance occurs. If it is the contingency that is studied in the routine security analysis, the corresponding control means can be selected form the saved methods. If it is not studied before, that will require online high-speed security analysis to indicate whether the emergency control is needed to mitigate the overload or transient stability problem.

Two major techniques for the both security analysis tasks are based on the fast power flow and transient stability analysis. Some of the improved methods have been reported in [151–153].

D. Interactive Scheme to Prevent Blackouts

An example of a field application of the proposed local and system monitoring and control tools is shown in Fig. 46. The local relay monitoring tool is synchronized by GPS satellite and hence the synchronized sampling based fault diagnosis approach in the integrated fault analysis tool can reach an accurate analysis result. High-speed communication medium is preferred between the system tool and local tool, as well as between the different local tools. The information and control command can be rapidly delivered. That idea is a fit to recently introduces of Wide Area Measurement Systems (WAMS).

The interactive scheme between the system and local monitoring tools is shown in Fig. 47.

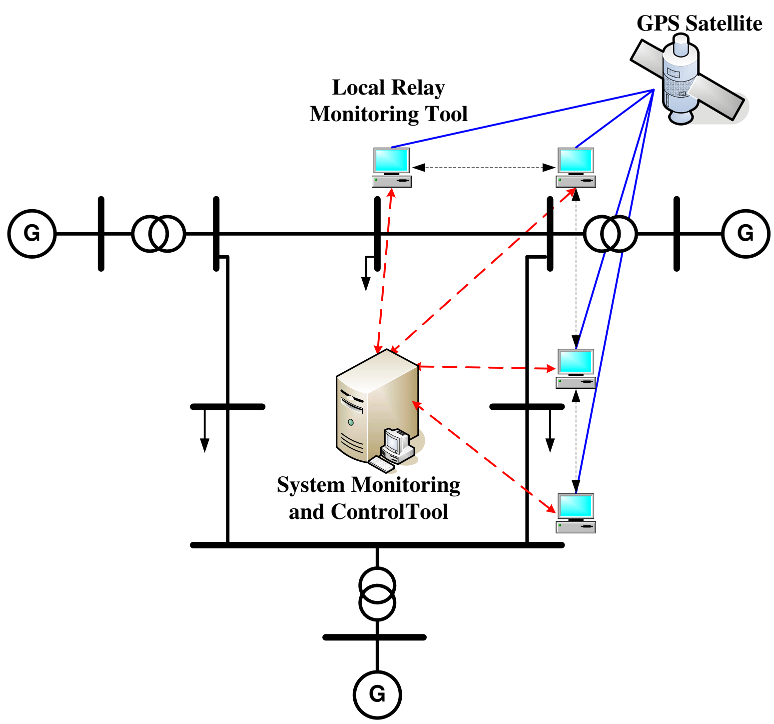

Fig. 46. Field application for proposed system and local monitoring and control

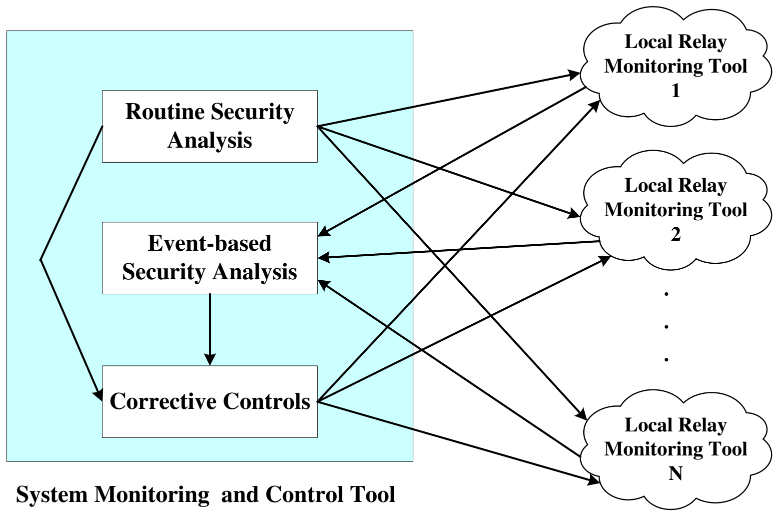

Fig. 47. Interactive scheme for system and local monitoring and control

When the system is operating in the steady state, the system monitoring and control tool performs vulnerability and security analysis and decides the system security level and identifies the vulnerable relays. The information will be sent to the corresponding local relay monitoring tool. Depending on the system emergency level, the system tool may give the authorization to the local tool to send block or trip signal to the circuit breaker directly. At the same time the system tool also identifies the critical contingencies, and selects the associated control means for those expected events.

The local relay monitoring tool performs real time fault analysis along with the traditional relays. When the system experiences a disturbance due to a transient event, such as fault, switching, etc, event tree analysis is triggered to verify if the relay operation is correct. If relay misoperation or unintended operation is found, the relay monitoring tool will directly correct the misoperation or report the problem to the system tool. That provides a local event diagnostic support to the system tool. Typically, when the system emergency level is low, which means there is no operating violation in the system, the local monitoring tool should not intervene in relay operations. In this case even a relay misoperation or unintended operation will not likely initiate a cascading blackout. There is enough time for the system operator to issue the control means based on a broad view of the system status. When the system emergency level is high, which means there are operating violations in the system and the probability of a cascade is high, the local monitoring tool should be assigned the priority to correct relay operation since every relay misoperation or unintended operation could result in an unfolding event. By preventing the relay from tripping during the power swing, the system operator could have the time to perform the controlled islanding and hence reduce the loss of a probable blackout.

No matter how the local relay monitoring tool intervenes to correct relay misbehavior, the information will be collected by the system tool to aid operator in event-based analysis. If such events are studied by the routine security analysis, predetermined emergency control means will be activated. If the events are unexpected, transient stability analysis and power flow analysis will be run to see whether there are transient stability or steady state problems. If so, associated control means will be found and issued to mitigate such events.

E. Case Study

In order to illustrate the interactive scheme of system-wide and local monitoring and control, a case study is demonstrated in this section using the IEEE 39-bus New England test system shown in Fig. 48. The detailed system data can be found in [154].

In the steady state condition, the routine security analysis of the system monitoring tool is implemented offline and the vulnerable lines in the system are identified using the vulnerability index (VI) and network contribution factor (NCF) method [153].

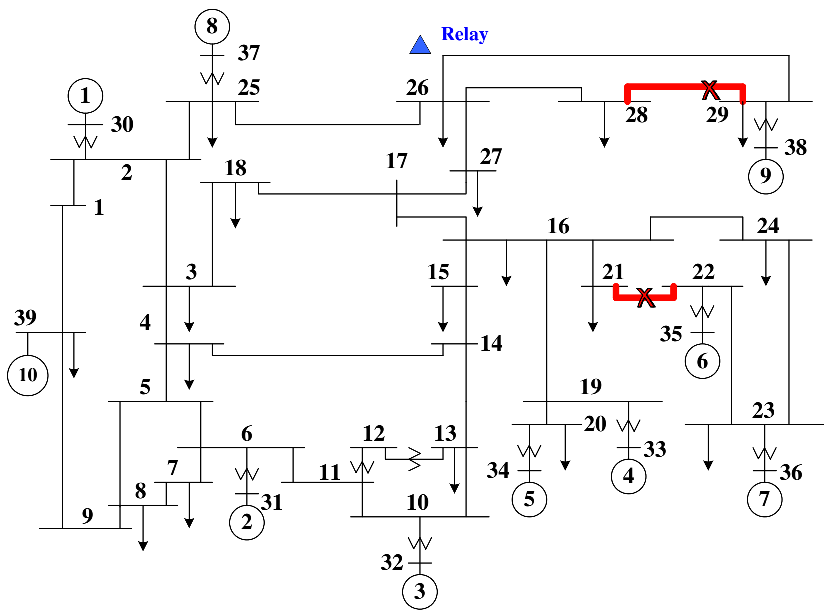

Fig. 48. IEEE 39-bus system

The top 2 most vulnerable lines according to their vulnerable indices are: Line 21-22, 28-29. The outage of those lines will have a large impact for the system stability since the original loads in those two lines will be re-distributed to the neighboring lines causing more overloading issues. The system monitoring tool will inform the local relay monitoring tool on those lines to monitor the relay operations closely.

Assume a series of disturbances occur in the system, with the event sequence shown in Fig. 49. The related system components are marked in Fig. 48. These two faults are permanent faults and thus removed by the relays. After the line 21-22 are removed due to the first fault, the top 2 most vulnerable lines are changed to: Line 28-29, 2-3. After the line 28-29 are removed due to the second fault, the top 2 most vulnerable lines are changed to: Line 23-24, 26-29.

