INTELLIGENT ECONOMIC ALARM PROCESSOR (IEAP)

A Dissertation

by

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ABSTRACT

The advent of electricity market deregulation has placed great emphasis on the availability of information, the analysis of this information, and the subsequent decision-making to optimize system operation in a competitive environment. This creates a need for better ways of correlating the market activity with the physical grid operating states in real time and sharing such information among market participants. Choices of command and control actions may result in different financial consequences for market participants and severely impact their profits.

This work provides a solution, the Intelligent Economic Alarm Processor to be implemented in a control center to assist the grid operator in rapidly identifying the faulted sections and market operation management.

The task of fault section estimation is difficult when multiple faults, failures of protection devices, and false data are involved. A Fuzzy Reasoning Petri-nets approach has been proposed to tackle the complexities. In this approach, the fuzzy reasoning starting from protection system status data and ending with estimation of faulted power system section is formulated by Petri-nets. The reasoning process is implemented by matrix operations.

Next, in order to better feed the FRPN model with more accurate inputs, the failure rates of the protections devices are analyzed. A new approach to assess the circuit breaker's life cycle or deterioration stages using its control circuit data is introduced. Unlike the traditional "mean time" criteria, the deterioration stages have been

mathematically defined by setting up the limits of various performance indices. The model can be automatically updated as the new real-time condition-based data become available to assess the CB's operation performance using probability distributions.

The economic alarm processor module is discussed in the end. This processor firstly analyzes the fault severity based on the information retrieved from the fault section estimation module, and gives the changes in the LMPs, total generation cost, congestion revenue etc. with electricity market schedules and trends. Then some suggested restorative actions are given to optimize the overall system benefit. When market participants receive such information in advance, they make estimation about the system operator's restorative action and their competitors' reaction to it.

DEDICATION

To My Family for their love, patience and support.

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NOMENCLATURE

IAP	Intelligent Alarm Processor
IEAP	Intelligent Economic Alarm Processor
EMS	Energy Management System
MMS	Market Management System
SCADA	Supervisory Control and Data Acquisition
PMU	Phasor Measurement Unit
IED	Intelligent Electronic Device
ISO	Independent System Operator
SPS	Special Protection Schemes
ATC	Available Transmission Capability
OASIS	Open Access Same Time Information System
MP	Market Participants
LMP	Locational Marginal Price
ES	Expert System
FL	Fuzzy Logic
PN	Petri-nets
FRPN	Fuzzy Reasoning Petri-nets
OPF	Optimal Power Flow
NN	Neural Network
DFR	Digital Fault Recorder

DPR	Digital Protective Relay
CBM	Circuit Breaker Monitor
GPS	Global Positioning System
PQDIF	Power Quality Data Interchange Format
PQM	Power quality Meter
SER	Sequence of Event Recorder

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1. INTRODUCTION

1.1 Introduction

Transitions from the zonal based market system to a nodal based market system are happening in the U.S. regions, like California ISO and ERCOT etc. [1]. The transition brings more complexities in the system operation and electricity market as there is larger amount of data and more price signals, as shown in Figure 1[2]. It also has placed great emphasis on the availability of the grid information, the analysis of this information, and the subsequent decision-making to optimize system operation in a competitive environment.

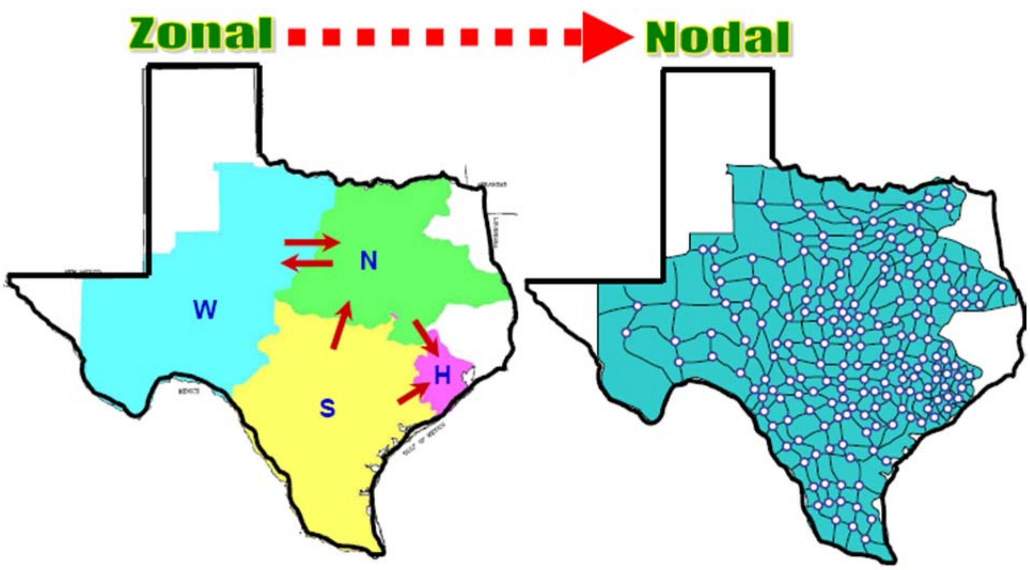


Figure 1 Market transition in Texas

1.2 Problem Formulation

1.2.1 Reactive Control System

Power system operators need to operate the transmission system under increasingly complex conditions. The formulations of power markets and open access policies have introduced a variety of challenges in system operations. Renewable generation, energy storage, demand response, and electric vehicles introduce further complexity to system operation. The current monitoring, analysis, and control technology for transmission networks may not be able to meet these increasingly diverse future challenges.

Looking ahead, we can see that enhancing the functionalities of system operation will be necessary to maintain and improve power system reliability and power quality. Energy research organizations have made considerable progress in formulating and promoting a vision for of the future smart power grids [3]-[14].

Monitoring, analysis and control are three main functions in power system operation. If we use human system operators as a metaphor, the monitoring functions are the operators' eyes, the analysis functions are the operators' brains, and the control functions are the operators' hands.

The present power system operation, especially monitoring, analysis, and control functions, were initially developed in the 1960s. The technologies invented at that time have led to computerized one-line diagram visualization, state estimation, and contingency analysis. The typical present technology of monitoring, analysis, and control is briefly summarized here.

The monitoring system is based on raw data or output from state estimation, which is subject to a considerable delay at the scale of tens of seconds to minutes. It is usually based on the local information of a control area. Interaction with neighboring systems is limited. Computer-aided visualizations are available, but only in one-line diagrams without customization.

The security assessment is based on contingency screening, which is essentially a steady-state power flow analysis. Voltage stability analysis is simulation-based, which depends on the accuracy of the models and the performance of the state estimator.

The protection and control system is mostly based on local information. Some recent work considering global impact using special protection schemes (SPS) is based on offline studies to adjust control strategies. In general, the coordination of different protection and control systems is limited. The process of system restoration is mainly based upon operators' experience and results from offline studies.

As shown in

Figure 2, the current system operation at control centers is reactive. Operators' eyes are reading the raw data, with limited information provided to the brains. The brains are trying to comprehend the current situation, generally based on past experience and preliminary assumptions. Such limited functionality may not be adequate to meet the needs of an increasingly complex and stressed power grid.

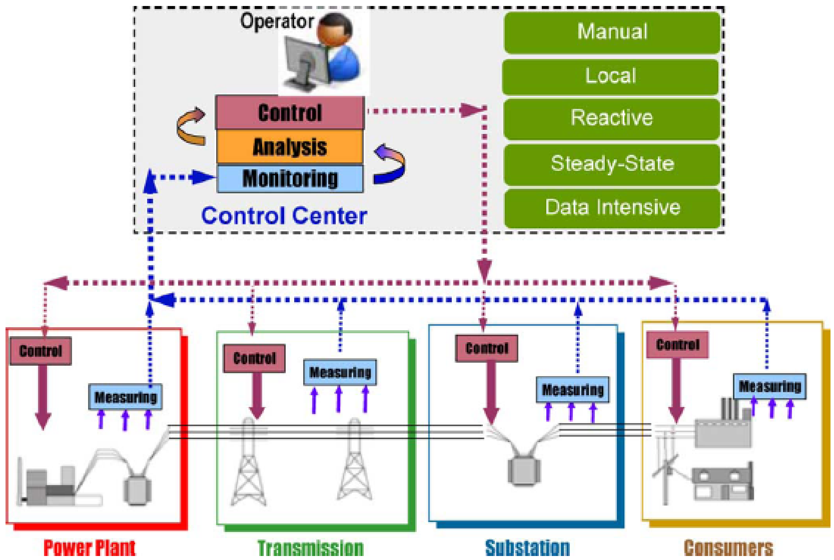


Figure 2 Current control center and its functions

On the other hand, the vision for future control centers, also referred to as smart control centers, can be a critical part of the overall framework of the future smart grid. This vision has the following five characteristics:

- Human-centered;
- Comprehensive;
- Proactive;
- Coordinated;
- Self-healing.

The growth of new energy resources, the emerging transmission and substation technologies, and advances in communication and computing infrastructures [15]-[19], require power system engineers to re-think how to perform real-time monitoring, analysis, and control.

1.2.2 Grid and Market Relationship

The Independent System Operator (ISO) has the basic responsibilities to perform system security monitoring functions and re-dispatch generation as necessary to eliminate real-time transmission congestion and to maintain system reliability, including taking all necessary emergency actions to maintain the security of the system in both normal and abnormal operating conditions. The main functions of the ISO can be categorized into reliability-related functions and market-related functions.

The reliability-related functions include two aspects:

- System operation and coordination. The ISO should perform system security monitoring functions and re-dispatch generation as necessary to eliminate real-time transmission congestion and to maintain system reliability, including taking all necessary emergency actions to maintain the security of the system in both normal and abnormal operating conditions.
- Transmission planning and construction. The ISO should carry out reliability studies and planning activities in coordination with the transmission owners and other market participants to assure the adequacy of the transmission system. The ISO should publish data, studies and plans relating to the adequacy of the transmission system. Data might include locational congestion prices and planning studies that identify options for actions that might be taken to remedy reliability problems on the grid and cost data for some of these actions.

The market-related functions of an ISO must be carried out according to transparent, understandable rules and protocols. The following operational functions are necessary to enable a competitive generation market:

- Determine Available Transmission Capability (ATC) for all paths of interest within the ISO region.
- Receive and process all requests for transmission service within and through the ISO region from all participants, including transmission owners.
- Schedule all transactions it has approved.
- Operate or participate in an Open Access Same Time Information System (OASIS) for information publishing.
- Establish a clear ranking of transmission rights of all the participants on the ISO transmission system. Facilitate trading of transmission rights on its grid among participants.
- Manage transmission congestion in accordance with established rules and procedures for generation re-dispatch and its cost allocation.
- Assure the provision of ancillary services required to support all scheduled delivery transactions.
- Market settlement and billing functions.

The minimum functions of the ISO should include the operation and coordination of the power system to ensure security. In this case, a separate market operator (for example, the Power Exchange in California) is needed to perform the market-related functions. On the other hand, the maximum functions of the ISO will include all the reliability-related and market-related functions mentioned above and in addition the ISO is the transmission owner (for example, the National Grid Company of UK). The reliability-related and market-related functions of the ISO at various sizes and time scales are shown below in Figure 3 [20].

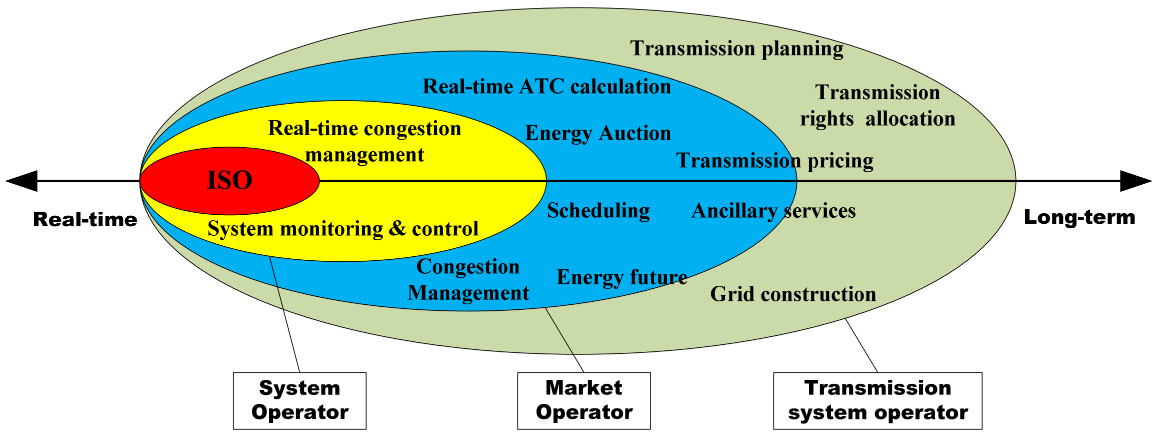
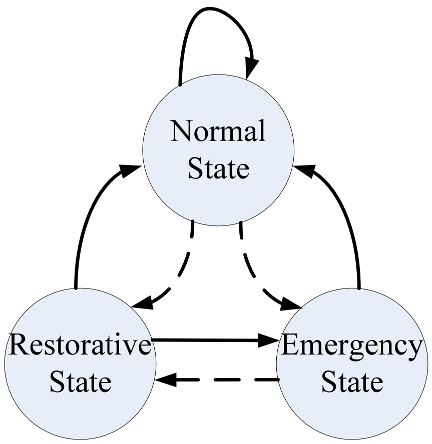


Figure 3 ISO responsibilities

However, the system reliability versus system economics is still an issue that has not been fully resolved yet. In addition, current Energy Management System (EMS) and Market Management System (MMS) are still two individually-operated system and closer links need to be provided. This creates an urgent need for better ways of correlating the market activity with the physical grid operating states in real time and sharing such information among market participants. Choices of command and control actions may result in different financial consequences for market participants and severely impact their profits. Because of this, new solutions have to be implemented toward integrating grid control and market operations taking into account both good engineering practices and appropriate economic incentives.