This contingency may cause relay at Bus 26 of Line 26-29 to misoperate. The trajectory of impedance seen by that relay is shown in Fig. 50 with the event sequence labeled. Although the two faults are not related to the healthy line 26-29, the power

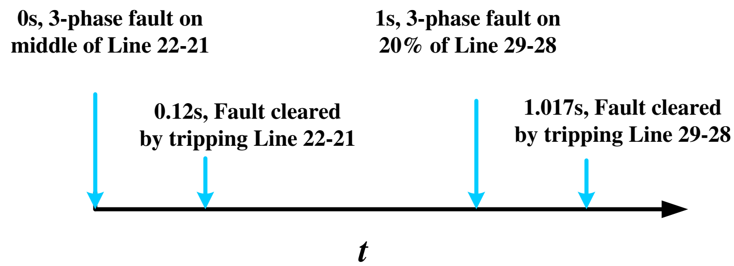

Fig. 49. The sequence of simulated fault scenarios

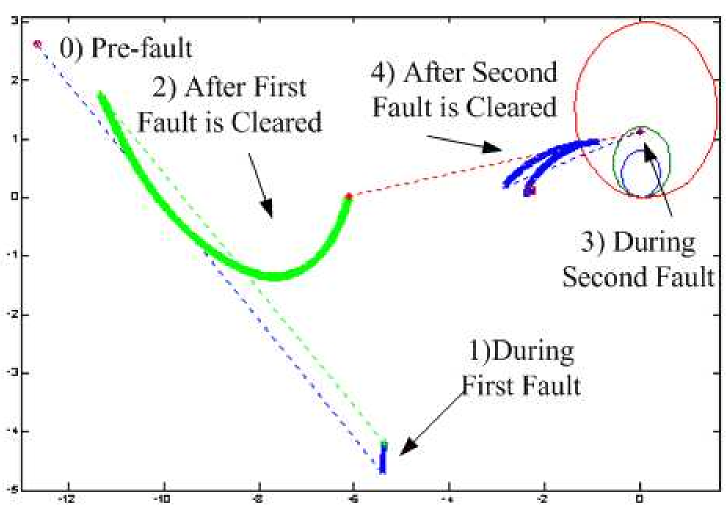

Fig. 50. Apparent impedance seen by distance relay at Line 26-29 during the disturbances

swing caused by the two faults will have an impact on the distance relay. It observes a Zone 3 fault at 1.627s after the second fault clearing until the trajectory leaves Zone 3 circle at 1.998s. The distance relay may trip Line 26-29 when its Zone 3 timer expires. As a result, buses 29, 38 will be isolated from the system, including the G9 and loads at bus 29. This will results in the oscillation in the rest of the system and further cascading outage may happen.

The mentioned situation can be prevented by the proposed interactive system and local monitoring tool. When the first fault occurs, the faulted line 21-22 is removed and no other operation happens. The relay monitoring tool for the relay at Line 21-22 will inform the system monitoring tool about the relay operation for the three-phase fault. The event-based system security analysis is activated after the first fault. An alert signal will be sent to the local relay monitoring tool at vulnerable lines at this stage. Since the first fault will not degrade the system stability very much, the local relay monitoring tool will not be authorized to intervene with relay operations at this stage. When the second fault happens and Line 28-29 is removed, the local relay monitoring tools for the most vulnerable lines 23-24 and 26-29 will be authorized to correct the potential relay misoperation or unintended operation in real time since the misoperation of those relays will directly separate the system. After the second fault, the local relay monitoring tool at Line 26-29 will draw a conclusion to block the relay from tripping for Zone 3 fault. That information will be sent back to the system. The system will issue appropriate control means to mitigate the disturbances.

In an actual large scale system, it is impossible that one or two contingencies like the ones discussed in this scenario can cause large scale system oscillation. Usually there is enough time for coordinating the system-wide and local analysis in the initial stages of the disturbances to mitigate the impact of the disturbances before they unfold into the large one. An interactive system-wide and local monitoring and control means can really help reduce the probability of a cascading blackout since the disturbances can be fully analyzed at both the local and system level.

F. Benefits of Proposed Interactive Scheme

The benefits of the proposed interactive scheme are summarized as follows:

- Through the analysis result from the local relay monitoring tool, the system side can understand exactly the disturbance information in real time. It will help system operator evaluate system security and make better control actions to preserve it.
- Through the analysis result from the system-wide monitoring tool, the local side can know whether its relay system needs to be monitored closely.
- The two monitoring tools monitor the system security level and the system disturbances in an precise way to help preventing the cascading blackout.

G. Summary

The power system cascading blackouts are usually initialized by a chain of accumulated disturbances and relay operations in the system. The first effort to prevent the blackout is to rapidly and precisely understand the system disturbances and issue the corrective countermeasures. The proposed interactive scheme in this chapter is aimed at this effort. The role of the system-wide monitoring and control tool is to evaluate the security level of the system components and inform the related local monitoring tool, as well as to select effective corrective control means when disturbances occur. It should consist a preventive step achieved by the routine security analysis and control, as well as a fast-response step achieved by the event-based security analysis and control. The role of the local relay monitoring tool is to provide detailed disturbance information using its advanced fault diagnosis techniques and inform the system about what exactly happened in the local relay. It assists the system tool to effectively understand the disturbance, evaluate system security and make better control actions to preserve it. A simple heuristic case study in this chapter illustrated the basic idea and benefits of the proposed scheme in preventing cascading blackout.

CHAPTER IX

COMPREHENSIVE SIMULATION TOOL*

A. Introduction

In order to study the performance of proposed fault diagnosis approaches discussed in Chapters III through VI, a comprehensive simulation tool is needed. Some solutions can be found in the literature [155–157]. In [72], a simulation tool using MATLAB [54] and Alternative Transients Program (ATP) [55] is developed. The model-dependent design of the tool limits its flexibility when used in different power system applications. In this chapter, the simulation tool further enhanced for the use in the performance studies is described.

In Section B, the overall framework of the simulation software is introduced. Details about the power system simulation part and fault diagnosis algorithm evaluation part are given in Section C and Section D respectively.

B. Framework of the Simulation Tool

The overall framework of the developed software simulation package is shown in Fig. 51. The software has an interactive structure by using MATLAB and ATP. MATLAB is a widely used general purpose modeling and simulation tool and ATP is free version of Electromagnetic Transient Program (EMTP) [158], which is widely used to implement accurate and fast electromagnetic transient simulation. The combination of these two simulation tools can benefit from advantages of both. The

*Part of the material in this chapter is reprinted from "Implementing an advanced simulation tool for comprehensive fault analysis" by Nan Zhang and Mladen Kezunovic, *In Proc. IEEE PES Transmission and Distribution Conference and Exhibition: Asia and Pacific*, Dalian, China, August 2005 ©2005 IEEE, with permission from IEEE.

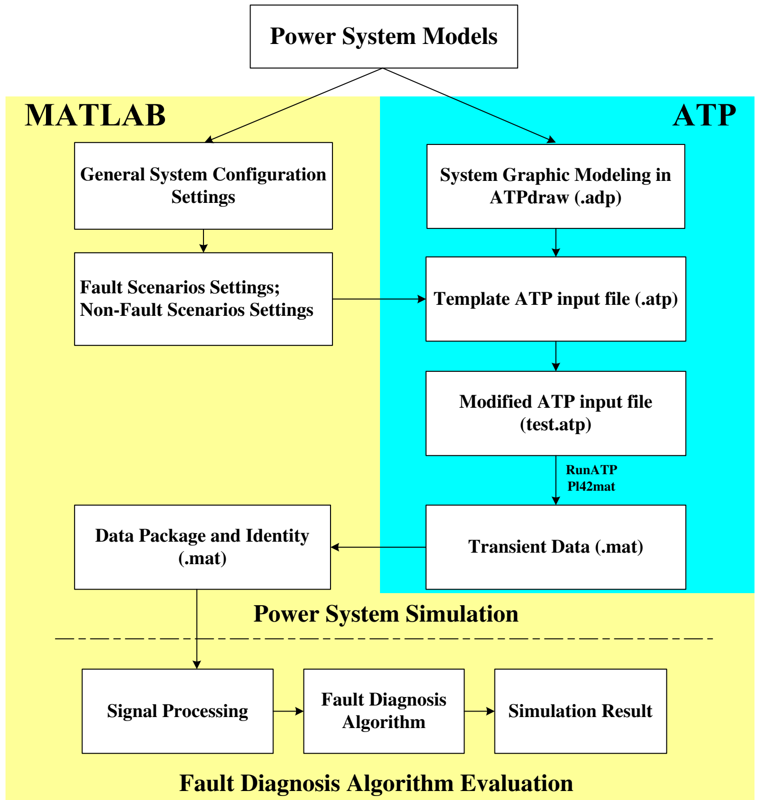

Fig. 51. The framework of the simulation tool

existing ATP software does not have the capability to automatically generate the scenarios in a batch. That is very inconvenient in our performance studies that require simulation of thousands of scenarios to be carried out. MATLAB is a powerful programming and simulation software. It can be used to implement flexible control of the ATP simulation and interface used to evaluate the performance of the fault diagnosis algorithms.

The entire software consists of two parts: simulation of power system and evaluation of fault diagnosis algorithm. In the part devoted to simulation of power systems, the power system model of interest is built in ATPdraw and a template *.atp* file without any events is then generated. The system components and their parameters are set in MATLAB. The user defines disturbance scenarios through the interface in MATLAB. For each scenario, the MATLAB program will load the template *.atp* file and create a temporary file by modifying the settings of the template *.atp* file. After the ATP is executed, the transient measurements for each scenario are then stored for evaluation of relays or other fault analysis algorithms.

In the part devoted to evaluation of fault diagnosis algorithms, the raw data obtained from measurements are then preprocessed according to the algorithm requirements. The processed data is analyzed by different fault diagnosis algorithms and the analysis results are recorded and compared based on the actual characteristics of the fault scenarios.

When applied for different power system models, the software only needs to rebuild the ATP template and update the system configuration settings in MATLAB. The other parts need not be changed.

C. Simulation of Power Systems

The power system is modeled using the graphic tool of ATP, ATPdraw, and the corresponding system parameters are set in MATLAB. There are several features in the modeling stage that can facilitate the programming and simulation procedure: a) In ATPdraw modeling, all the lines of interest should be identified and the components representing line faults, switches, and measurements on the transmission lines of interest on those lines preserved. As the example shown in Fig. 52, the line is broken up into two sections. The name of each node should be easily identifiable. Numbers are preferred when naming the nodes, and all the components in a line section should refer to the same numbers of their two bus nodes. This helps to easily locate the system component in MATLAB program. b) In MATLAB setup, a component list file

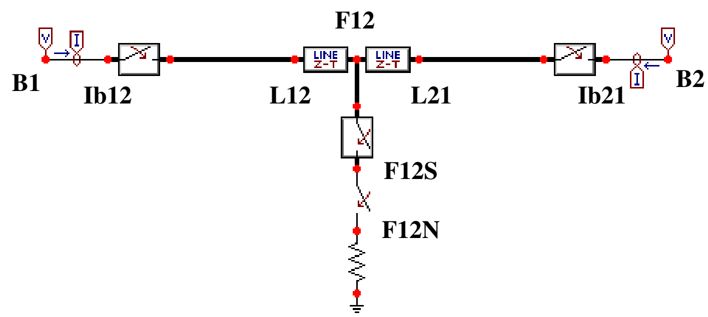

Fig. 52. Setup for the line of interest

should be generated to identify the system components and configure their parameters when setting the scenarios.