In order to establish an effective real-time monitoring and control system for integrated grid and market operations, the relationship between the two needs to be examined. The market structure for scheduling electricity includes forward bilateral contracts and centrally coordinated markets for day ahead, hour ahead and real-time energy and ancillary services. Once the forward markets have closed, the real time market operation coincides with real time system operations. Schedules from the forward markets are implemented in the real time dispatch and resources made available through the markets to provide ancillary services are selected and dispatched by the system operator for balancing and regulation.

When some operating parameters, such as voltage/current, exceed acceptable limits, the system shifts spontaneously (dotted line in Figure 4) to an unstable "Emergency" state. The result is usually an automatic control action (solid line in Figure 4), such as the tripping of a relay, which takes the system into a more stable but not fully functional "Restorative" state. Analogous states and transitions are also applicable in electricity markets, with some notable differences, as shown in Figure 4.



Type	Configuration	Market Parameters
Normal	All MPs complete	Within Limits
Emergency	All MPs complete	Parameter(s) violate the limits
Restorative	Structure incomplete	Within limits

***MPs(Market Participants) include generator companies, transmission owners, load serving entities and other non-asset owners such as energy traders.**

Figure 4 System and market operating states

1.2.3 Challenges of Alarm Processing

As the power system get operated closer to the limits and operating conditions get more complex, operators are often overloaded with tremendous number of alarm messages generated by the events in the system. A major power system disturbance could trigger hundreds and sometimes thousands of individual alarms and events [21]. Some estimates of the maximum number of alarms which could be triggered by several types of events have been established for the regional control centers of Hydro Quebec [22]:

- Up to 150 alarms for a transformer fault
- Up to 2000 alarms for a generation substation fault, the first 300 alarms being generated during the first five seconds
- Up to 20 alarms per seconds during a thunderstorm

- Up to 15,000 alarms for each regional center during the first five seconds of a complete system collapse

Obviously this is beyond the capacity of any operators to handle quickly and reliably. Thus, under stressful conditions operators may not be able to respond to the unfolding events in a timely manner, and even worse, the alarm interpretation by the operators may be either wrong or inconclusive.

Nowadays, many supervisory control and data acquisition (SCADA) systems have already employed Intelligent Alarm Processing (IAP). The past work [21]-[24] seems to point out that an intelligent alarm processor that can analyze large number of alarm messages efficiently and extract information that explains the network events quickly is utilizing experts systems and/or fuzzy logic techniques [24][25] to improve processing of data from either SCADA system or from substation intelligent electronic devices (IEDs) [26]. A consensus is that the intelligent alarm processors need to meet the following requirements [27]:

- Reduce the number of alarms presented to the operator
- Convey a clearer idea of the power system condition causing the alarms
- Recommend corrective action to the operator if such action is needed

These goals are clearly not independent. An effective reduction in the number of alarms cannot be achieved just by reorganizing the overall list of alarms into categorized lists that contain smaller number of related alarms. More informative messages must be generated by combining simpler messages. Reciprocally, if a better description of the problem affecting the power system is displayed for the operator, there is often no need to present all the details. Finally, recommending a corrective action is not possible until the problem has been fully understood and explained.

1.3 Current Research Efforts

1.3.1 Coordination between Grid and Market

Many studies have been done to illustrate the relationship between physical system operations and market activities from different aspects. One of the them is that Jonathan W. Stahlhut and Gerald Thomas Heydt in Arizona State University have proposed to use locational marginal prices (LMPs) to evaluate the impact on the power system [28]. Since power markets play a key role in the flow of power in the transmission network, power market transactions, influenced by the LMP values as well as other economic signals, should play a role in everyday operations of the power system. Other references [29][30] have been put efforts to replicate the real time competitive process in the contemporary deregulated power market environment. Reference [31] describes the interface and persistent gap between market and system operations in restructured electricity markets along with some lessoned learned through the restructuring experience in the United States and abroad. References [32][33] discuss how the market risks in operations can be measured and those risks may be managed in both operational and financial ways. Models have been proposed to demonstrate the financial effects of power purchase based on probability and consequences. The work in [34] analyzes the impacts of emergency events on day-ahead and real-time market LMPs. The concept of "economic alarm" was first raised in [28] to augment conventional electrical alarms and to bring to the attention of transmission system operators and market participants changes in system operating and economic conditions in an electric power system. The authors ranked the alarm based on the economic severity, and a set of predetermined events that would give certain suppliers the ability to exercise market power will trigger an alarm.

1.3.2 Alarm Processing Techniques

Since the late eighties, the concepts of filtering and suppressing alarms have been used in many practical systems [35]. This was achieved using intelligent techniques. The major intelligent techniques used so far include:

Expert System (ES) Technique

Expert system (ES) technique [36]-[39] is well suited for a diagnosis problem like fault section estimation because it mimics the behavior of fault analysis experts which perform fact-rule comparisons and search consequent steps. The disadvantage is that an expert system has to be developed using formalized knowledge that correctly captures the expertise, which may require an extensive expert interviewing effort.

Fuzzy Logic (FL) Technique

FL technique [40][41] offers a convenient means for modeling inexactness and uncertainties; hence a powerful solution to handle the imprecise and incomplete data may be implemented. The disadvantage is the need to have empirical data that helps determine the membership function and properties of fuzzy variables.

Petri-nets (PN) Technique

Petri-nets (PN) based technique [42]-[45] possesses the characteristics of graphical discrete event representation and parallel information processing. While very fast, the dynamic nature of the temporal change of the alarms cannot be easily captured with the standard Petri-net approach unless further adjustments are made.

Fuzzy Reasoning Petri-nets (FRPN) Technique

Fuzzy Reasoning Petri-nets (FRPN) technique [46]-[48] gains the advantages of Expert System and Fuzzy Logic, as well as parallel information processing. Some of the disadvantages of previously mentioned individual techniques may be offset by the benefits coming from combining the techniques.

An implicit disadvantage of the traditional knowledge-based systems is that they may be incapable of handling complex scenarios that are not encountered during knowledge acquisition, implementation, or validation. They may also suffer from the slowness in analysis due to involved knowledge representation and inference mechanism. Solutions based on discrete event view of Petri-nets also have several limitations. For instance, the number of initial inputs is limited and it is difficult to model inexactness and uncertainties. Consequently, to accurately identify fault sections under complex circumstances, substantial heuristic rules and information are additionally required.

1.3.3 The Impacts of Topology Changes on Electricity Market

Traditionally, transmission elements in electrical networks are characterized as static assets. In regulated areas, the utility dispatches generators over this fixed system to minimize cost and in restructured regions generators use this network as a means to compete with one another. However, it is acknowledged, both formally and informally, that system operators can and do change the grid topology to improve voltage profiles or increase transfer capacity of a flowgate [49][50]. These decisions are made at the discretion of the operators, rather than in an automated or systematic way. Anecdotal evidence exists that some system operators switch lines in and out because of reactive power consumption or production of lines, or other reasons [49]. The Northeast Power Coordinating Council includes "switch out internal transmission lines" in the list of possible actions to avoid abnormal voltage conditions [51][52]. There is also a national push to model the grid in a more sophisticated, smarter way as well as to introduce advanced technologies and control mechanisms into grid operations.

A Corrective Mechanism

Glavitsch [53] gives an overview of the use of transmission switching as a corrective mechanism in response to a contingency. He discusses the formulation of such a problem and provides an overview on search techniques to solve the problem. Mazi et al. [54] propose a method to alleviate line overloading due to a contingency by the use of transmission switching as a corrective mechanism. This method is limited since it is a heuristic technique, which does not consider all possible transmission switching solutions and it does not co-optimize the topology with the generation. Gorenstin et al.

[55] study a similar problem concerning transmission switching as a corrective mechanism; they use a linear approximate Optimal Power Flow (OPF) formulation and solve the problem based on branch and bound. Bacher et al. [56] further examine transmission switching in the AC setting to relieve line overloads; however, they assume that the generation dispatch is already determined and fixed thereby not capturing the benefit of co-optimizing the network topology with generation. Bakitzis et al. [57] examine transmission switching as a corrective mechanism both with a continuous variable formulation for the switching decision as well as with discrete control variables.

Schnyder *et al.* [58][59] proposed a fast corrective switching algorithm to be used in response to a contingency. The benefit of this algorithm over past research is that they simultaneously consider the control over the network topology and the ability to redispatch generation whereas other methods would assume that the generation is fixed when trying to determine the appropriate switching action. Due to the complexity of this problem for its time, this method does not search for the actual optimal topology but rather considers limited switching actions. Rolim *et al*. [60] provide a review of past transmission switching methods, the solution techniques used, the objective at hand, etc. Shao *et al*. [61] continued previous research on the use of transmission switching as a corrective mechanism to relieve line overloads and voltage violations. They propose a new solution technique to find the best switching actions. Their technique employs a sparse inverse technique and involves a fast decoupled power flow in order to reduce the number of required iterations. In Shao *et al*. [62], a binary integer programming technique is used for the same motivation: to use switching actions as a corrective mechanism to relieve line overloads and voltage violations.

A Loss Minimization Tool

In Bacher *et al.* [63], they propose switching to minimize system losses. This paper demonstrates that contrary to general belief, it is possible to reduce electrical losses in the network by temporarily opening a transmission line. Fliscounakis [64] proposed a mixed integer linear program to determine the optimal transmission topology with the objective to minimize losses. Unlike past research, this model does search for the optimal topology but it does not consider the impact on generation and, therefore, their method does not provide the true social welfare maximizing solution that is desired by co-optimizing the generation along with the transmission topology. It is in fact possible that the true social welfare maximizing solution may have an increase in losses but by accounting for the influence between generation and transmission, the overall costs may still be lower. This possibility further emphasizes the need to co-optimize the generation with the topology and that the objective should not be to minimize losses but rather to maximize the total social welfare, i.e., the market surplus. In contrast to these approaches, the optimal transmission switching concept maximizes the market surplus by co-optimizing the transmission topology along with generation.

A Congestion Management Tool

Granelli et al. [65] propose transmission switching as a tool to manage congestion in the electrical grid. They discuss ways to solve this problem by genetic algorithms as well as deterministic approaches. This approach attempts to minimize the amount of overloads in the network since they are not co-optimizing the generation with the topology. Thus, this is an after the fact approach where generation is first dispatched optimally but then this method is employed to reduce network congestion.

Maintenance Scheduling

The focus of past transmission line maintenance scheduling was on the effect on reliability. However, just as transmission lines affect reliability they also affect the operational costs of the electrical grid. Operators are now acknowledging the importance of transmission line maintenance scheduling not only regarding its effect on reliability but on operational costs. For instance, ISONE recently released a report stating that they saved $72 million in 2008 by considering the impact of transmission line maintenance scheduling on the overall operational costs, see ISONE [66].

Dispatchable Networks

The initial concept of a dispatchable network was first proposed by O'Neill *et al.* [67]. Fisher *et al.* [49] further developed and examined the concept of incorporating the control of transmission assets into dispatch optimization formulations. They claimed that real-time control can result in more efficient transmission topologies than static ones, even if the static ones were originally designed to be optimal.

1.4 Proposed Research

A breakdown of the proposed research in this dissertation is as follows:

- Develop a quick and effective fault section estimation module that can quickly make a cause-effect reasoning using logic-based network.

- Handles incomplete or false alarms such as missing relay signals or malfunction of circuit breaker operation
- Allows easy modification of the model setup and input data choices.
- Provides a methodology to assess the protection devices' reliability and life cycle/deterioration stages to help better make decisions to optimally allocate the maintenance resources. In addition, it gives insight into which component of the breaker is causing the problem instead of just reporting the failure rate (number of failures per year).
- A proposed Intelligent Economic Alarm Processor will take electrical grid alarms and power market schedules and trends, such as LMPs and prices as inputs and have the system operational alarms, fault severity indications and solutions as well as the impact on the electricity market as outputs

1.5 Organization of the Dissertation

This dissertation starts with the review of the background knowledge of the power system elements in Section 2. A Fuzzy-Reasoning Petri-nets model is proposed as an effective alarm processing tool in Section 3. Section 4 discusses the performance characteristics of the substation IED data measurement chain by focusing on industry standards for the instruments used. It also focuses how efficiently substation IED data along with the traditional SCADA data and other available data can be integrated to enhance the intelligent alarm processor application. In Section 5, a novel life cycle assessment model using condition-based data is proposed to evaluate protection devices' deterioration stages and failure rates. The FPRN model is extended to an Intelligent Economic Alarm Processor in Section 6 to integrate grid control and market operations taking into account both engineering practices and appropriate economic incentives.

2. BACKGROUND

2.1 Introduction

This Section describes the background knowledge of the power system elements for the dissertation study. First, different sections of a power system and their corresponding protection systems are explained. Then the application of SCADA system, circuit breaker and digital protective relays, which are the data source for fault analysis are introduced.

2.2 Protection Systems

A power system is composed of a lot of sections such as generators, transformers, bus bars and transmission lines. These sections are protected by protective relaying systems comprising instrument transformers, protective relays, circuit breakers and communication equipment. In case of a fault occurring on a section, its associated protective relays should detect the fault and issue trip signals to open their associated circuit breakers to isolate the faulted section from the rest of the power system, in order to avoid further damage to the power system. Figure 5 is an example of power system sections with their protection systems. G1 is a generator. T1 is a transformer B1,...,B5 are bus bars. L45 is a transmission line. RG is a generator protective relay. RT is a transformer protective relay. RB is a bus protective relay. RL-4,...,RL-9 are transmission line protective relays. C1,..., C9 are circuit breakers.