After the power system models are built in ATP and configured in MATLAB, the next steps are setting the scenarios and initiating simulation automatically. The details are as follows:

1) User sets the fault or non-fault scenarios. The scenarios can be set in a batch using deterministic or random method. By the deterministic method, the user can define the parameters for fault type, location, impedance, inception angle, etc. The software then creates a batch of scenarios by combining the parameters in different sets. By the random method, the user only defines the range of the parameters and the software generates the parameters and scenarios randomly.

2) Based on the user definition, the software sorts out the fault scenarios or non-fault scenarios according to the parameters.

3) For all the fault scenarios, the software automatically copies the template *.atp* file to a temporary *.atp* file, modifies the parameters in temporary *.atp* file, and runs ATP. As an example *.atp* file shown in Fig. 53, no matter what system is used,

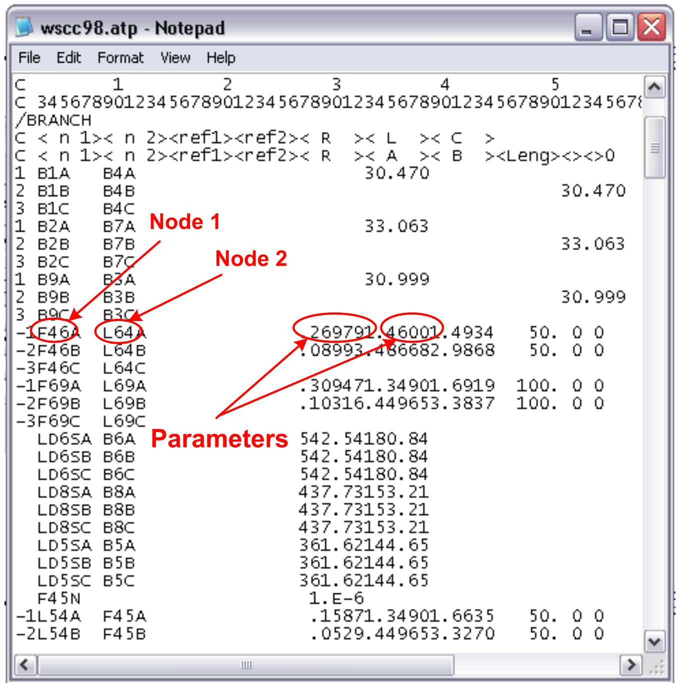

Fig. 53. Locate the component in the ATP file

all the system components can be found by locating the names of the nodes at its two ends. Since the system nodes are easily identifiable by the mentioned method in the modeling stage, a universal program *row_locator.m* is used for locating any component's row position in *.atp* file. The column positions of the component parameters are fixed as long as we know the component type. Therefore, we can create a set of universal programs to modify the parameters for each kind of system component. By this method, all system component parameters can be automatically modified in MATLAB. The detailed method can be found in [72].

4) For each scenario, ATP will generate a *.pl4* file. Using *Pl42MAT.exe*, we can transform the *.pl4* file to *.mat* file and obtain related data in MATLAB format. As shown in Fig. 54, for each scenario, the three-phase voltage and current data along with the time label are extracted as the variable "Output" and packed with

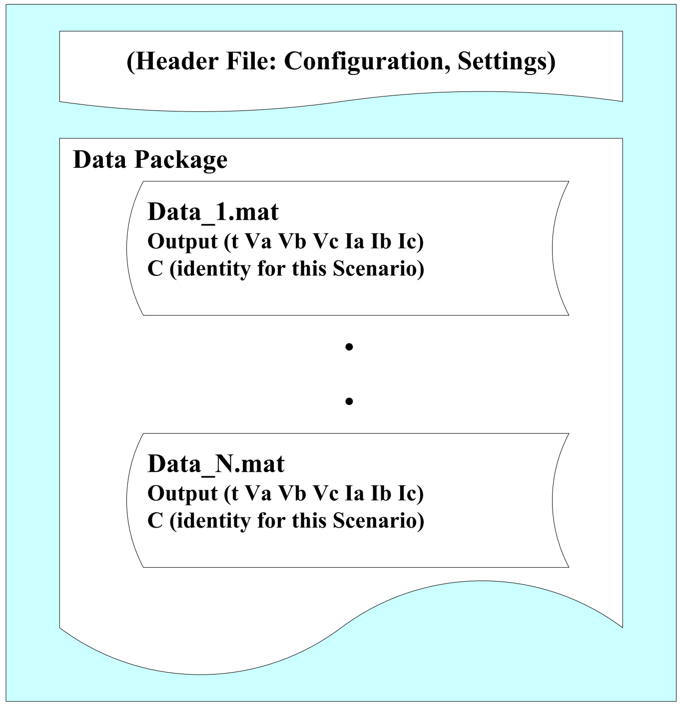

Fig. 54. The structure of the data package

its identity variable "C". Then the final data package is formed using data and a header file, which includes the configuration and setting information, such as scenarios number, sampling rate, etc.

5) Repeat the step 3) and 4) for non-fault scenarios.

D. Evaluation of Fault Diagnosis Algorithms

The data generated in power system simulations are used for evaluating different fault diagnosis algorithms. The previously mentioned fault diagnosis algorithms, neural network based fault diagnosis, synchronized sampling based fault diagnosis, along with the traditional distance relay are programmed in MATLAB. The evaluation procedure is shown in Fig. 55 and described as follows:

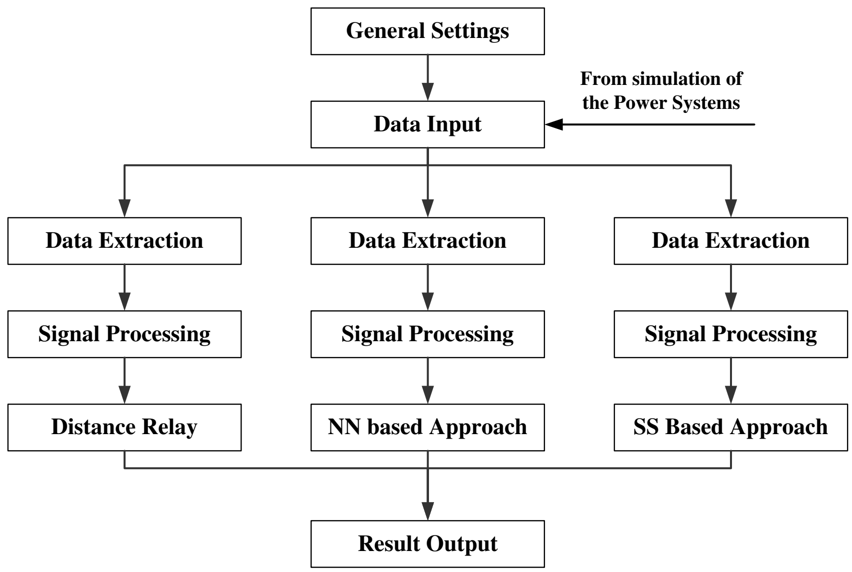

Fig. 55. The procedure for evaluating fault diagnosis algorithms

1) General Settings. Preset data re-sampling rate, protection zones, and algorithm parameters.

2) Data Input. Load the source data file, which is generated by simulation of the power systems, into MATLAB program.

3) Data Extraction. According to the requirement of the algorithm, extract the useful data from the source data file with re-defined sampling rate.

4) Signal Processing. Signal processing is different for different algorithms. For distance relay, the waveform is conditioned using low pass filter and fundamental frequency phasors of voltages and currents are computed using full cycle Fourier Transform. For neural network based approaches, the three-phase voltages and currents are normalized and arranged in a row to form a pattern. For synchronized sampling based approaches, only raw samples in time-domain are required.

5) Fault Diagnosis. The preprocessed data is sent to the algorithm to implement

fault detection, classification and location.

6) Result Output. The results of fault diagnosis are compared with the scenarios to measure the analysis errors. The results are saved for further studies.

E. Summary

A handy software simulation tool is helpful for development of new fault diagnosis techniques. The improved software package described in this chapter can handle a variety of complex fault analysis tasks under different system conditions. Thousands of scenarios can be simulated at one time. The structure of the software benefits from both programming flexibility of MATLAB and simulation efficiency of ATP. The software implementation makes it easy to adapt different system models and evaluate other fault diagnosis algorithms. The performance studies of all the techniques developed in this dissertation are based on this simulation tool.

CHAPTER X

PERFORMANCE STUDIES*

A. Introduction

This chapter presents the performance studies of proposed fault diagnosis approaches introduced in Chapters III through VI. The result of the performance will decide how effectively they can be used in the relay monitoring tool mentioned in Chapter VIII. A lot of studies have been performed in developing the proposed fault diagnosis approaches [44–48]. The performance of coordinated fuzzy ART neural networks introduced in Chapter III is compared with the original fuzzy ART algorithm [44]. The simulation result confirms the improvement in accuracy of the new fuzzy ART algorithm over the original one. Evaluation of the synchronized sampling based fault location (SSFL) algorithm under power swing and out-of-step conditions is provided in [45]. The test result indicates that SSFL algorithm performs much better than distance relay. The complete fault diagnosis approach using synchronized sampling, which is introduced in Chapter V, is evaluated in [46]. The comprehensive study proves the excellent accuracy in fault detection, classification and location of the proposed approach. It is not possible to list all of the performance studies in this chapter. Two major results, one for integrated fault analysis tool introduced in Chapter VI and the other for boundary protection introduced in Chapter IV are reported in Section B and Section C of this chapter respectively.