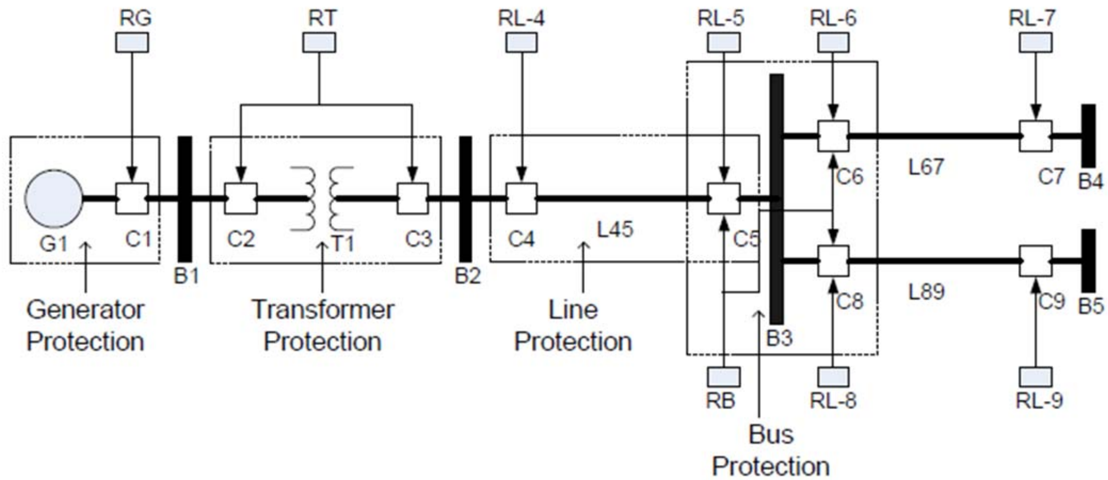


Figure 5 Example of power system sections with their protection systems

2.3 SCADA System

SCADA, which stands for Supervisory Control And Data Acquisition, usually refers to centralized systems that monitor and control the entire site. Remote Terminal Unit (RTU) of Supervisory Control and Data Acquisition (SCADA) System is most widely used data acquisition equipment in substations. They are capable of recording status signals such as relay targets, circuit breaker status, transformer status and substation alarms, as well as analog signals such as bus voltages and line currents [68]. The recorded data from RTUs distributed in substations at different locations can be transferred to a central control center via certain communication links. Figure 6 shows the common structure of SCADA systems.

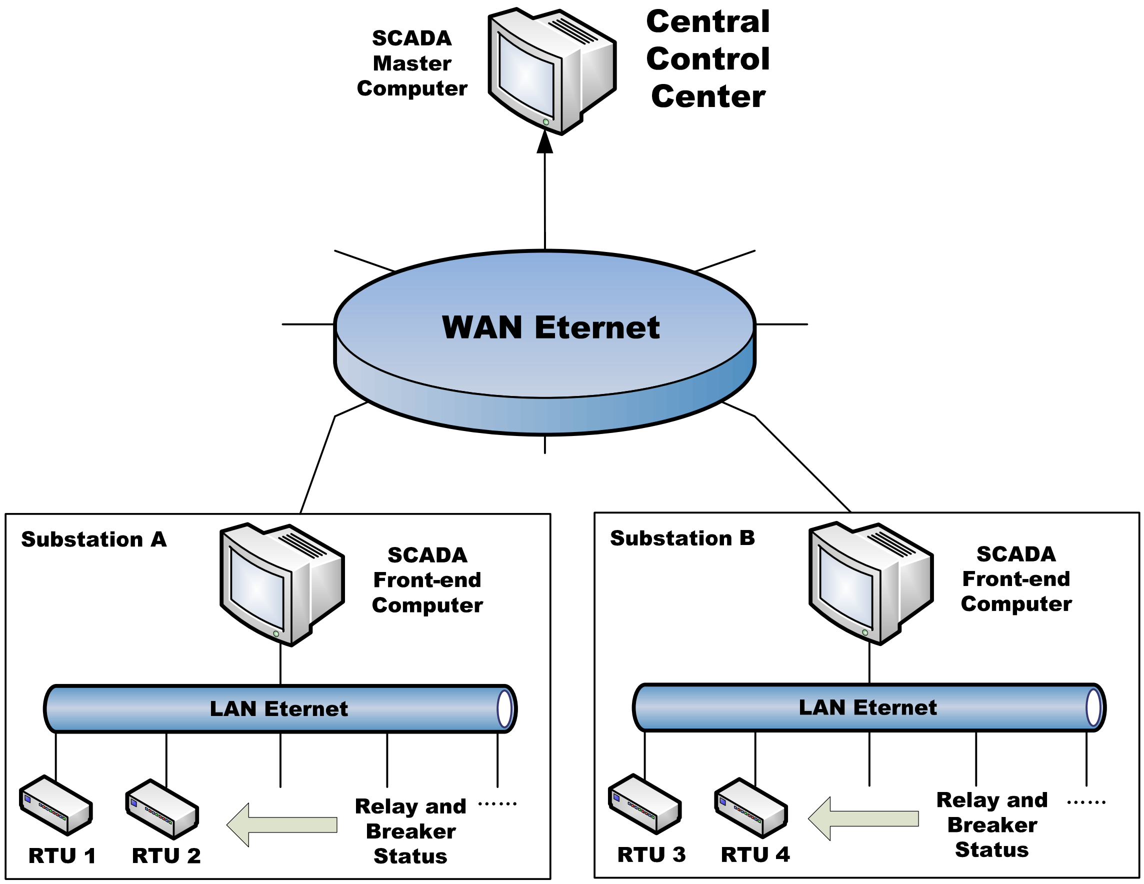


Figure 6 SCADA system structure

There are several limitations of SCADA systems, which may restrict its performance in power system fault analysis applications.

1. The number of I/O ports of RTUs is limited. For monitoring of protection system status, usually only relay trip signals and circuit breaker status signals are selected to be recorded. Due to the limitation, it is difficult to use additional information such as zone of operation, pickup, circuit breaker control circuit status to improve the determination of relay trip and circuit breaker switching

status signals.

2. The timing accuracy of events recorded by RTUs is limited. RTUs usually have low scanning rates, which may be in the order of seconds. In practice, some RTUs use flags to label recorded events and then time-tag them using the scanning time. That means many events occurring in a short time interval may have the same time-stamp. Some other RTUs do not time-tag recorded events in the first place. Instead, the time when the master computer of the SCADA system receives event information is used as the time-stamp. Since there are always time delays because of data transmission, the timing accuracy of events is further degraded. Such limitation makes using sequence of events information difficult.

2.4 Circuit Breaker

Main components of a circuit breaker are its operating mechanism, contacts, control circuit and interrupting medium. The function of operating mechanism is to open or close the breaker contacts upon a command. As shown in Figure 7 the operating mechanism consists of various components such as operating rod, springs, valves, latches, cams, rollers, bolts, washers etc.

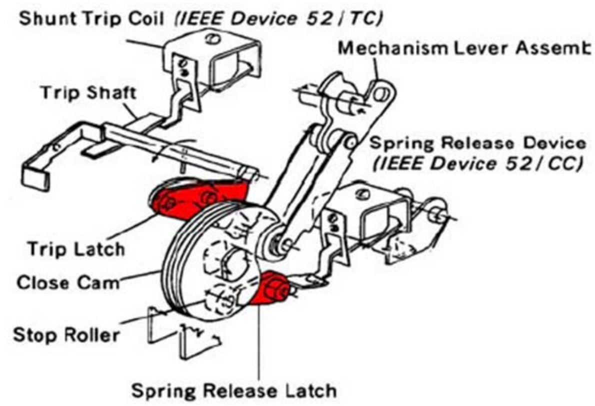


Figure 7 Circuit breaker operating mechanism [69]

Contacts are metal parts and carry the load current when circuit breaker is in closed position. The electrical representation of the control circuit is shown in Figure 8. Control circuit issues a command to the circuit breaker, and in turn the operating mechanism reacts and opens the breaker contacts. Contacts are located in interrupting chamber where arc extinction takes place. Air Blast and Oil circuit breakers are considered in this study.

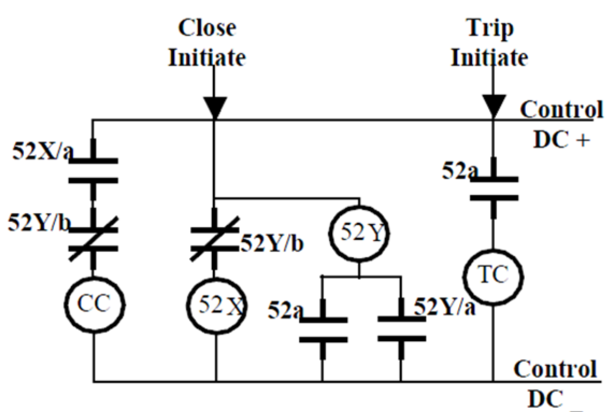


Figure 8 Electrical representation of circuit breaker control circuit [70]

The circuit breaker monitoring device can monitor 15 electrical signals from the circuit breaker control circuit. The signals are generated during either tripping or closing of the circuit breaker. Of these 15 signals, 11 are analog and 4 are status signals. The monitored signals are listed in Table 1.

Table 1 Signals of Circuit Breaker Control Circuit

Group	Signal Name
Digital signals	Trip Initiate
	Close Initiate
	X Coil signal
	Y Coil signal
Contacts	"A" Contact
	"B" Contact
DC Voltages	Control DC Voltage
	Yard DC Voltage
	Light Wire
Coil Currents	Trip Coil (TC) Current 1
	Trip Coil (TC) Current 2
	Closing Coil (CC) Current
Phase Currents	Phase Current A
	Phase Current B
	Phase Current C

The most important signals are Trip Initiate and Close Initiate. These signals, initiated by the relay or the operator, cause generation of some other signals, as a result of the circuit breaker tripping or closing. All of the monitored signals are voltage signals. The signals representing currents are taken from shunts, thus converting them to appropriate voltage signals. In the worst case scenario time between the fault occurrence and the breaker lockout is about one minute. The monitoring device is designed to record and store recorded data for this duration.

A block diagram of the Circuit Breaker Monitor IED is shown in Figure 9 [70]. The system consists of following modules:

1. Signal conditioning boards: The Signal conditioning and isolation module provides appropriate voltage levels for data acquisition. The voltage levels of signals at circuit breaker are either 130VDC or 1 VDC. The signal conditioning module conditions the input signals to be in the [-5, +5]V range as required at the input of the A/D converter module. The module has adjustable gain for all 15 channels. A user determines suitable gain values for the hardware to be used with input signals during set up. The gain can be adjusted by software within a certain range for precise calibration in case of drift over time. The module also provides galvanic isolation of the signals at the input to prevent faults at the input of the module from damaging the rest of the system.
2. Analog to digital converter: The A/D converter employed has 16 channels and a 16 bit resolution. It takes the input from signal conditioning board and converts it to digital form. The sampling on the 15 channels utilized is synchronous. The sampling rate used is 5760 Hz but can be modified by software depending on the capability of the A/D converter.
3. Microprocessor: A microprocessor belonging to the x86 family is used for controlling the data acquisition and running the communication protocols. The microprocessor is equipped with 32 MB of memory to store 1 minute of

data in case of offline monitoring.

4. Wireless Transmitter: A wireless system capable of transmitting data to distances over 200m is used for transmitting the recorded data to the concentrator PC. A transfer protocol for data transfer is established and the receiving software is set up appropriately. The transmission bandwidth of the transmitter for real time monitoring is chosen to be larger than 1.4Mbps (5760Hz x 15 channels x 16 bits).

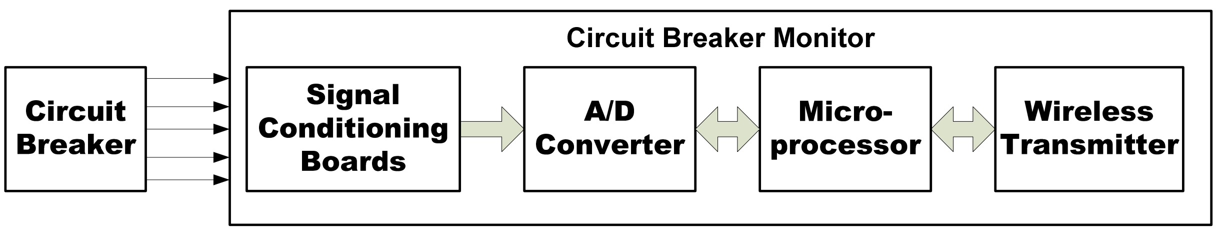


Figure 9 Circuit breaker monitor diagram

2.5 Digital Protective Relay

To achieve maximum flexibility, the firmware of digital relays is designed using the concept of functional elements. These elements usually include protection elements, control elements, and input and output contacts. The statuses of each element are represented by a set of predefined logic operands. As examples, Table 2 shows several logic operands for Ground Distance Zone 1 Element of GE's D60 relay [71].

Table 2   Operands for Ground Distance ZONE 1 Element of D60 relay

Group	Signal Name
Digital signals	Ground Distance Zone 1 has picked up
Contacts	Ground Distance Zone 1 has operated
DC Voltages	Ground Distance Zone 1 Phase A has picked up
Coil Currents	Ground Distance Zone 1 Phase B has operated
Phase Currents	Ground Distance Zone 1 Phase C has dropped out

Although relays from different manufacturers have different syntax for their logic operands, the functions of logic operands remain the same. First, logic operands can be used as logic variables to produce more complex schemes by logic operators in field programmable logic function provided by relays. Second, logic operands give information on the actual statuses of elements. Time-stamped logic operands are used as event record data to reflect detailed relay behaviors. Logic operands can also be recorded as digital oscillography data so that the statuses of elements can be visualized [72].

When fault occurs, elements change their statuses according to their design principles and settings. A timed protection operation chain will be formed in order to trip the circuit breaker associated with the relay to interrupt fault currents in predetermined time. Figure 10 illustrates the protection operation chain. In this chain, pickup of individual phases of elements is the first step and the current interruption by circuit breaker is the last step.

Along the chain, operation of any individual phase of an element will cause operation of the entire element. That is to say, operation of individual phases of a protection element triggers operation of the entire element through “or” relation.

Likewise, operation of several protection elements also triggers the relay trip through "or" relation. Operation of an element may be blocked by pickup or operation of another element or external block signals if pilot communication schemes are involved.

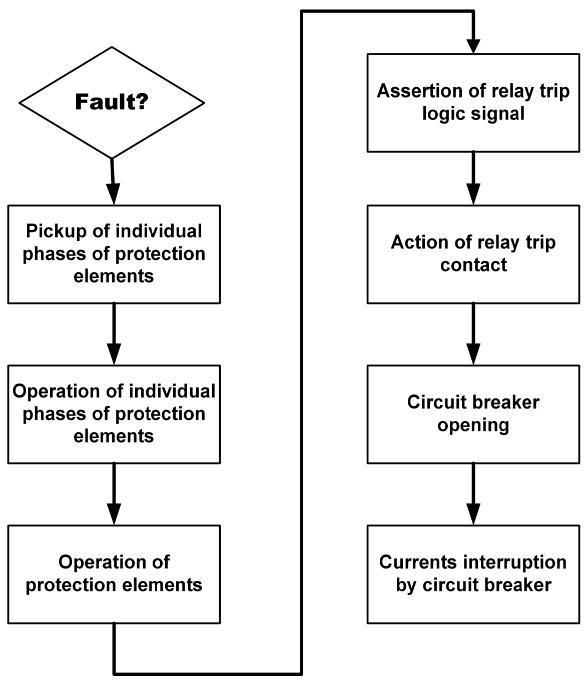


Figure 10 Protection operation flowchart

Most digital protective relays possess the capability of generating ¯les which contain detailed data about power system fault disturbances and corresponding responses of protection system components. These data can be classified into four categories, namely oscillography data, setting data, fault data and event record data. Generally, oscillography data contain the records of what a relay "sees" during a disturbance event. Setting data specifies how the relay is configured. Fault data presents fault disturbance information calculated by the relay. Event data reveal how the relay and associated protection components actually respond to the disturbance event. Besides these relay-generated data, performance specification data such as the average pickup time for a phase distance element and average opening time for a circuit breaker are also important information.

2.6 Summary

This Section explores the background knowledge of the power system elements for the dissertation study. A power system consists of a lot of sections, which are protected by their corresponding protection systems. Based on such a relation, protection system data can be utilized for fault analysis. SCADA systems are the traditional data source in power systems. Several limitations of SCADA systems may restrict their performance in fault analysis applications. The use of circuit breaker monitor makes it attractive to retrieve electrical signals from the circuit breaker control circuit to monitor the reliability of the operating status of the circuit breaker. Intelligent electronic devices such as digital protective relays provide additional information about protection system operation as well as fault events for fault analysis applications.

3. INTELLIGENT ALARM PROCESSOR USING FUZZY REASONING PETRI-NET ALGORITHM*

3.1 Introduction

A major power system disturbance could trigger hundreds and sometimes thousands of individual alarms and events. A better and simpler description of the problems affecting the power system is an urgent need for the operators. The task of an Intelligent Alarm Processor (IAP) is to analyze thousands of alarm messages and extract the information that explains cause-effect sequences associated with the network events. In this sense, Fuzzy Reasoning Petri-nets is a very powerful intelligent technique to deal with the complexities of the power system fault and alarm processing. A graphical FRPN model is built in this section based on the optimal structure and uses fuzzy logic parameters to effectively tackle the uncertainties. Case studies are presented to demonstrate the capability of the IAP under real fault scenarios.

3.2 Fundamental Fault Analysis Techniques

3.2.1 Backward Reasoning

Backward chaining is reasoning in reverse from a hypothesis, which is a potential conclusion to be proved, to the facts which support the hypothesis. A hypothesis can be viewed as a fact whose truth is in doubt and needs to be established. The hypothesis can

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* Part of the material in this section is reprinted from "Grid Monitoring and Market Risk Management using Intelligent Economic Alarm Processor," by Yufan Guan, and Mladen Kezunovic, *IEEE Intelligent Systems*., Vol. 26, No. 2, pp. 18-21, March-April 2011. DOI: 10.1109/MIS.2011.6 ©2011 IEEE, with permission from IEEE.

then be interpreted as a goal to be proven [73]. Figure 11 illustrates the concept of backward chaining. In order to prove hypothesis H1, at least one of the intermediate hypothesis H2, H3 and H4 must be proven. To prove H2, fact A must exist. Since fact A is not present, H2 is disproven. To prove hypothesis H3, both hypothesis H5 and H6 must be proven. Since the absence of fact B will disprove hypothesis H5, Hypothesis H3 is disproven. To prove hypothesis H4, hypothesis H7 must be proven. The existence of fact E and F will prove hypothesis H7, hence hypothesis H4 is proven. Finally hypothesis H1 is proven.

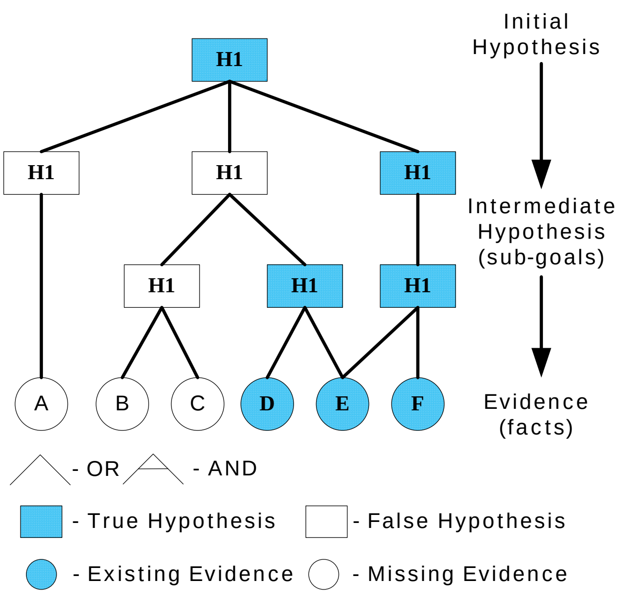

Figure 11 Backward reasoning example

3.2.2 Fuzzy Logic

Fuzzy logic is a logic based system that generalizes the classical two-valued logic for reasoning under uncertainty. The concept of fuzzy sets, the core of fuzzy logic, was first introduced by Lotfi A. Zadeh in 1965 [74].

A classical Boolean set A, may be equated with its characteristic function:

$$\varphi_A: X \to \{0,1\} \tag{3.1}$$

which associates with each element x of a universe of discourse X a number $\varphi(x) \in \{0,1\}$ such that $\varphi(x) = 0$ means that *x* does not belong to the set *A*, and $\varphi(x) = 1$ means that *x* does not belong to the set *A*.

Unlike the classical Boolean set, elements of a fuzzy set may belong to it to partial degree, from full belongingness to the full nonbelongingness through all intermediate values. Thus the characteristic function can be rewritten as:

$$\varphi_A: X \to [0,1] \tag{3.2}$$

such that $\varphi(x) \in [0,1]$ is the degree to which an element *x* belongs to the fuzzy set *A*. $\varphi(x) \in [0,1]$ is called the grade of membership [75].

Similarly as in the classical Boolean set theory, the basic operations in fuzzy set theory are complement, intersection and union.

The complement of a fuzzy set *A* in *X*, written as $\neg A$, is defined as:

$$\mu_{\neg A}(x) = 1 - \mu_A(x) \;\; \forall x \in X \tag{3.3}$$

The complement corresponds to the negation 'not'.

The intersection of two fuzzy sets *A* and *B* in *X*, written as $A \cap B$, is defined as:

$$\mu_{A \cap B}(x) = \mu_A(x) \wedge \mu_B(x) \tag{3.4}$$

where '$\wedge$' is usually a minimum operation, i.e. $a \wedge b = min(a, b)$. The intersection of two fuzzy sets corresponds to the connective 'and'.

The union of two fuzzy sets A and B in X, written as $A \cup B$, is defined as:

$$\mu_{A\cup B}(x) = \mu_A(x) \vee \mu_B(x) \tag{3.5}$$

where '$\vee$' is usually a maximum operation, i.e. $a \vee b = max(a, b)$. The intersection of two fuzzy sets corresponds to the connective 'or'.

In order to properly represent real-world knowledge where ambiguous, vague and imprecise data are involved, fuzzy rules have been used for knowledge representation [76]. A fuzzy rule is a rule describing the fuzzy relation between two propositions. Let R be a set of fuzzy rules $R = \{R_1, R_2, \dots, R_n\}$. The general formulation of the *i*th fuzzy rule as follows:

$R_i(c_i)$: IF $P_j(\theta_j)$ THEN $P_k(\theta_k)$

where P_j and P_k are propositions which may contion some fuzzy variables. The truth of each proposition, θ_j and θ_k are real values. $\theta_j \in [0,1]$, $\theta_k \in [0,1]$, $c_i \in [0,1]$. It represents the strength of the belief in the rule. The larger the value is, the more the rule is believed in.

3.2.3 Petri-nets

Petri-nets technique was first introduced by Carl A. Petri in 1962. It is a graphical and mathematical tool. The graphical aspect allows easy representation of the interaction between discrete events: parallelism, synchronism, precedence, alternatives and so on. The mathematical aspect allows formal modeling of these interactions and analysis of the properties of the modeled system. A formal definition of Petri-nets is as follows [75]:

Let *N* be the set of natural numbers and zero. A Petri-nets is a 4-tuple:

$$(P, T, Pre, Post)$$

where

1. $P = \{p_1, p_2, \dots, p_n\}$ is a finite set of places.
2. $T = \{t_1, t_2, \dots, t_n\}$ is a finite set of set of transitions.
3. *Pre* is the input incidence function:

$$Pre: P \times T \to N$$

4. *Post* is the output incidence function:

$$Post: P \times T \to N$$

In the graphical representation of a Petri-net, places are denoted by circles and transitions by bars. Places are the nodes describing the states (a place is a partial state) and the transitions depict the state changes. The *Pre* incidence function describes the directed arcs connecting places to transitions. $Pre(p, t)$ is the weight of the arc (p, t). The absence of an arc between a place p and a transition t is denoted by $Pre(p, t) = 0$. The Post incidence function describes the directed arcs connecting transitions to places. $Post(p, t)$ is the weight of the arc (t, p). The absence of an arc between a transition and a place is donated by $Post(p, t)$.

In the metrical representation of a Petri-net, *Pre* is a $n \times m$ matrix of n rows (the places) and *m* columns (the transitions) whose elements belong to *N*. The vector $Pre(\cdot, t)$ denotes the input arcs of transition *t* with their weights. *Post* is a $n \times m$ matrix of *n* rows (the places) and *m* columns (the transitions) whose elements belong to *N*. The vector $Post(\cdot, t)$ denotes the output arcs of transition t with their weights.

3.3 Fault Section Estimation Module Establishment

This Section proposes an advanced Fuzzy Reasoning Petri-nets (FRPN) diagnosis model after the structure adopted in [23]. This Intelligent Alarm Processor (IAP) model is expected to achieve the following goals:

- Suppress multiple alarms from one event
- Generate a single conclusion through logical cause-effect relationship
- Automate the process to get answers quickly
- Make graphical and numerical information concise and easy to follow

3.3.1 Definitions

Paper [77] has defined Fuzzy Reasoning Petri-nets as an 8-tuple:

$$(P, R, I, O, H, \theta, \gamma, C)$$

where

1) $P = \{p_1, p_2, \cdots, p_n\}$ is a finite set of places or called propositions.

2) $R = \{r_1, r_2, \cdots, r_m\}$ is a finite set of transitions or called rules.

3) $I : P \times R \rightarrow \{0,1\}$ is an $n \times m$ input matrix defining the directed arcs from propositions to rules. $I(p_i, r_j) = 1$, if there is a directed arc from p_i to r_j, and $I(p_i, r_j) = 0$, if there is no directed arcs from p_i to r_j, for $i = 1, 2, \cdots n,$ and $j = 1, 2, \cdots, m$.

4) $O : P \times R \rightarrow \{0,1\}$ is an $n \times m$ output matrix defining the directed arcs from rules to propositions.

5) $H: P \times R \to \{0,1\}$ is an $n \times m$ matrix defining the complementary arcs from propositions to rules. $H(p_i, r_j) = 1$, if there is a complementary arc from p_i to r_j, and $H(p_i, r_j) = 0$, if there is no directed arcs from p_i to r_j, for $i = 1, 2, \cdots n,$ and $j = 1, 2, \cdots, m$.

6) θ is a true degree vector. $\theta = (\theta_1, \theta_2, \cdots \theta_n)^T$, where $\theta \in [0,1]$ means the truth degree of p_i, $i = 1, 2, \cdots n$. The initial truth degree vector is denoted by θ^0.

7) $\gamma: P \to \{0,1\}$ is a marking vector. $\gamma = (\gamma_1, \gamma_2, \cdots \gamma_n)^T$. $\gamma_i = 1$, if there is a token in p_i, and $\gamma_i = 0$, if p_i is not marked. An initial marking is denoted by γ^0.

8) $C = diag\{c_1, c_2, \cdots c_m\}$. c_i is the confidence of r_i, $j = 1, 2, \cdots, m$.

The 5-tuple (P, R, I, O, H) is the basic FRPN structure that defines a directed graph. The updates of the truth degree vector θ through execution of a set of rules describe the dynamic reasoning process of the modeled system. If the truth degree of a proposition is known at a certain reasoning step, a token is assigned to the corresponding proposition, which is associated with the value between 0 and 1. The token is represented by a dot. When a proposition p_i has no token, which means that the truth degree is unknown at that step, $\theta_i = 0$.

3.3.2 Execution Rules

In order to describe the execution rules of a FRPN, the following operators are used:

1) $\oplus : \mathrm{A} \oplus \mathrm{B} = \mathrm{D}$, where A, B, and D are all $m \times n$ - dimensional matrices, such that

$d_{ij} = \max\{a_{ij}, b_{ij}\}$.