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*Part of the material in this chapter is reprinted from "A real time fault analysis tool for monitoring operation of transmission line protective relay" by Nan Zhang and Mladen Kezunovic, *Electric Power Systems Research*, (Accepted, In Press), doi:10.1016/j.epsr.2006.03.015 ©2006 Elsevier B.V., with permission from Elsevier; "Transmission line boundary protection using wavelet transform and neural network" by Nan Zhang and Mladen Kezunovic, *IEEE Trans. Power Delivery*, (Accepted, In Press), paper no. TPWRD.00747.2005 ©2006 IEEE, with permission from IEEE.

B. Study of Real Time Fault Analysis Tool

This section implements a comprehensive study aimed at evaluating the performance of the integrated fault analysis tool introduced in Chapter VI. The performance of each individual function in the fault analysis tool is demonstrated and compared to the traditional relay. The simulation is carried out by the same sets of tests for each individual functions.

Three types of tests, with their objectives and methods, are listed in Table X. The first two tests compare the performance of the integrated fault analysis tool with the distance relay using numerous fault scenarios with different fault parameters and system operating conditions. The third test compares the performance of the integrated fault analysis tool with the distance relay using typical non-fault scenarios. Two complex power system models are selected to implement those tests, as shown in Fig. 56 and Fig. 57 respectively.

1. Power System Models

Test #1 is performed using Power system #1, which is a model of a real 345kV system section from CenterPoint Energy [159]. It is suitable to generate realistic fault scenarios in different system conditions. The STP-SKY line is the line of inter-

Table X. Test cases implemented for integrated fault analysis tool

Test Case	**System Used**	**Objective and Method**
#1	#1	Test the overall dependability/security of the algorithm using randomly generated scenarios under different fault parameters and system conditions.
#2	#2	Test the selectivity of the algorithm using randomly generated system-wide disturbances.
#3	#2	Test the particular security performance of the algorithm during power swing and out-of-step situation caused by initial disturbances

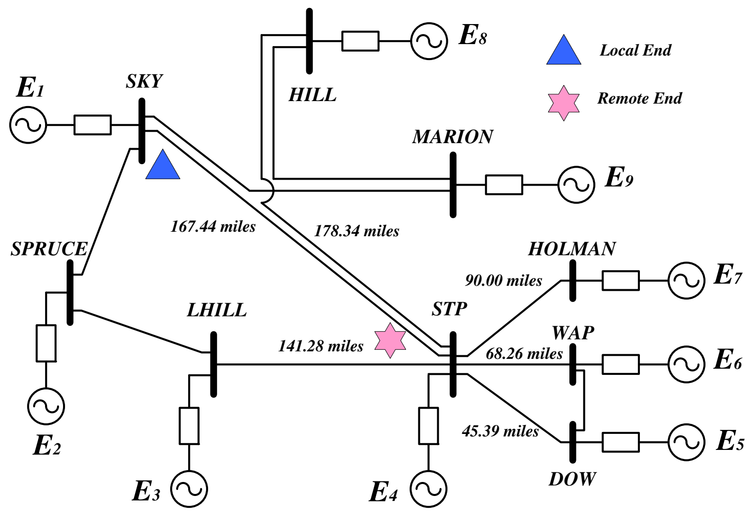

Fig. 56. Power system model #1: Centerpoint SKY-STP system

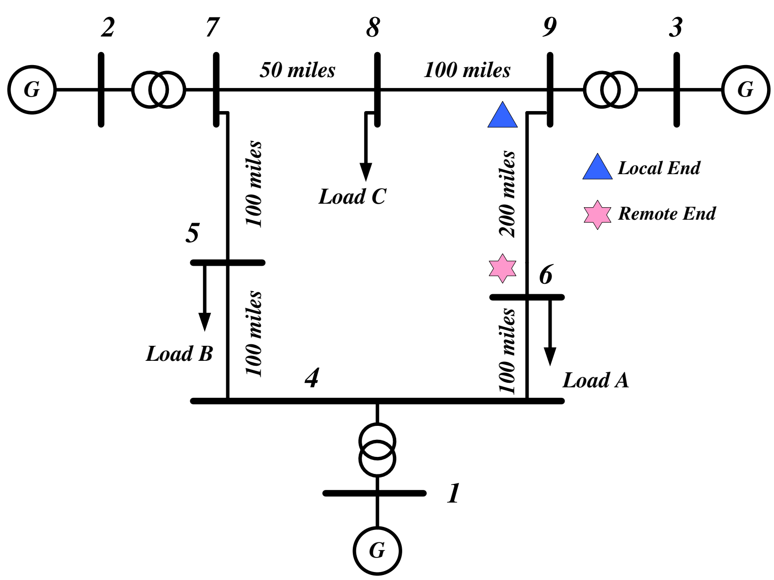

Fig. 57. Power system model #2: WECC 9-bus system

est in this study. This is a long transmission line represented with distributed line parameters.

Test #2 and #3 are performed using power system #2, which is the WECC 9-bus system usually used in power flow and transient stability studies [160]. Unlike system #1, which is quite "strong" by having quite a few ideal sources, the 9-bus system represents a typical topology suitable for studying the influence of system-wide disturbances. Since the generator data is also available in this system, a "dynamic" model is set up using the embedded synchronous machine component $SM59$ in ATP. The dynamic scenarios such as power swing and out-of-step condition can be simulated as a result. The original lumped transmission line parameters are modified to represent lines with distributed parameters in our studies. The transmission line of interest in this model is Line 9-6 with length of 200 miles, as shown in Fig. 57.

For both systems, the proposed fault analysis algorithm is installed at the local transmission line ends and the synchronized data used in SSFD, SSFC and SSFL are transmitted from the remote ends, as marked in Fig. 56 and Fig. 57.

2. Scenarios

For test #1, the disturbances involve only the events on SKY-STP line since the faults occurring in other areas have less influence on this line due to the strong infeed configuration of the system. The integrated algorithm is used for classifying and locating the faults occurring on the SKY-STP line.

Instead of scenarios which would only demonstrate the best performance of the algorithm, the randomly generated scenarios can demonstrate the overall performance and robustness of the proposed algorithm in different situations. The fault parameters are randomly selected from uniform distribution of: all fault types, fault distances $(5\% - 95\%)$, fault resistances $(0 - 30\Omega)$, and fault inception angles $(0 - 360^o)$. There are five types of system conditions in this test and each has 500 random scenarios: a) Nominal system, b) Weak infeed (Disconnect E1 and E9), c) Phase Shift (E1 with phase shift -30^o), and d) Frequency Shift (System frequency of $59Hz$).

Test #2 evaluates selectivity of the proposed algorithm on Line 9-6 under system-wide events occurring in system #2. The test scenarios are generated randomly using the same fault parameter pool as in test #1. Each of the six lines in system #2 experiences 500 fault cases.

Power swing usually follows line switching, load change, or fault. In test #3, three kinds of typical scenarios outside Line 9-6 are selected to trigger the power swing phenomenon caused by oscillation of the machine angles of the three generators. Stable swing is simulated by line switching and line fault cleared before the critical clearing time (CCT). Unstable swing (out-of-step) is simulated by the most severe three-phase fault cleared after CCT. The example of power swing waveforms in Fig. 9 is generated using this method in system #2.

For all three tests, the sampling rate is $20kHz$ originally used by SSFL. The data is decimated to 32 points per cycle used for distance relay, as well as the PU, NNFDC, SSFD and SSFC of the integrated fault analysis tool. The data window for voltage and current samples is fixed to one cycle. In test #1 and #2, the data window is "static" and taken from the post-fault value. In test #3, the data window is "dynamic" and slides throughout the entire power swing process. Before the integrated tool is tested, NNFDC is trained for both of the two power system models with thousands of well designed scenarios respectively.

3. Test Results

The results of test set #1 and test set #2 are listed in Table XI, where the decision errors (%) of each functions against the each group of test scenarios are shown. The

Table XI. Test results for test case #1 and #2, error(%)

	Test Case #1				Test Case #2	
	norm	**weak**	**phase**	**freq**	**prim**	**other**
Distance Relay						
Detection	0.600	0.600	1.000	0.800	0	0
Classification	1.000	1.400	7.400	1.400	1.200	1.440
Zone Estimation	8.600	12.000	15.800	9.000	10.400	11.400
Integrated Fault Analysis Tool						
NN: Detection	0	0	0	0	0	0
NN: Classification	0	0	0.200	0.200	0	0
NN: Zone Estimation	5.800	6.600	5.600	5.400	5.600	2.240
SS: Detection	0	0	0	0	0	0
SS: Classification	0	0	0	0	0	0
SS: Location	0.545	0.585	0.513	0.529	0.720	–

error of fault location shown in the table is the average fault location error for each set of tests.

The error of fault location for a single fault scenario is defined as:

$$\text{error}(\%) = \frac{|\text{Actual Location - Computed Location}|}{\text{Line Length}} \tag{10.1}$$

The functions in distance relay and integrated tools are broken down to make a clear comparison. In test set #1, “norm”, “weak”, “phase” and “freq” stand for nominal system, weak infeed, phase shift and frequency shift respectively. In test set #2, “prim” and “other” stand for the events on the primary line 9-6 and events on the other lines respectively.

The test results indicate that for all test sets, the integrated tool has much better performance than distance relay. For all test sets, the pick-up unit can find the fault inception time within 2 samples with respect to 32 points per cycle, which is sufficient for NNFDC, SSFD, SSFC and SSFL. NNFDC has exactly the same functions as distance relay. The result shows an overall improvement of the performance over distance relay. NNFDC especially provides a good classification for the fault types. SSFD successfully differentiates all the internal faults from the normal cases and external faults. It can provide an exact confirmation when NNFDC is confused with the events around the zone boundaries. SSFC successfully classified all fault types. SSFL provides very good accuracy of fault location. The performance of integrated tool is less affected by different fault parameters, system operating conditions and system-wide events than the distance relay. It is expected so since the unique advantages of neural network based approach and synchronized sampling based approach mentioned in Chapter III and V respectively.

The desired behavior of the line protection in test #3 is that it should not initiate a trip signal during the power swing. As mentioned in Chapter II, the reason is that power swing, whether stable or unstable, is not a fault within the line of interest. Therefore, the distance relay or other fault detection algorithm should not trip during the power swing unless it receives an order by other out-of-step relays.

The results of test #3 listed in Table XII demonstrate the behavior of both the distance relay and integrated analysis tool during the power swing caused by different situations. The result indicates that the distance relay will operate during some situation but the integrated analysis tool will not be affected in any case.

C. Study of Boundary Protection

1. System Model

The performance study for boundary protection scheme is based on the $500kV$ power system model shown in Fig. 58. The system is modeled in alternative transient program (ATP), where the three transmission lines are J. Marti frequency-dependent models created in ATP-LCC subroutine in order to observe the frequency effects more

Table XII. Test results for power swing simulation

Power Swing	**Case**	**Line**	**Dist. Relay**	**Fault Analysis Tool**
Stable	Line Open	6-4	stand-by	stand-by
		9-8	stand-by	stand-by
		4-5	stand-by	stand-by
		5-7	stand-by	stand-by
		7-8	stand-by	stand-by
	Line Fault (Clear Time <CCT)	4-5	Zone 3 pick-up	stand-by
		5-7	stand-by	stand-by
		7-8	stand-by	stand-by
Unstable	Line Fault (Clear Time >CCT)	4-5	Zone 1 trip	stand-by
		5-7	Zone 1 trip	stand-by
		7-8	Zone 1 trip	stand-by

accurately. The length of the three lines is set identically to 200 miles for simplicity. The busbar capacitance is set identically to $0.1\mu F$, which is the typical value from the literature. The detailed parameters are listed in the Appendix.

2. Feature Comparison

This section will give some examples of the feature comparison from different fault scenarios.

For the boundary protection, six fault points are selected for comparison, as shown in Fig. 58. Those fault points are located 5 miles away from the nearest bus. For illustration, we randomly selected an ABG fault, with fault resistance of 10Ω and fault angle of 70^o identical for all six fault points. If the six fault scenarios form the entire input space, we can obtain the patterns for boundary protection (neural network #1) as shown in Fig. 59.

The arrangement for each pattern is the same as the one shown in Fig. 29 (a). The first half represents the voltage features and the second half the current features. Comparatively, the internal faults at $F1$ and $F2$ have higher values for both voltage

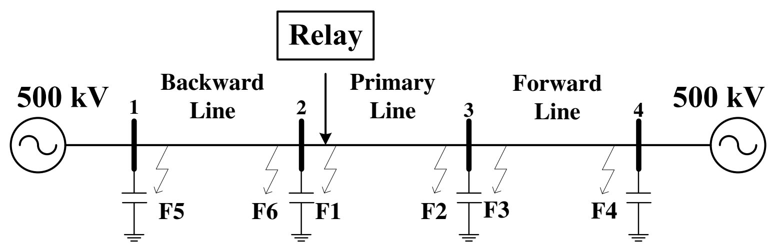

Fig. 58. The multi-line system for testing boundary protection scheme

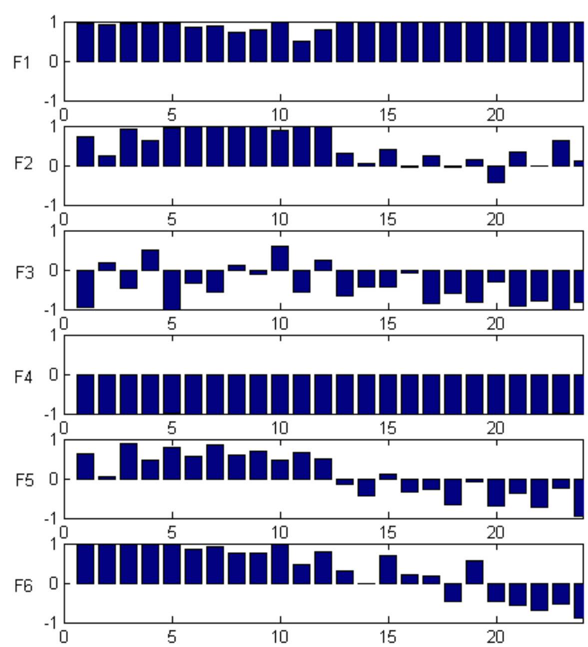

Fig. 59. Pattern comparison for boundary protection (neural network #1)

and current features. The forward faults at $F3$ and $F4$ have smaller value for both voltage and current features. The backward line faults at $F5$ and $F6$ have higher value for voltage features and smaller value for current features. The effect is much clearer for the fault point pairs ($F1$ and $F6$, $F2$ and $F3$) located on opposite side of the same bus. Those results confirm the conclusion that the faults on different line sections are clearly differentiable.

At $F1$, a set of scenarios including all fault types is generated to demonstrate the features for fault type classification. The fault resistance and fault angle are also selected as 10Ω and 70^o respectively. The patterns of all fault types for neural network #2 are shown in Fig. 60. The arrangement for each pattern is the same as the one shown in Fig. 29 (b). It is seen that the waveform is clearly presented only

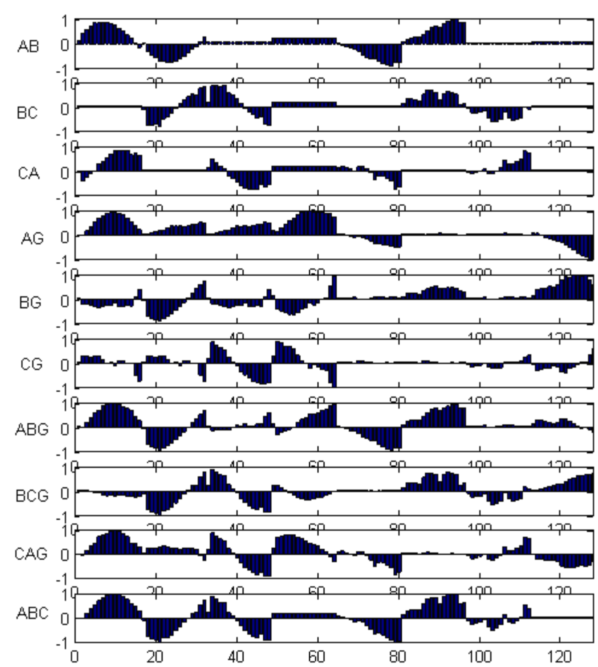

Fig. 60. Pattern comparison for fault classification (neural network #2)

for the phases involving the fault. In that case, all the fault types are also easily differentiable by this pattern arrangement approach.

3. Neural Network Training

A set of 3960 fault scenarios was generated for the system shown in Fig. 58 using interactive ATP and MALTAB as simulation tool for training the neural networks. For each line section, the selection includes 1320 fault cases taking into account all the fault types, 5 fault locations at $2.5, 50, 100, 150, 197.5$ miles from the bus at the left-hand side, several fault resistances in the range of $0 - 100\Omega$, and several fault angles in the range of $0 - 180^o$.

For neural network #1, all 3960 cases are used as inputs for training. The outputs of the neural network are “Normal”, “Primary line fault”, “Forward line fault” and “Backward line fault”. For a comparison, we select two features from the input pattern of the entire set of 3960 cases to compare the feature differences, as shown in Fig. 61. The meaning of those two features of each pattern can be found using Fig. 29 (a) and equation (4.4). We can see that in general, the features from different line sections can easily be differentiated since they are generally distributed in different ranges. We can also see that there are exceptions observed for certain fault types, fault resistances and fault angles. That is where we can benefit from the neural network algorithm to deal with the problem. If those exceptions do not exist, we can use “hard” thresholds directly for the boundary protection.

For neural network #2, only 1320 fault cases on the primary line are used as the inputs for training since only the events on the primary line are of concern in this case. The outputs of neural network #2 indicate the fault type directly.

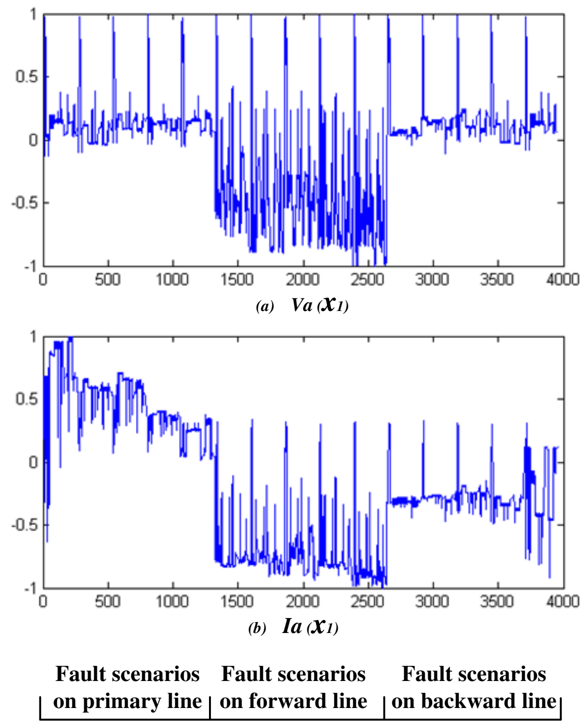

Fig. 61. Selected two features for generated 3960 cases

4. Performance Testing

Another 2000 fault scenarios were generated for testing the protection schemes. There are 1000 fault cases on primary line and 500 each of the other two lines. Those cases are selected from 15 fault points, including the six points shown in Fig. 58 and nine in other locations distributed along the three lines. The fault points are different from those in the training scenarios. For each fault point, other fault parameters are generated randomly for all fault types, fault resistances in the range of $0 - 100\Omega$, and fault angles in the range of $0 - 180^o$. The randomly generated scenarios may consist of some extreme cases and thus can demonstrate an overall statistical performance of the proposed scheme.