2) $\otimes$: $\mathrm{A} \otimes \mathrm{B}{=}\mathrm{D}$, where A, B, and D are all $(m \times p)$, $(p \times n)$, $(m \times n)$- dimensional matrices, such that $d_{ij} = \max_{1 \le k \le p}\{a_{ij} \cdot b_{ij}\}$.

The execution rules include enabling and firing rules.

1) A rule $r_j \in R$ is enabled if and only if p_i is marked, or $\gamma_i = 1$, $\forall p_i \in$ {input propositions of r_j }.

2) Enabled at marking γ, r_j firing results in a new γ'.

$$\gamma'(p) = \gamma(p) \oplus O(p, r_j), \qquad \forall p \in P \tag{3.6}$$

The truth degree vector changes from θ to θ'

$$\theta'(p) = \theta(p) \oplus c_j \cdot \rho_j \cdot O(p, r_j), \qquad \forall p_i \in P \tag{3.7}$$

where

$$\begin{aligned}\rho_j = \min_{p_i \in \overset{\square}{r_i}} \{x_i \mid x_i = \theta_i,\ if\ I(p_i, r_j) = 1; \\ x_i = 1\text{-}\theta_i\ if\ H(p_i, r_j) = 1\}\end{aligned} \tag{3.8}$$

and

$$\overset{\square}{r_i} = \{p_i \mid I(p_i, r_j) = 1\ or\ H(p_i, r_j) = 1,\ p_i \in P\} \tag{3.9}$$

3) All the enabled rules can fire at the same time. A firing vector μ is introduced such that $\mu_j = 1$, if r_j fires. After firing a set of rules, the marking and truth degree vectors of the FRPN become

$$\gamma' = \gamma \oplus [O \otimes \mu] \tag{3.10}$$

$$\theta' = \theta \oplus [(O \cdot C) \otimes \rho] \tag{3.11}$$

where $\rho = (\rho_1, \rho_2, \cdots \rho_m)^T$, which is called control vector. $\mu : T \to \{0,1\}$ is the firing vector.

From Eq. (3.10) and Eq. (3.11), we notice that as long as μ and ρ are known, the next step marking and truth degree vectors can be derived from the current values. To obtain μ, an 'neg' operator is used. μ^k can be calculated as follows:

$$neg\gamma^k = 1_m - \gamma^k = \overline{\gamma^k} \tag{3.12}$$

$$neg\theta^k = 1_m - \theta^k = \overline{\theta^k} \tag{3.13}$$

$$\mu^k = \overline{(I+H)^T \otimes \overline{\gamma^k}} \tag{3.14}$$

$$\rho_k = ((I^T .* W^T) \cdot \theta^k + (H^T .* W^T) \cdot \overline{\theta^k}) .* \mu^k \tag{3.15}$$

where $1_m = (1,1,\dots,1)^T$, k is the kth reasoning step, $neg\theta^k$ is an n-dimensional vector. Its components express the confidence of proposition p_i being false at the kth reasoning step, $i = 1,2,\dots,n$. γ^k is the marking. μ^k is an m-dimensional firing vector. $\mu^k = 1$, if r_j is enabled, and $\mu^k = 0$, if r_j is not enabled, $j = 1,2,\dots,m$. W is the weight matrix. ρ^k is an m-dimensional control vector at the kth reasoning step. Its components express the truth degrees of enabled rule r_j's preconditions. $\rho^k = 0$, if r_j is not enabled.

From the Eq. (3.10) and Eq. (3.14), we get:

$$\gamma^{k+1} = \gamma^k \oplus [O \otimes \overline{(I+H)^T \otimes \overline{\gamma^k}}] \tag{3.15}$$

From the Eq. (3.11) and Eq. (3.15), we get:

$$\theta^{k+1} = \theta^k \oplus (O \cdot C) \otimes (((I^T .* W^T) \cdot \theta^k + (H^T .* W^T) \cdot \overline{\theta^k}) .* \mu^k)] \tag{3.15}$$

To summarize, the FRPN algorithm can be described as follows:

1. Read initial inputs I, O, H, C, γ^0 and θ^0.
2. Let k=0.
3. Compute γ^{k+1} from γ^k according to Eq. (3.14); Compute θ^{k+1} from θ^k

according to Eq. (3.15);

4. If $\theta^{k+1} \neq \theta^{k}$ or $\gamma^{k+1} \neq \gamma^{k}$, let $k = k + 1$ and return to step 3; Otherwise, the reasoning is over.

3.4 FRPN Model Implementation

A 14-bus power system shown in Figure 12 is used for the study of fault section estimation problem. The system consists of 34 sections, including 14 buses and 20 transmission lines. The buses are denoted as Bnn. The transmission lines are denoted as Lnnmm.

The protection system of the 14-bus system consists of 174 protection devices, including 40 circuit breakers, 40 main transmission line relays, 40 primary backup transmission line relays and 40 secondary backup transmission line relays, and 14 bus relays.

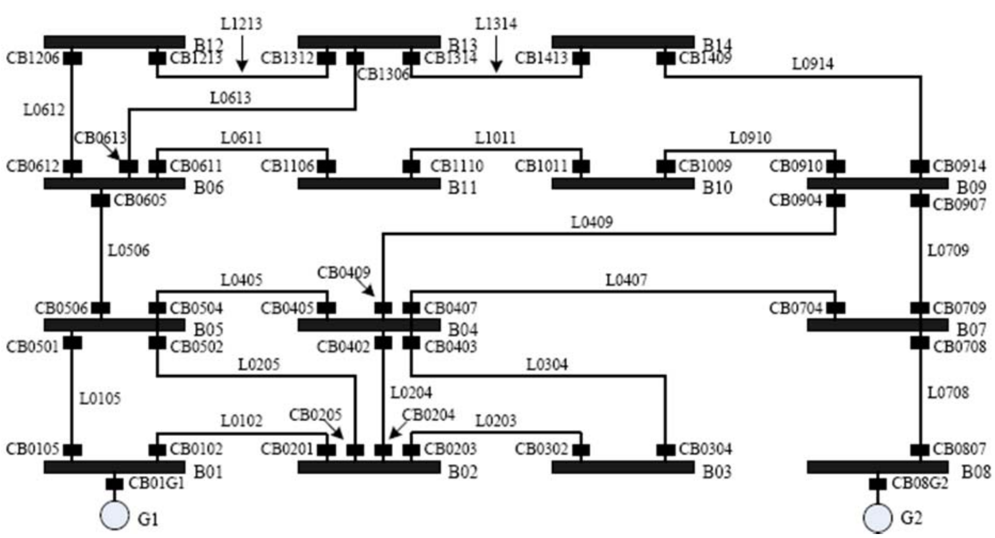

Figure 12   A 14-bus power system model

To explain the configuration and denotation of the protection system, a portion of the 14-bus power system is taken as an example as shown in Fig. 2. The portion includes a transmission line L1314, and its adjacent bus B13, B14 and adjacent transmission lines L1213, L0613, L0914. The main transmission line relay MLR1314 has forward protection zone and protects the entire line L1314. It will operate to trip its associated circuit breaker CB1314 to clear a fault on the line L1314. The bus relay BR13 protects the bus B13. It will operate to trip the circuit breakers CB1312, CB1306, CB1314 if a fault occurs on the bus B13. The primary backup transmission line relay BLR1314 is the local backup of the relay MLR1314 and has the same protection zone. If the fault clearance by the relay MLR1314 fails, the relay BLR1314 will operate to trip the circuit breaker CB1314 to clear the fault. Secondary backup transmission line relays SLR1213, SLR0613 are the remote backup of the relays MLR1314, BLR1314. If the fault clearance by both the relays MLR1314, BLR1314 fails, they will operate to trip their associated circuit breakers CB1213, CB0613, respectively, to clear the fault. The relays SLR1213, SLR0613 are also the remote backup of the relay BR13. If the fault clearance by the relay BR13 fails, they will operate to trip circuit breakers CB1213, CB0613, respectively, to clear the fault. The relays MLR1413, BLR1413, SLR0914, BR14 and circuit breakers CB1413, CB1409, CB0914 have similar roles in protecting the line L1314 and bus B14. The configuration and denotation of the protection system for other sections of the 14-bus power system are similar.

When one or more faults occur on certain sections of the power system, protection devices will reach certain status accordingly. The observed circuit breaker status signals obtained from RTUs of SCADA systems are used as inputs for estimation of the faulted sections. The logic reasoning method uses the relay status obtained from the online-database to validate each candidate fault section. The strategy is to build one FRPN diagnosis model for each section of the power system. Each model establishes reasoning starting from a set of SCADA data to the conclusion of fault occurrence on its associated section with certain truth degree value.

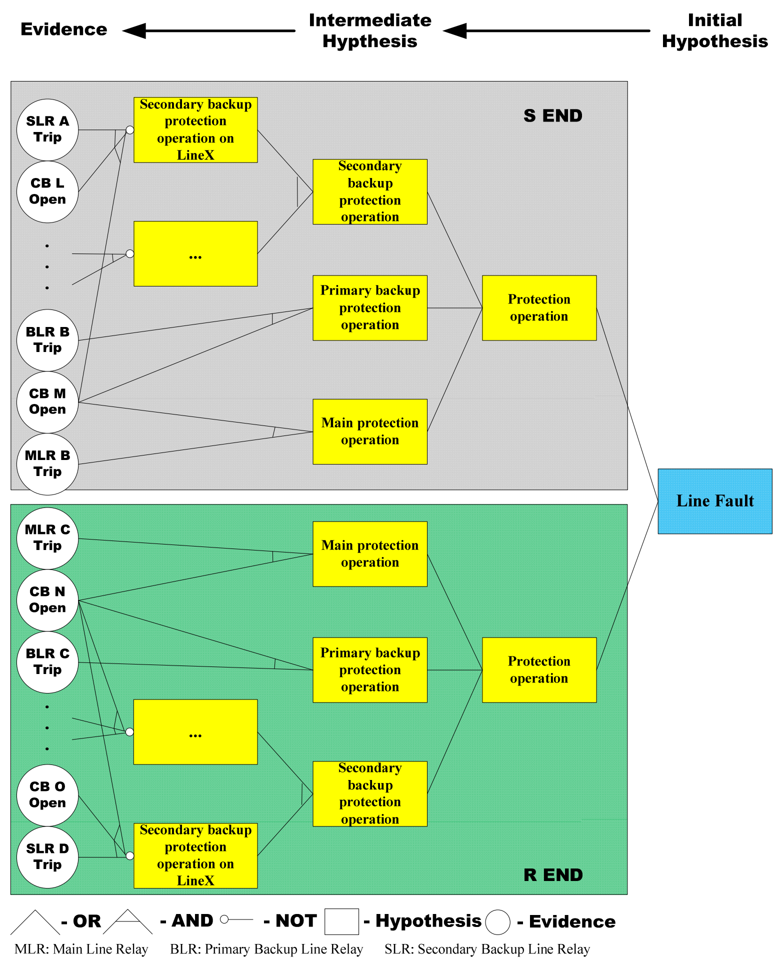

Figure 13 Backward reasoning concept for structuring transmission line diagnosis models

We use backward reasoning concept to structure the FRPN diagnosis models and generalize the design for transmission lines and buses. Figure 13 and Figure 14 illustrate backward reasoning concept for structuring transmission line and bus diagnosis models respectively. The 'AND-OR' structure concisely represents all the possible combinations of main, primary backup and secondary backup protection operations for inferring a fault.

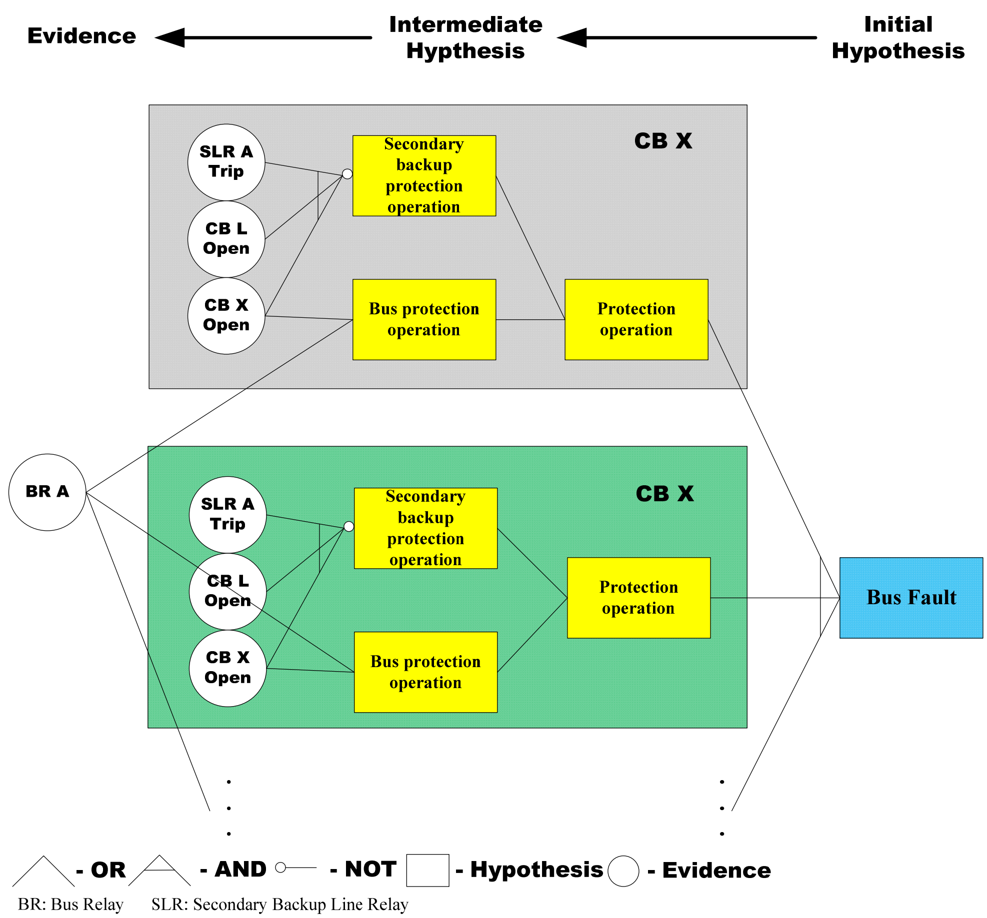

Figure 14 Backward reasoning concept for structuring transmission bus diagnosis models

Based on the proposed structure, all the FRPN diagnosis models are developed. Each model establishes reasoning from a set of SCADA data to the conclusion of fault occurrence on its associated section with certain truth degree value. In case of single fault, the conclusion with the highest truth degree value is the final conclusion. As an example, Figure 15 shows the FRPN models for the transmission line L1314, and Figure 16 shows the FRPN models for the bus B13.