For boundary protection, the accuracy of fault detection is 99.7%. Among the six incorrect cases, only one involves a fault event on the primary line. For other five cases, the algorithm confuses the forward faults with the backward faults. Regarding fault type classification, only one out of 1000 cases is incorrect. The accuracy is 99.9%. The overall accuracy combining the boundary protection and fault classification can be calculated as $(1 - 7/2000) \times 100\% = 99.65\%$. As we can see in Table XI, the traditional distance relay can only achieve its best accuracy of 91.4% in estimating the protection zone and 99% in fault classification. Obviously, the overall performance of the proposed boundary protection scheme is much better than that of distance relay.

D. Summary

Comprehensive performance studies have been implemented in this chapter. For the proposed fault analysis tool introduced in Chapter VI that includes the neural network based fault diagnosis approach and synchronized sampling based approach, the tests are carried out based on the comprehensive fault and non-fault scenarios using two complex power system models. The test results indicate that the integrated tool has better dependability/security and selectivity than a distance relay. It is feasible to use it as an accurate reference for relay monitoring. For boundary protection scheme proposed in Chapter IV, the tests are carried out using a typical system model based on frequency-dependent line. The results reflect its unique advantages over the traditional non-unit protection schemes. Compared to the traditional unit protection schemes, it uses only the measurements from one end of the transmission line and does not need a communication link.

CHAPTER XI

CONCLUSIONS

A. Summary of Achievements

Cascading blackout is one of the most catastrophic events in a power system. It is a result of accumulation of a chain of contingencies and system reactions. Relay misbehavior is believed to be one of the most contributing factors to the cascading blackouts according to the historical record. Lacking a verification mechanism for relay operation is another factor that keeps the system operator from knowing exactly the disturbance information and enabling a fast corrective control scheme.

This dissertation is proposing an integrated relay monitoring tool to be installed at major substations of transmission system, aimed at preventing and mitigating cascading bleackouts. The relay monitoring tool includes a real time fault analysis tool combined by neural network (NN) based approach and synchronized sampling (SS) based approach. Both NN and SS based techniques use time-domain based schemes which are more accurate than the traditional phasor based protection schemes. The integrated solution utilizes the strength of neural network algorithm in fault classification and that of synchronized sampling algorithm in fault location. It is easy to check the consistency of decisions made by each technique to improve accuracy of fault analysis to enhance the dependability and security of protection system simultaneously. The relay monitoring tool also contains a relay operation monitoring tool using event tree analysis. It provides a self-explainable, easy-to-use way for real time monitoring of relay operations. It also predefines remedial action in the case of relay misoperation or unintended operation. That will provide a local disturbance diagnostic support tool to assist operators in preventing and mitigating cascading blackouts.

The achievements of this dissertation are summarized as follows:

Chapter II has explored the existing transmission line relaying techniques and its problems. It is pointed out that the speed and accuracy of transmission line relay will directly affect system transient stability and its behavior such as overload and power swing. Such events may affect the judgment of a distance relay so that it can issue an incorrect command for removal of a healthy line. This phenomenon was evidenced in different historical account of major blackouts.

Chapter III has been dedicated to enhancing the transmission line fault diagnosis schemes using neural network. A previously developed fault diagnosis scheme based on fuzzy Adaptive Resonance Theory (ART) neural network has been explored. The design improvement proposed in this dissertation applies multiple neural networks and a feature extraction method. It solves the application issues such as dealing with large input data set, blocking the impact from power swing and locating the fault inception time, etc.

A boundary protection scheme has been developed in Chapter IV. It is an extension of the neural network based fault diagnosis scheme introduced in Chapter III. It is aimed at solving the problem of differentiating the internal faults from external using measurements from one end of transmission line only. The wavelet transform is utilized to extract low frequency and high frequency components of the fault signals that are then used as inputs for two coordinated neural networks aimed at detecting and classifying the fault. The new boundary protection scheme accuracy is improved over the accuracy of traditional non-unit protection. Hence, it can work as a unit protection scheme to protect the entire length of transmission line while it does not have to use the communication link.

An alternate fault diagnosis approach based on synchronized sampling algorithm has been studied in Chapter V. The effort was made to extend the previously introduced fault location scheme to a complete fault detection, classification and location scheme. Without extra data requirement, the new approach enhances the functions of fault diagnosis and improves the performance of the previous approach by the extended derivation of the synchronized sampling algorithm.

The two fault diagnosis techniques: neural network based, and synchronized sampling based, are further integrated into a real time fault analysis tool in Chapter VI. Using the same source of data, the fault analysis tool provides a comprehensive fault analysis functions and enhanced fault location with an improved accuracy. The proposed hardware and software solutions make the tool feasible for use as an online reference for monitoring the traditional transmission line relay.

An effective real time relay monitoring tool based on event tree analysis (ETA) has been proposed in Chapter VII. The structure of generic event tree proposed in the literature has been modified to be more self-understandable for online monitoring purpose. A group of event trees have been designed for a typical relay system. The demonstrated case study shows its efficiency and easy-to-use feature when monitoring and correcting the relay operations. Knowing the information delivered by the proposed event tree analysis, the system operator will have accurate information about the relay operations during a disturbance when the operator needs to issue corrective control actions.

Chapter VIII proposes an interactive scheme for preventing and mitigating cascading blackouts. The local relay monitoring tool works with the system-wide monitoring and control tool to enable better understanding and interactive control for the system disturbances. The role of the system-wide monitoring and control tool is to evaluate the security level of the system components and inform the related local monitoring tool. The role of the local relay monitoring tool is to provide the detailed disturbance information using its advanced fault diagnosis techniques and inform the system tool what exactly happened in the local relay system. Corrective control means are issued after the elaborate analysis of the disturbances at both system-wide and local levels. The detailed scheme is described and demonstrated using a case study implemented in IEEE 39-bus system.

Chapters IX and X have been devoted to evaluation of the proposed fault diagnosis techniques. An improved software package has been developed to handle a variety of complex fault analysis tasks under different system conditions. The structure of the software benefits from both programming flexibility of MATLAB and simulation efficiency of ATP. Comprehensive performance studies have been implemented. The test result indicates that integrated fault analysis tool has better dependability/security and selectivity than distance relay when analyzing thousands of generated fault scenarios in different conditions. It is feasible to use it as a reference for accuracy of the local relay monitoring. The integration of the two techniques is necessary since they can complement each other to get an convincible fault analysis result. Neural network based approach has an enhanced accuracy over the distance relay and duplicates its fault diagnosis functions. It uses local measurements and implements the fast calculation. But its accuracy when detecting the fault occurring around transmission line boundaries is not so good. Synchronized sampling based approach introduces time delay for transmitting data from remote end. But it is very accurate when determining whether the fault is internal or external and finding the exact fault location. The new boundary protection scheme, which is an extension of neural network based approach, can protect the entire transmission line length accurately when compared to the traditional relay by using one-end measurements only. As long as the required data can be readily available from instrument transformers using high-speed sampling unit, the boundary protection scheme can be used as a substitute for the neural network part of the integrated fault analysis tool to achieve a much more accurate result.

B. Research Contribution

Occurrence of power system blackouts is more frequent world-widely recently. The reason is that power systems operate close to their design limits and with more uncertainty of the system operating mode due to the ever-increasing load demand and the advent of the deregulated power market. An urgent task for the power industry is to seek the solutions to prevent the future blackouts. As mentioned in Chapter I, the key contributions in preventing the cascading blackout would be reducing the relay misbehavior and enhancing local level diagnostic support during the system disturbances.

For several decades, the traditional protective relaying approaches are dominantly based on calculation of phasors and relay settings. As a result, its performance may be affected in some extreme system operating conditions with unusual fault parameters, as explained in Chapter I.

This dissertation introduces and utilizes several new techniques, including self-organized neural network, fuzzy logic, wavelet transform, GPS based synchronized sampling, etc. Those techniques are integrated together to achieve a specific goal, which is to improve the dependability and security of protection system simultaneously. This dissertation indicates how the new technology can find a role in improving transmission line protection and reducing relay misbehavior. Major work of this dissertation has been focused on two kinds of time-domain fault diagnosis approaches, namely neural network based approach and synchronized sampling based approach. The comprehensive studies in this dissertation have demonstrated that significant improvements over the traditional methods can be achieved. The flexibility of proposed approaches enables them to be used in a variety of feasible applications. They can be used as a single protective relay to improve overall performance and can be incorporated in an IED as an additional function. They can also be combined as a comprehensive fault analysis tool to be a reference for determining accurate fault detection, classification and location.

In existing practice, the relay operation is automatic. Whether it behaves correctly in all circumstances is not known due to the lack of verification tool. The system operator has to assume relay operation is correct and then evaluate it offline after disturbance unfolds to confirm this assumption. When the system operates close to its limits, every single relay operation could cause a chain of unfolding events eventually. Without the verification of relay operations, system operator is not able to correct the relay misbehavior and make appropriate decision to relief the system disturbances. The proposed relay monitoring tool based on event tree analysis can fill the need in this area. As a real time monitoring tool to be installed in the substations, it works with the system-wide monitoring tool, which is installed in the system control center, to provide a dynamic picture of the system status. It effectively detects system disturbances and allows implementation of a control action that will prevent them from spreading over a larger area.

C. Suggestions for Future Research

The dissertation has made an extensive effort in designing the overall solution of local relay monitoring tool for preventing and mitigating cascading blackouts and studying each individual technique of neural network, synchronized sampling and event tree analysis. The research and study of both the overall scheme and individual techniques could be extended in the future to make them more feasible for practical use.

The understanding of cascading blackouts should be further studied. A scenario of cascading blackout simulated by the dynamic simulation program based on a large scale system model is needed for better understanding. The studies about fault analysis tool and relay monitoring scheme should be evaluated using this blackout scenario.