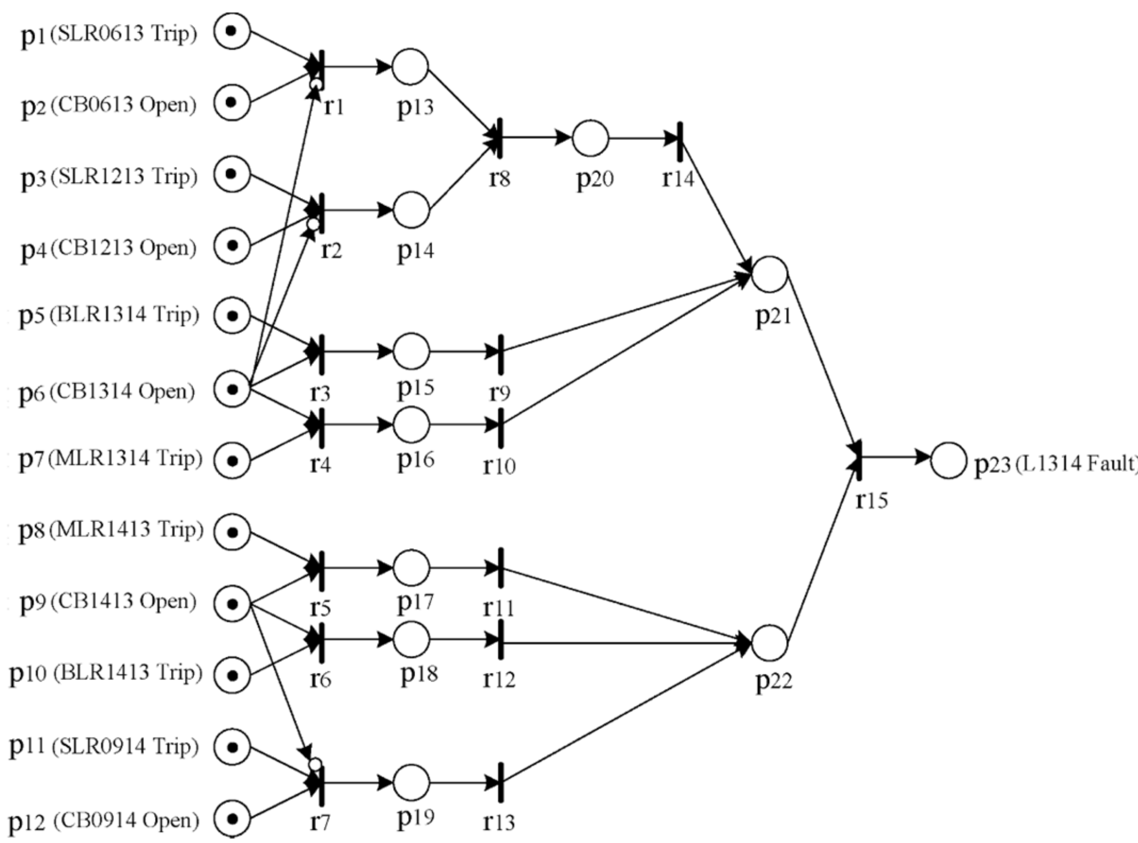

Figure 15 FRPN model for L1314 fault based on SCADA data

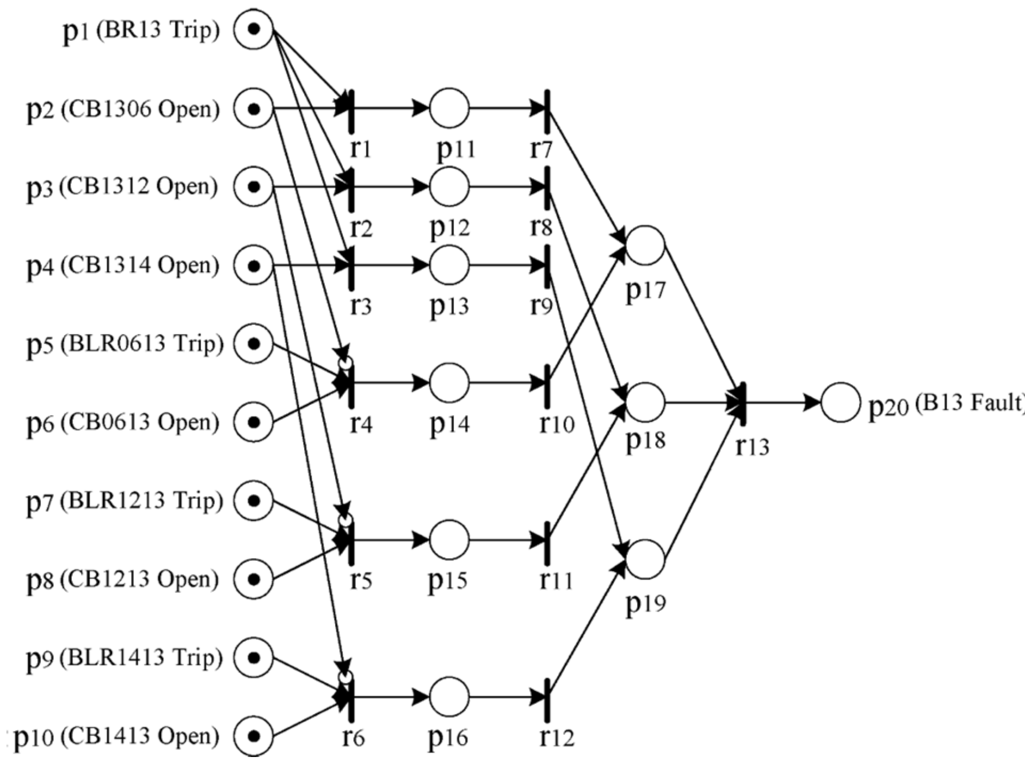

Figure 16 FRPN model for B13 fault based on SCADA data

Moreover, each proposition is given a "truth degree value" to illustrate the strength of confirmation. We use a "weighted average" operation when calculating the truth degree value of a consequent proposition from the truth degree values of its antecedent propositions. Figure 19 illustrates the operation for r1 in Figure 17.

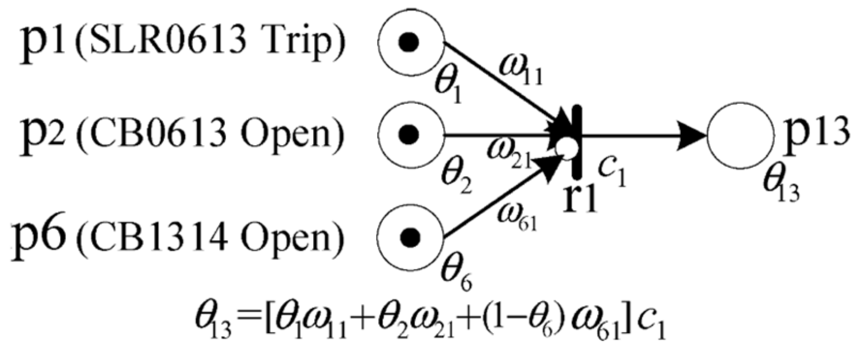

Figure 17 Example of "weighted average" operation

The "weighted average" operation has two benefits. First, the relative significance of antecedent propositions in implicating the consequent proposition is recognized by the weights of antecedent propositions. This is particularly meaningful when the cause-effect relation among antecedent propositions is considered. In our assumption, circuit breaker opening is the effect of relay trip. The "circuit breaker opens" proposition is generally given larger weight than that of the "relay trips" proposition because circuit breaker opening indicates the completion of a protection operation more directly. For example, regarding the rule r3 in Figure 18, the proposition p5 "BLR1314 Trip" will be given a weight 0.4; the proposition p6 "CB1314 Open" will be given a weight 0.6.

Second, the false data problem is effectively handled by averaging the truth degree values of antecedent propositions. For example, when the relay MLR1314 trips and the circuit breaker CB1314 opens as a consequence of a fault on the line L1314, and "MLR1314 Trip" is not observed, p15, which stands for "main protection operates", will still get a moderate truth degree value instead of 0, hence a moderate truth degree value for the final conclusion. It is apparent that the larger the number of input data, the impact of false data is more effectively countered.

3.5 Deployment Strategy

The fault section estimation application may be implemented in a control center to assist the system operator in rapidly identifying faulted sections for restoration process, as shown in Figure 18.

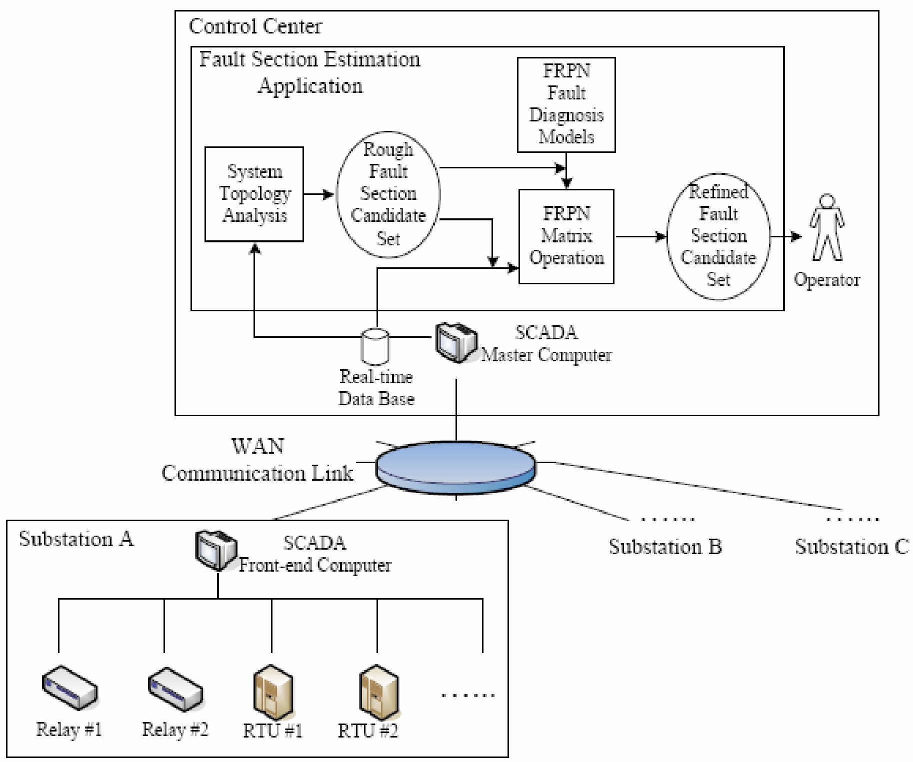

Figure 18 Overall fault estimation module structure

The fault section estimation application includes two stage analyses.

- First Stage

The system's topology is analyzed based on circuit breaker status data from the real-time data base. The analysis includes all sections isolated by the opening of circuit breakers into a rough candidate set. The set is rough because it may include sections which are not faulted but are isolated due to backup relay operation.

- Second Stage

The Fuzzy Reasoning Petri-net diagnosis model as well as data in the real-time data base corresponding to each section in the rough candidate set is used and Fuzzy Reasoning Petri-net matrix operation is implemented. As a result, each section will be associated with a truth degree value. The section with a truth degree value greater than a certain threshold will be included in the refined candidate set. Such a refined candidate set is presented to the system operator for decision-making.

In such a solution, the FRPN models which are represented by various matrices are separated from FRPN matrix operations. This is analogous to an expert system whose rule base is separated from its inference engine. The FRPN models can be built in advance based on power system and protection system configurations and stored in files. In such a way, the FRPN models can be easily modified according to the changes of input data as well as power system and protection system configuration.

3.6 Case Study

Case 1:

A permanent fault occurred on the transmission line L0910 at 0.05 s. All of the protection devices operated correctly. No false data occurred. The observed SCADA data are listed in Table 3.

Table 3 SCADA Data for Case 1

Sequence No.	**Time Stamp (sec)**	**Observed Signal**
1	0.1000	MLR0910 TRIP
2	0.1000	MLR1009 TRIP
3	0.2000	CB0910 OPEN
4	0.2000	CB1009 OPEN

Based on the SCADA data in Table 3, the only candidate for the fault section is estimated as the transmission line L0910, with a truth degree value 0.855.

Case 2:

A permanent fault occurred on the bus B04 at 0.05s. A second permanent fault occurred on the bus B09 at 0.09 s. All of the protection devices operated correctly. No false data occurred. The observed SCADA data are listed in Table 4.

Table 4 SCADA Data for Case 2

Sequence No.	Time Stamp (sec)	Observed Signal
1	0.1000	BR04 TRIP
2	0.1000	CB0402 OPEN
3	0.2000	CB0403 OPEN
4	0.2000	CB0405 OPEN
5	0.2000	CB0407 OPEN
6	0.2000	CB0409 OPEN
7	0.2000	BR09 TRIP
8	0.2000	CB0904 OPEN

Based on the SCADA data in Table 4, the estimated fault sections are listed in Table 5.

Table 5 Estimated Fault Sections based on SCADA DATA for Case 2

No.	Fault Section	Truth Degree Value
1	B04	0.855
2	B09	0.855
3	L0409	0.513

Besides the buses B04 and B09, on which faults actually occur, the transmission line L0409, which has no fault, is included in the candidate set. The transmission line L0409 has a far small truth degree value than the other two candidates, which indicates very small possibility of fault occurrence.

Case 3:

A permanent fault occurred on the transmission line L1314 at 0.05 s. A second permanent fault occurred on the bus B13 at 0.11 s. The circuit breakers CB1312 and CB1306 failed to open. The BR13 TRIP signal should be observed but it was not observed. The observed SCADA data are listed in Table 6.

Table 6 SCADA Data for Case 3

Sequence No.	**Time Stamp (sec)**	**Observed Signal**
1	0.1000	MLR1314 TRIP
2	0.1000	MLR1413 TRIP
3	0.2000	CB1314 OPEN
4	0.2000	CB1413 OPEN
5	0.3000	BLR0613 TRIP
6	0.3000	BLR1213 TRIP
7	0.3000	CB0613 OPEN
8	0.3000	CB1213 OPEN

Based on the SCADA data in Table 6, the estimated fault sections are listed in Table 7.

Table 7 Estimated Fault Sections based on SCADA DATA for Case 3

No.	**Fault Section**	**Truth Degree Value**
1	L1314	0.855
2	B13	0.729

Case 3 has additional complexity, because not only multiple faults but also protection device failure and false data are involved. However, with the proposed FRPN model, the actual fault sections can still be correctly identified.

3.7 Summary

The traditional alarm processing approaches mostly rely on direct representation of raw alarm points, which becomes overwhelming to observe and interpret when operating the system under stressed conditions. This requires implementing new alarm processor to help the operator deal with the tremendous amount alarms by effectively converting raw data to useful information.

In this Section, a Fuzzy Reasoning Petri-nets (FRPN) approach to solve the fault section estimation problem is proposed. The fundamental fault analysis techniques including backward reasoning, fuzzy logic and Petri-nets are reviewed first. The reasoning process can be graphically represented in a form of Petri-nets and implemented by matrix operations. Data acquired by RTUs of SCADA systems, including relay trip signals and circuit breaker status signals, are used as the inputs to the diagnosis models.

The FRPN diagnosis model is analogous to an expert system whose rule-base is separated from its inference engine, which can be built in advance based on power system and protection system configurations and stored in files. In such a way, the FRPN models can be easily modified according to the changes of input data as well as power system and protection system configuration.

4. USE OF SUBSTATION IED DATA TO IMPROVE ALARM PROCESSING

4.1 Introduction

Traditionally in a substation, supervisory control and data acquisition system (SCADA) data are typically bus voltages, flows (amps, MW, MVAR), frequency, breaker status, transformer tap position) acquired using remote terminal units (RTUs) and sent to the energy management systems (EMS) in every two to ten seconds. With the rapid advancement of technology, Intelligent Electronic Devices (IED) come into picture, such as Digital Protective Relay (DPR), Digital Fault Recorders (DFR), Phasor Measurement Units (PMU). These modern day digital devices can record and store a huge amount of data with a periodicity depending upon the intended purpose of the device (DFRs only capture data during occurrence of a fault whereas PMUs take continuous time-synchronized data with high sampling rates). Thus we are having a great amount of data, which if used properly can become a great benefit for the EMS to predict, operate, monitor and post-mortem analyze power system events.

This Section will firstly discuss about the characteristics of IED data and extraction of useful information from huge amount of redundant data. Then the next Section will show how the IED data integrated with SCADA can be applied in the FRPN model mentioned in Section 3 [78].

4.2 Substation IED Data

In a modern day integrated substation, various types of IEDs are employed for monitoring and control purposes. Once the substation data at high power level are collected they must be transformed to instrumentation level using current and voltage instrument transformers. The data are then filtered and digitized, and submitted for the processing in IEDs. Finally, the intended information is extracted and supplied as output of these devices. This is the typical measurement data processing chain for the data.

4.2.1 Data Sources

The different measurement devices (collectively termed as sensors) that are source of data fall into the following categories:

- Transducer
- Relaying transformers
- Metering transformers
- Electronic (optical) transformers

Traditionally, the data processing is done by substation RTUs. Nowadays the different IEDs used to process data in a typical substation are [79]:

- Digital protective relay (DPR)
- Digital fault recorder (DFR)
- Phasor measurement units (PMUs)
- Power quality meter (PQM)
- Sequence of event recorder (SER)
- Fault locator (FL)

- Circuit breaker monitor (CBM)
- Programmable logic controller (PLC)
- Remote terminal unit (RTU)

These IEDs are intended for specific function (sometimes for multiple functions) and depending upon power system events IEDs record analog and/or status data either in a specific location or for the entire substation.

Distortion in magnitude and phase angle of current and voltage signal is introduced in each stage of the measurement chain. Ideally the output waveform should be an exact replica of the input signal, but the error introduced in several stages make the output distorted. This Section is aimed at discussing the desired performance characteristics of the different stages in the measurement chain.

4.2.2 Sensors

Sensors (instrument transformers and transducers) measure current and voltage (for either metering or protection purposes) from high voltage electric circuit (primary side) and supply the RTUs or other IEDs (secondary side) these quantities proportional to those of the power circuit but in substantially reduced level and thereby provide galvanic isolation and signal scaling of signals for these devices from high voltage circuitry. Generally, conventional instrument transformers (current transformers CT, voltage transformers VT and capacitive coupled voltage transformers CCVT) are relatively inaccurate comparing to the microprocessor based IEDs. The accuracy of data is highly dependent on the accuracy of instrument transformers, control cables and burdens (the external load connected to secondary transformer terminals, including IEDs for this discussion). The detailed specification requirements can be found in IEEE standard C57.13 [80] and IEC standard 60044 [81].

4.2.3 Intelligent Electronic Devices

Usually the microprocessor based IEDs have very good accuracy. While the basic data processing stages for IEDs are similar (as shown in Figure 19), the recording performance may differ. In all of the IEDs, the basic data processing steps are:

- Galvanic isolation using auxiliary transformer
- Low pass (anti-aliasing) filtering of the analog input waveforms to eliminate the high frequency components
- Sampling of the analog input waveforms
- Analog to Digital (A/D) conversion
- Processing of the digital signal samples

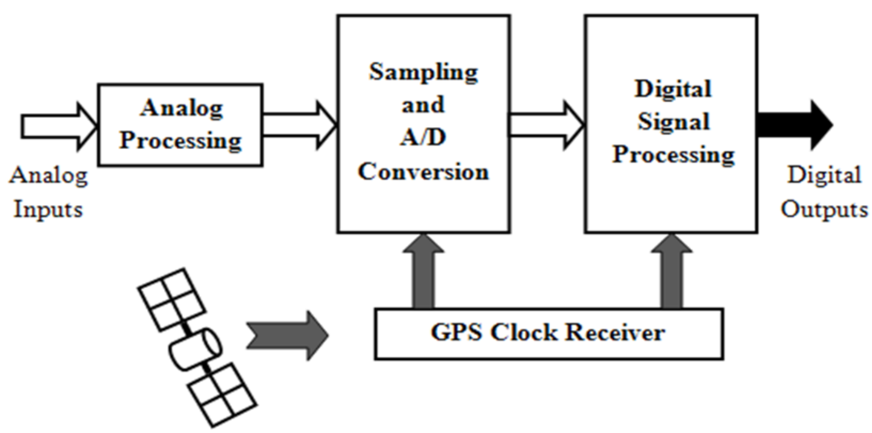

Figure 19 Data processing in IED

The overall accuracy of the IED analog signal input channel depends on several factors [82]:

- Impact of auxiliary transformers
- Mode of sampling
- Anti-aliasing filtering
- Sampling rate
- Resolution of A/D conversion

Some of the IEDs (DPR, DFR, FL etc) operate on synchronous sampling and some (RTU) operate on scanning of samples. As shown in Figure 20, when scanning, one analog input channel is sampled at a time and then converted to digital signal, whereas in synchronous sampling all the input channels are sampled at the same time and then they are converted to digital signal (there may be only one ADC serving all channels or each of the analog input channels has combined sample-and-hold circuit and ADC). Retrieving the actual phase difference between analog signals is easy in synchronous sampling as all signals are sampled at the same time. In case of synchronized sampling, the clock signal may be provided locally or from a receiver for the Global Positioning System (GPS) of satellites [83]. Most of the IEDs of modern day are using GPS for sampling and time stamping.

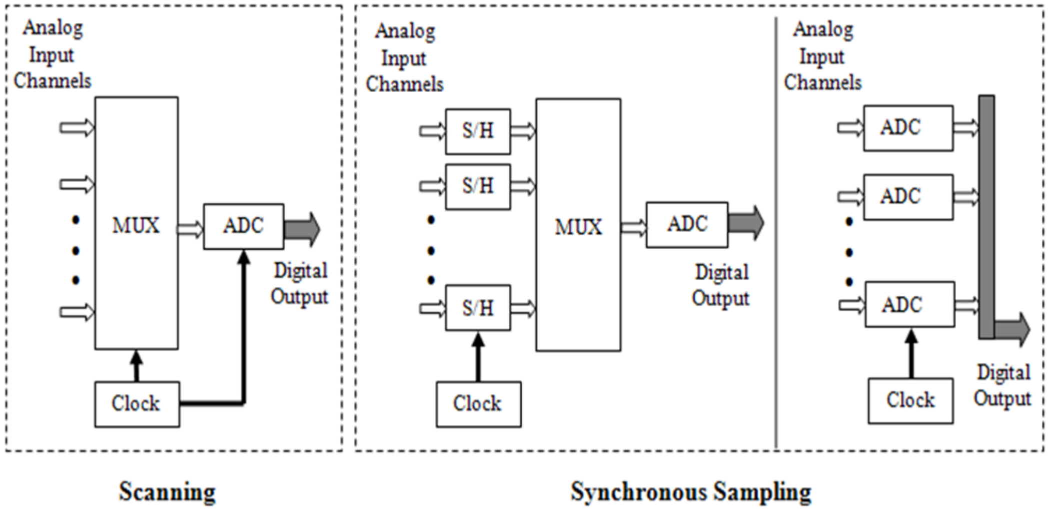

Figure 20 Scanning and synchronous sampling of analog inputs

The replication of signal largely depends on the "horizontal" resolution (sampling rate) and "vertical" resolution (number of bits for ADC). With higher sampling rate, the better signal representation is achieved. With more bits, better signal accuracy is achieved). Sampling rate also affects the choice of anti-aliasing filters. DPR generally is a device with low sampling rate (16 samples/cycle i.e. 960Hz for 60Hz system). Some of the DFRs of modern day achieved much higher sampling rates of 48 kHz. Again the higher value of vertical ADC resolution is desirable. Most of the IEDs use 16 bit ADC resolution. The selection of the resolution is driven by the ADC cost and dynamic behavior of the measured signal.

While most of the other IEDs allow access to samples of signal, Phasor Measurement Unit (PMU) provides measurements of synchronous phasors of analog inputs. The GPS synchronized PMUs are the most accurate among all IEDs. Such GPS synchronized devices provide phasor data termed as synchrophasor. The IEEE C37.118

[84] is used for accuracy definition of synchrophasors:

- Magnitude accuracy of 0.1% or better
- Time accuracy better than 1 μs or phase angle accuracy of 0.02º at 60 Hz.

4.2.4 Data Formats and Uses

Getting required information from huge amount of redundant data obtained from different IEDs (having different data format) is an issue that requires particular attention [85]. Whenever the data from different IEDs is retrieved in a database, the data integration requires [86][87]:

- Interpreting the data obtained from IEDs of different vendors
- Exchanging data using standard COMTRADE file format [88]
- Adding the static system configuration data according to the recorded data

To integrate data among different IEDs and IEDs from different vendors, standardized data format is necessary. After the introduction of COMTRADE data format [88], most of the vendors are accepting this standardized data format, while some are still others are keeping their own native data formats [86]. The power quality meter data representation is standardized using Power Quality Data Interchange Format (PQDIF) [89]. Most recently, another useful standard has been adopted for representation of time-sequence data [90].

The use of data available from IEDs as well as the other data (SCADA data collected using RTUs, satellite data, and static system data) enhances some power system functions.

The basic idea is to collect all the data in a substation database and use further for extracting information automatically. This extracted information then may be used for several power system applications [91]. To import the IED data into the central repository requires means of data format conversion and communication among different IEDs. In addition to the automatically retrieved RTU and other IED data, the database should contain several other data, such as:

- Static system data containing description of the system components and their connections (i.e. topology)
- Substation interpretation data to correlate the naming convention between the recording devices and static system model
- SCADA EMS PI Historian data to tune the static system model with real time data.

By integrating data from all the sources, quality of data is improved due to the redundancy of the great amount of data collected. The next two Sections give examples of how the integration of data can benefit new applications.

4.3 Enhanced FRPN Model with IED Data

In a digital protective relay, the pickup and operation information of protection elements is usually in the form of logic operands. These logic operands are in essence digital bits, which can be directly transmitted in the form of register values via a digital communication system. The pickup and operation logic operands are more reliable than

SCADA data because they are more redundant and have less uncertainty than relay trip signals and circuit breaker status signals. They can be utilized to improve the accuracy of fault section estimation based on SCADA data.

The detailed description of field needed for FRPN alarm processor is listed in Table 8.

Table 8 Estimated Fault Sections based on SCADA DATA for Case 3

Data from RTU of SCADA (Main data)	
1	CB status change alarms (Opening and Closing)
2	Trip signal of Main Transmission Line Relays
3	Trip signal of Primary Backup Transmission Line Relays
4	Trip signal of Secondary Backup Transmission Line Relays
5	Trip signal of Bus Relays
Data from Digital Protective Relays (Additional Data)	
1	Pickup & Operation signals of Main Transmission Line Relays
2	Pickup & Operation signals of Primary Backup Transmission Line Relays
3	Pickup & Operation signals of Secondary Backup Transmission Line Relays
4	Pickup & Operation signals of Bus Relays

Figure 21 illustrates how the pickup and operation information is added into the FRPN model built for diagnosing a fault on the transmission line L1314.