The fault diagnosis scheme can be further improved. For fuzzy ART neural network based method, it is useful to study the way of effectively selecting the training data. Among the different system configurations and fault parameters, a reasonable selection of different typical conditions may help to reduce the number of training data and hence reduce the neural network training burden. It is worth studying how effectively to implement online testing of the neural network trained by the simulated power system models. For boundary protection scheme, the actual value of the substation bus capacitance should be investigated. The adjustment of the proposed approach with respect to the availability of the hardware could be studied. For synchronized sampling based algorithm, a field test is necessary to study how the algorithm is affected by the measurement imperfection and different fault parameters.

The proposed relay monitoring tool and the interactive scheme with the system-wide monitoring tool should be studied in more specific system configurations. The design of event trees can be based on an actual protection system in a substation. The interaction with the system monitoring tool needs to be adjusted considering the availability of the data and communication links.

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APPENDIX A

MATHEMATICAL ASPECTS FOR FUZZY ART NEURAL NETWORK TRAINING

Assume K is the length of input pattern, N is the number of clusters or neurons, n_l is the number of patterns that belong to the cluster l. $\mathbf{x}_i = [x_{i1}, x_{i2}, \ldots, x_{iK}]$ is i-th input pattern and x_{ij} is j-th feature of the i-th input pattern, and $\mathbf{w}_l = [w_{l1}, w_{l2}, \ldots, w_{lK}]$ is a prototype of l-th cluster.

The Euclidean distance d_l between pattern $\mathbf{x}_i$ and the cluster $\mathbf{w}_l$:

$d_l = \sqrt{(\mathbf{w}_l - \mathbf{x}_i)(\mathbf{w}_l - \mathbf{x}_i)^T} \quad \text{for } l = 1, 2, \ldots, N;$

The nearest cluster for $\mathbf{x}_i$ is $\mathbf{w}_p$ for which $d_p = \min\limits_l d_l$.

If pattern $\mathbf{x}_i$ is assigned to the cluster $\mathbf{w}_p$, the winning prototype is updated:

$\mathbf{w}_p = \frac{n_p}{n_p + 1}\mathbf{w}_p + \frac{1}{n_p + 1}\mathbf{x}_i,\ n_p = n_p + 1.$

If pattern $\mathbf{x}_i$ is removed from the cluster $\mathbf{w}_p$, the original winning prototype is updated:

$\mathbf{w}_p = \frac{n_p}{n_p - 1}\mathbf{w}_p - \frac{1}{n_p - 1}\mathbf{x}_i,\ n_p = n_p - 1.$

APPENDIX B

ATPDRAW MODELS AND SYSTEM PARAMETERS

Three studied power system model are generated using ATPdraw 3.7p2. The system model and parameters are given below.

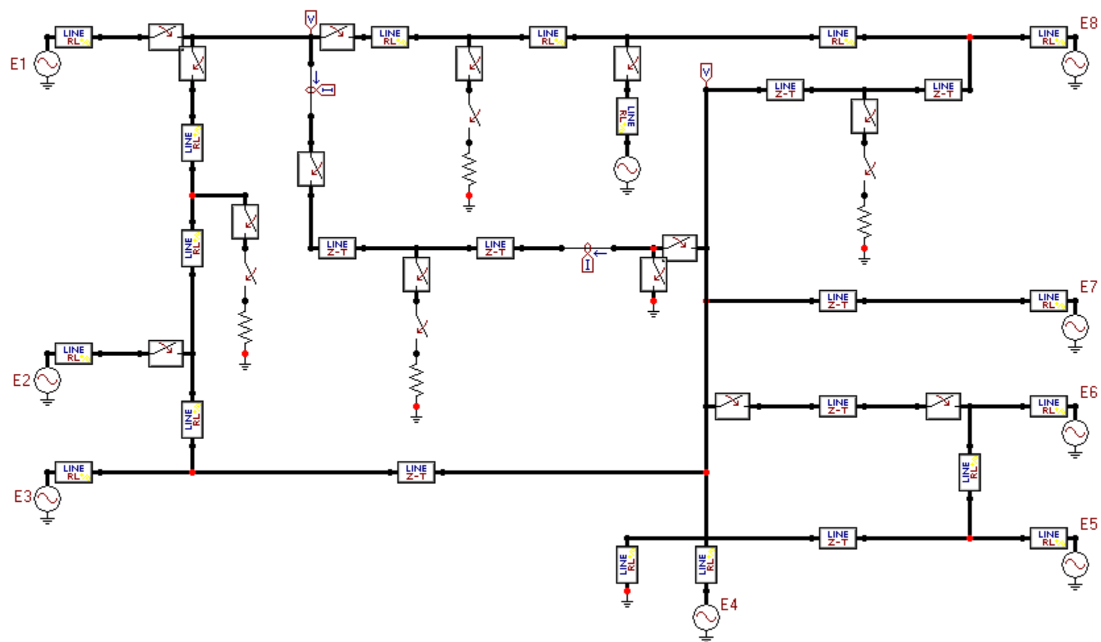


Fig. 62. ATPdraw model of SKY-STP system

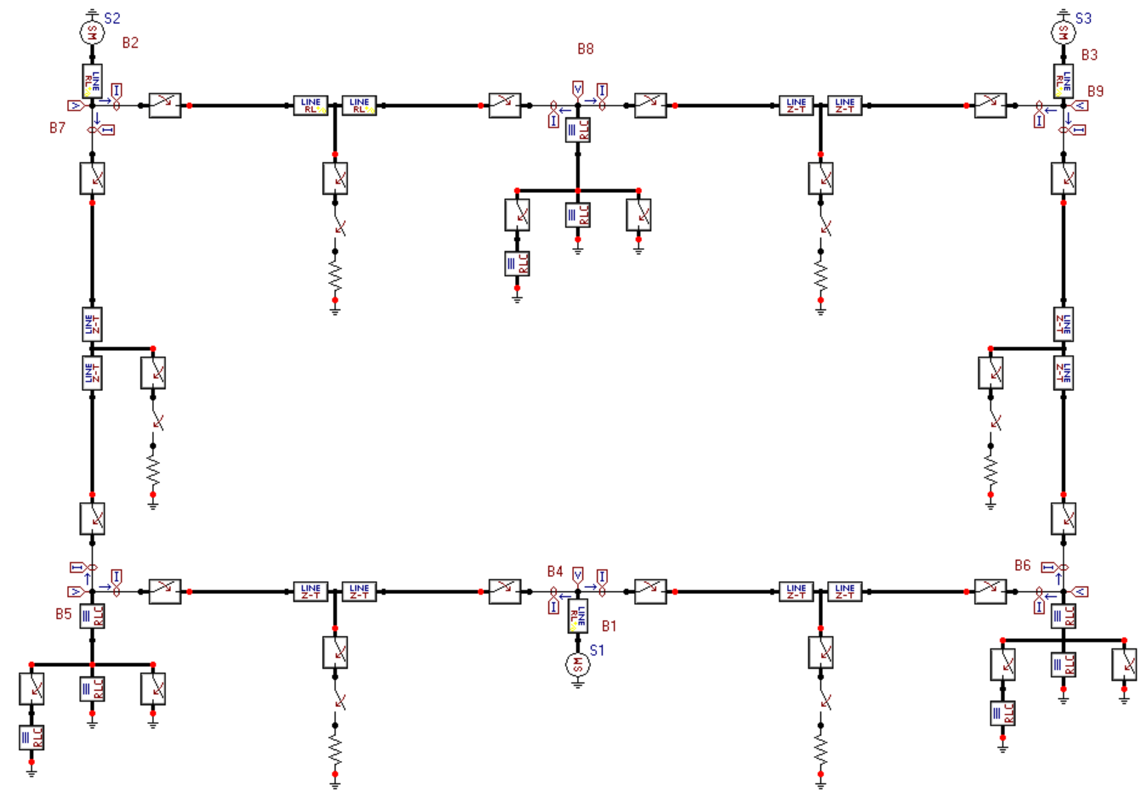


Fig. 63. ATPdraw model of WECC 9-bus system

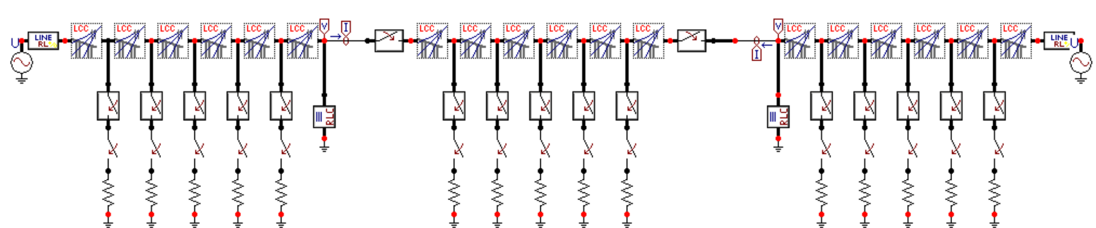


Fig. 64. ATPdraw model of two-machine system for boundary protection scheme

Table XIII. SKY-STP system source parameters in steady state

Source number	ATPdraw Component	$\|E\|(V)$	$\angle E$(deg)	$R_1(\Omega)$	$X_1(\Omega)$	$R_0(\Omega)$	$X_0(\Omega)$
1	AC3PH.SUP	340642.65	-53.35	1.512	37.1316	2.135	41.2228
2	AC3PH.SUP	359296.80	-45.32	0.988	22.5195	0.381	13.2594
3	AC3PH.SUP	347349.45	-57.39	1.883	26.8844	1.868	15.0786
4	AC3PH.SUP	386993.40	-15.36	0.345 0.950	17.4962 438.0000	0.272 0.950	15.0786 438.0000
5	AC3PH.SUP	350889.15	-40.89	1.463	18.5016	1.626	21.5459
6	AC3PH.SUP	353932.05	-39.00	0.207	3.9483	0.621	5.6827
7	AC3PH.SUP	347418.45	-36.49	1.070	12.7048	4.495	25.2697
8	AC3PH.SUP	344796.45	-54.64	1.488	30.6251	3.303	40.0388
9	AC3PH.SUP	347287.35	-45.54	1.738	16.8539	4.975	31.0060

Table XIV. SKY-STP system line parameters

Line	ATPdraw Component	Positive-sequence impedance $Z_1(\Omega)$		Zero-sequence impedance $Z_0(\Omega)$	
		R_1	X_1	R_0	X_0
SKY-MARION	LINESY_3.SUP	1.071	9.403	5.475	36.064
MARION-HILL	LINESY_3.SUP	1.785	16.430	9.522	62.840
SPRUCE-SKY	LINESY_3.SUP	0.952	12.022	11.308	41.896
SPRUCE-LHILL	LINESY_3.SUP	7.500	68.440	66.300	218.050
DOW-WAP	LINESY_3.SUP	3.214	33.327	21.540	96.291

Line	ATPdraw Component	Length (miles)	Resistance (Ω/mile)		Reactance (Ω/mile)		Susceptance (Ω/mile)	
			R_1	R_0	ωL_1	ωL_0	ωC_1	ωC_0
STP-WAP	LINEZT_3.SUP	68.26	0.06134	0.38980	0.56640	2.05080	7.60150	3.83770
STP-HOLMAN	LINEZT_3.SUP	90.02	0.06134	0.38980	0.56640	2.05080	7.60150	3.83770
STP-LHILL	LINEZT_3.SUP	141.28	0.06134	0.38980	0.56640	2.05080	7.60150	3.83770
STP-DOW	LINEZT_3.SUP	45.39	0.03092	0.40502	0.29693	1.63593	14.73960	5.99290
STP-SKY	LINEZT_3.SUP	167.44	0.06134	0.43594	0.56640	2.00988	7.62447	4.37250
STP-HILL	LINEZT_3.SUP	178.34	0.06134	0.43594	0.56640	2.00988	7.62447	4.37250

Table XV. WECC 9-bus system source parameters in steady state (slightly modified from original parameters)

Source number	ATPdraw Component	Voltage(V)	Angle(deg)	$x_L(pu)$	$x_d(pu)$	$x_q(pu)$	$x_d^{'}(pu)$	$x_q^{'}(pu)$	$x_d^{''}(pu)$
1	SM59_NC.SUP	195305	0	0.03	0.146	0.969	0.0608	0.0969	0.04
2	SM59_NC.SUP	192489	9.396	0.01	0.896	0.865	0.1198	0.1969	0.07
3	SM59_NC.SUP	192489	4.706	0.10	1.313	1.258	0.1813	0.2500	0.12
	$x_q^{''}(pu)$	$t_{do}^{'}(s)$	$t_{qo}^{'}(s)$	$t_{do}^{''}(s)$	$t_{qo}^{''}(s)$	$x_0(pu)$	HICO (million $kg-m^2$)		
1	0.06	8.96	0.31	0.032	0.05	0.04	0.0333		
2	0.13	6.00	0.54	0.032	0.05	0.13	0.0090		
3	0.17	5.89	0.60	0.032	0.05	0.12	0.0042		

Table XVI. WECC 9-bus system line parameters

Line	ATPdraw Component	Positive-sequence impedance $Z_1(\Omega)$		Zero-sequence impedance $Z_0(\Omega)$	
		R_1	X_1	R_0	X_0
1-4	LINESY_3.SUP	0	30.470	0	91.411
2-7	LINESY_3.SUP	0	33.063	0	99.188
3-9	LINESY_3.SUP	0	30.999	0	92.998
7-8	LINESY_3.SUP	4.4965	38.088	13.4895	114.264

Line	ATPdraw Component	Length (miles)	Resistance (Ω/mile)		Reactance (Ω/mile)		Susceptance (Ω/mile)	
			R_1	R_0	ωL_1	ωL_0	ωC_1	ωC_0
4-5	LINEZT_3.SUP	100	0.05290	0.15870	0.44965	1.34895	3.32703	1.66352
4-6	LINEZT_3.SUP	100	0.08993	0.26979	0.48668	1.46004	2.98677	1.49338
5-7	LINEZT_3.SUP	100	0.16928	0.50784	0.85169	2.55507	5.78450	2.89225
6-9	LINEZT_3.SUP	200	0.10316	0.30947	0.44965	1.34895	3.38374	1.69187
8-9	LINEZT_3.SUP	100	0.06295	0.18885	0.53323	1.59970	3.95085	1.97543

Table XVII. WECC 9-bus system load parameters

Line	ATPdraw Component	Phase A impedance (Ω)		Phase B impedance (Ω)		Phase C impedance (Ω)	
		R_a	X_a	R_b	X_b	R_c	X_c
Load-A (Bus 6)	RLC_3.SUP	542.5424	180.83865	542.5424	180.83865	542.5424	180.83865
Load-B (Bus 5)	RLC_3.SUP	361.6244	144.64976	361.6244	144.64976	361.6244	144.64976
Load-C (Bus 8)	RLC_3.SUP	486.3748	170.23114	486.3748	170.23114	486.3748	170.23114

Table XVIII. Two-machine system source parameters in steady state

Source number	ATPdraw Component	$\lvert E\rvert(V)$	$\angle E$(deg)	$R_1(\Omega)$	$X_1(\Omega)$	$R_0(\Omega)$	$X_0(\Omega)$
1	AC3PH.SUP	500000	15	1.512	100.3	2.135	109.3
2	AC3PH.SUP	500000	0	0.345	42.93	0.272	45.78

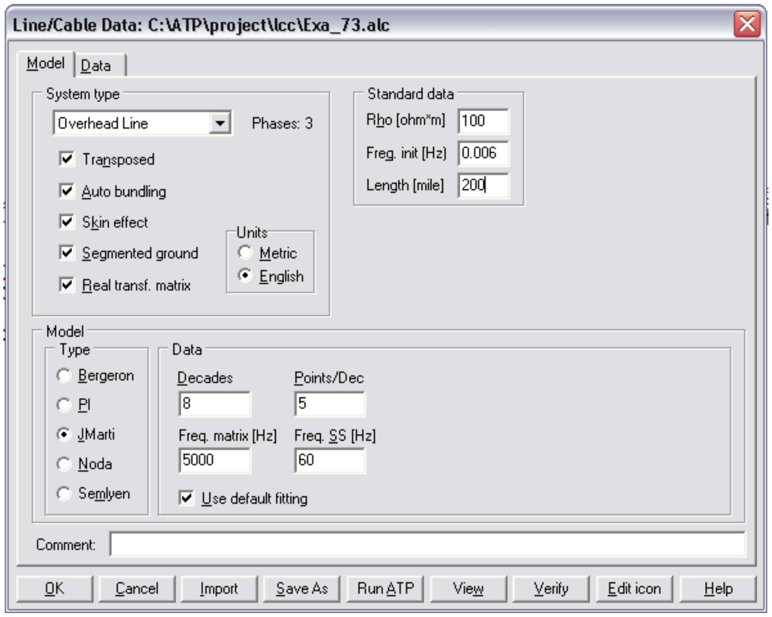
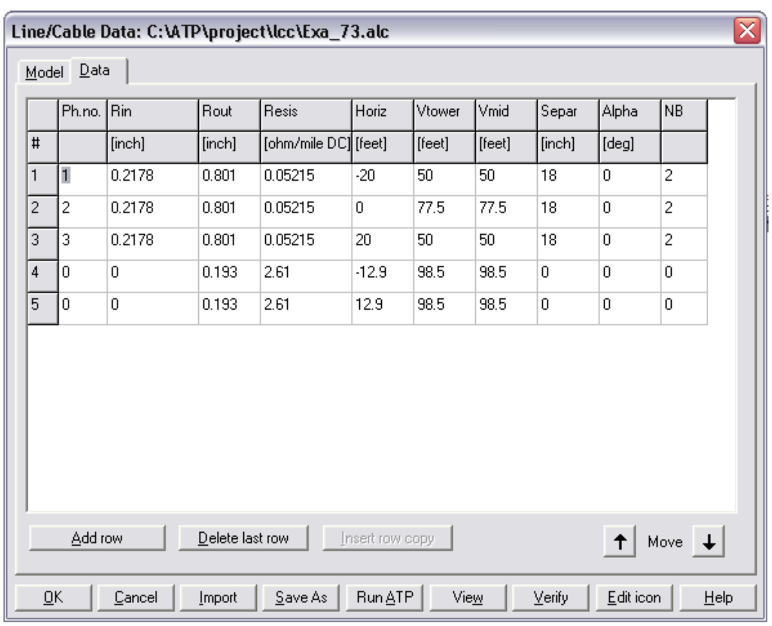


Fig. 65. Parameters setup for all three lines in two-machine system (1)



	Ph.no.	Rin	Rout	Resis	Horiz	Vtower	Vmid	Separ	Alpha	NB
#		[inch]	[inch]	[ohm/mile DC]	[feet]	[feet]	[feet]	[inch]	[deg]	
1	1	0.2178	0.801	0.05215	-20	50	50	18	0	2
2	2	0.2178	0.801	0.05215	0	77.5	77.5	18	0	2
3	3	0.2178	0.801	0.05215	20	50	50	18	0	2
4	0	0	0.193	2.61	-12.9	98.5	98.5	0	0	0
5	0	0	0.193	2.61	12.9	98.5	98.5	0	0	0

Fig. 66. Parameters setup for all three lines in two-machine system (2)

VITA

Nan Zhang received his B.S. and M.S. degrees from Tsinghua University, Beijing, China, both in electrical engineering, in 1999 and 2002 respectively. Since June 2002, he has been with Texas A&M University pursuing his Ph.D. degree. He was a student researcher at the Electric Power Research Institute (EPRI), Palo Alto, CA from April 2006 to July 2006. His research interests are power system protection and control, voltage and transient stability, substation automation, cascading blackouts, as well as signal processing and artificial intelligence applications in power systems. He received his Ph.D. Degree in electrical engineering in December 2006.

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