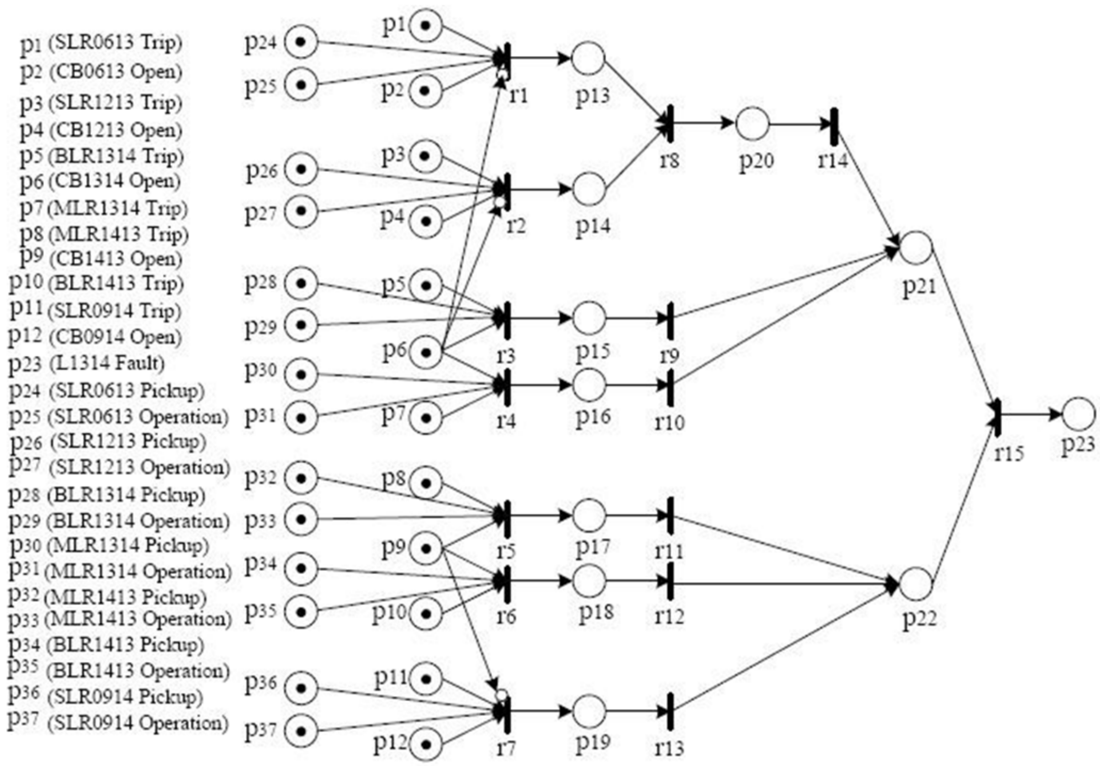

Figure 21 FRPN model for L1314 fault based on SCADA data and digital protective relay data

Take the reasoning process for the transmission line L1314 diagnosis model shown in Figure 17 as an example. The matrix representation of the model is given in Figure 22.

When a fault occurs on the line L1314, its associated protection system operated to respond to the fault. The following signals are observed in SCADA data: SLR0613 Trip, CB0613 Open, SLR1213 Trip, CB1213 Open, BLR1314 Trip,

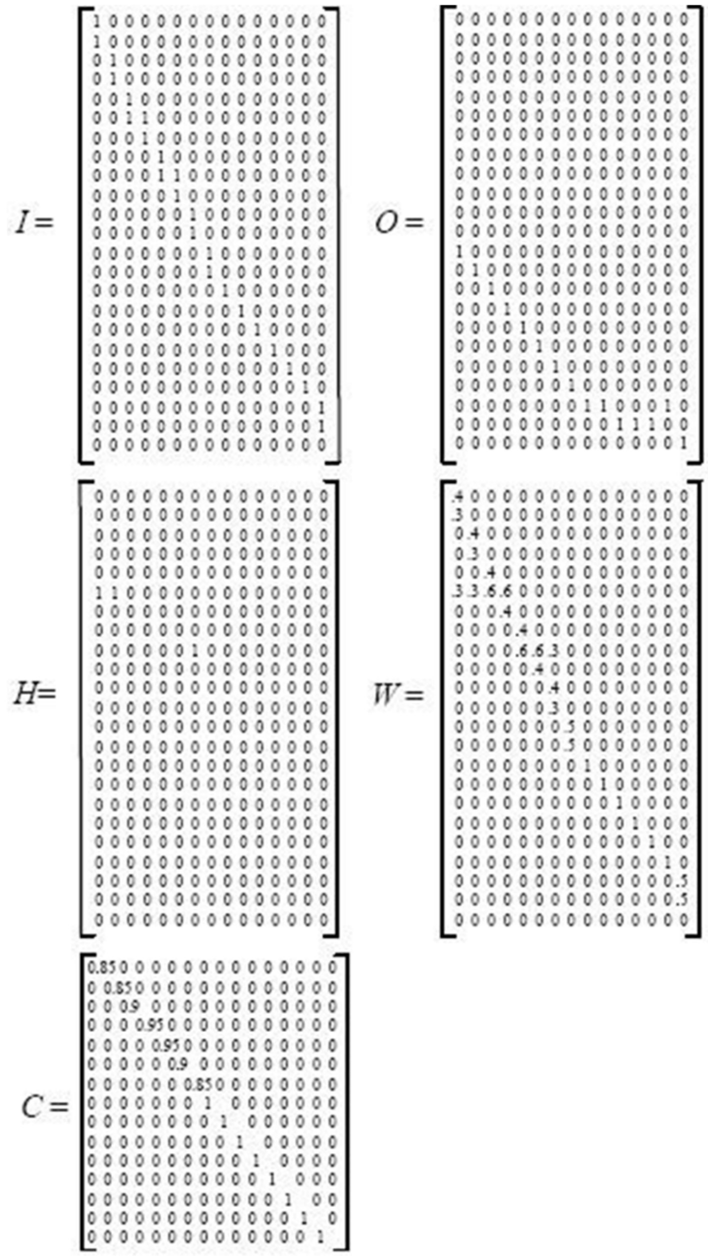

Figure 22 Matrix representation for FPRN model L1314

MLR1314 Trip, MLR1413 Trip and CB1413 Open. γ^0 and θ^0 are given as:

$$\gamma^0 = [1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0]^T$$

$\theta^0 = [0.9\ 0.9\ 0.9\ 0.9\ 0.9\ 0\ 0.9\ 0.9\ 0.9\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0]^T$

The first reasoning step will result in

$\gamma^1 = [1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 0\ 0\ 0\ 0]^T$

$\theta^1 = [0.9\ 0.9\ 0.9\ 0.9\ 0.9\ 0\ 0.9\ 0.9\ 0.9\ 0\ 0\ 0\ 0.791\ 0.791\ 0.324$
$0.342\ 0.855\ 0.486\ 0.026\ 0\ 0\ 0\ 0]^T$

The second reasoning step will result in

$\gamma^2 = [1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 0]^T$

$\theta^2 = [0.9\ 0.9\ 0.9\ 0.9\ 0.9\ 0\ 0.9\ 0.9\ 0.9\ 0\ 0\ 0\ 0.791\ 0.791\ 0.324$
$0.342\ 0.855\ 0.486\ 0.026\ 0.791\ 0.342\ 0.855\ 0]^T$

The third reasoning step will result in

$\gamma^3 = [1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1]^T$

$\theta^3 = [0.9\ 0.9\ 0.9\ 0.9\ 0.9\ 0\ 0.9\ 0.9\ 0.9\ 0\ 0\ 0\ 0.791\ 0.791\ 0.324$
$0.342\ 0.855\ 0.486\ 0.026\ 0.791\ 0.791\ 0.855\ 0.599]^T$

The final reasoning step will result in

$\gamma^4 = [1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1]^T$

$\theta^4 = [0.9\ 0.9\ 0.9\ 0.9\ 0.9\ 0\ 0.9\ 0.9\ 0.9\ 0\ 0\ 0\ 0.791\ 0.791\ 0.324$
$0.342\ 0.855\ 0.486\ 0.026\ 0.791\ 0.791\ 0.855\ 0.823]^T$

So the conclusion will be that a fault occurred on the transmission line L1314 with a truth degree value 0.823.

Taking the same example as above, if MLR1413 Trip is missing in the SCADA data due to data transmission error, the conclusion will be that a fault occurred on the transmission line L1314 with a truth degree value 0.652.

The matrix representation of the FRPN model described by Figure 21 can be easily generated based on the matrix representation of the FRPN model described by

Figure 15. The updated matrices I, O, H, W, are given in Figure 23. There is no change on matrix C. The weight assignment in W is adjusted to reflect the relative significance of input signals in determination of the occurrence of a protection operation. The operation of relay element has the largest weight and the pickup of relay element has the second largest weight. The relay trip and the circuit breaker opening have smaller weights. When the absence of the circuit breaker opening for the main protection and primary backup protection is taken into consideration of the secondary backup protection, it has the largest weight.

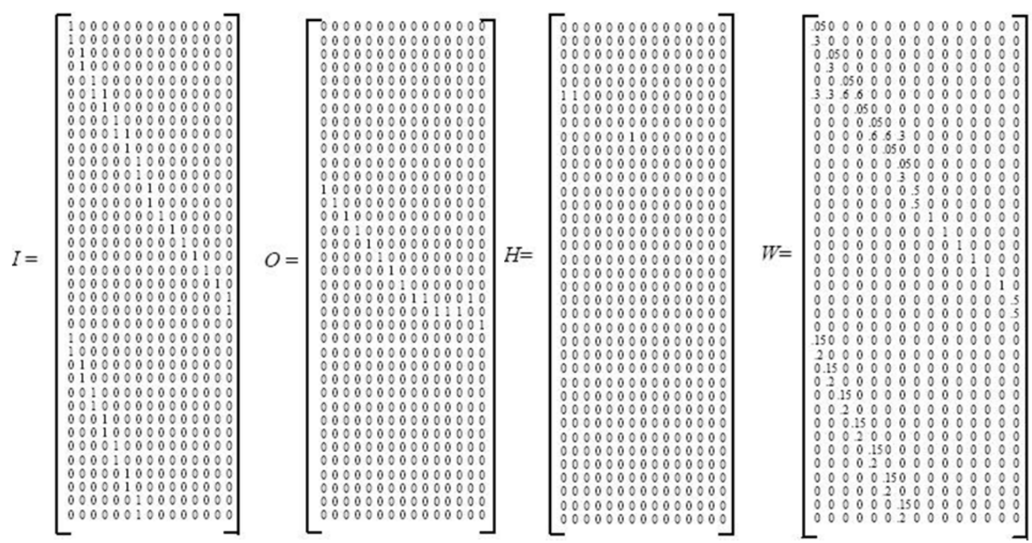

Figure 23 Updated matrix representation for FPRN model L1314

Take the same example as in previous Section. When a fault occurs on the transmission line L1314, its associated protection system operated to respond to the fault. In addition to the observed SCADA data, the following relay signals are also observed: SLR0613 Pickup, SLR0613 Operation, SLR1213 Pickup, SLR1213 Operation, BLR1314 Pickup, BLR1314 Operation, MLR1314 Pickup, MLR1314 Operation, MLR1413 Pickup, MLR1413 Operation, BLR1413 Pickup, SLR0914 Pickup. Since the relay data are more reliable than the SCADA data, they are given a larger truth value 0.98. γ^0 and θ^0 are given as:

$$\gamma^0 = [1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1]^T$$

$$\theta^0 = [0.9\ 0.9\ 0.9\ 0.9\ 0.9\ 0\ 0.9\ 0.9\ 0.9\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0 \\ 0.98\ 0.98\ 0.98\ 0.98\ 0.98\ 0.98\ 0.98\ 0.98\ 0.98\ 0.98\ 0.98\ 0.98\ 0]^T$$

The final conclusion will be that a fault occurs on the transmission line L1314 with a truth degree value 0.848.

Taking the same example as above, if MLR1413 Trip is missing in the SCADA data due to data transmission error while MLR1413 Pickup and MLR1413 Operation are observed, the conclusion will be that a fault occurs on the transmission line L1314 with a truth degree value 0.827.

4.4 Case Study

Case 1:

A permanent fault occurred on the transmission line L0910 at 0.05 s. All of the protection devices operated correctly. No false data occurred. The observed SCADA data are listed in Table 3, and the observed digital protective relay data are listed in Table 9.

Table 9   Digital Protective Relay Data for Case 1

Sequence No.	Time Stamp (sec)	Observed Signal
1	0.0662	SLR0409 PKP
2	0.0677	SLR0709 PKP
3	0.0693	BLR0910 PKP
4	0.0698	MLR0910 PKP
5	0.0703	MLR1009 PKP
6	0.0703	BLR1009 PKP
7	0.0703	SLR1110 PKP
8	0.0724	SLR1409 PKP
9	0.0740	MLR0910 OP
10	0.0745	MLR1009 OP

Based on the SCADA data and additional digital protective relay data, the only candidate for the fault section is estimated as the transmission line L0910, with a truth degree value 0.882.

Case 2:

A permanent fault occurred on the bus B04 at 0.05s. A second permanent fault occurred on the bus B09 at 0.09 s. All of the protection devices operated correctly. No false data occurred. The observed SCADA data are listed in Table 4, and the observed digital protective relay data are listed in Table 10.

Table 10 Digital Protective Relay Data for Case 2

Sequence No.	Time Stamp (sec)	Observed Signal
1	0.0537	BR04 PKP
2	0.0625	SLR0304 PKP
3	0.0651	SLR0904 PKP
4	0.0677	SLR0204 PKP
5	0.0667	SLR0504 PKP
6	0.0677	SLR0704 PKP
7	0.0703	BLR0704 PKP
8	0.0703	BLR0904 PKP
9	0.0766	BLR0204 PKP
10	0.0766	BLR0504 PKP
11	0.0771	BLR0304 PKP
12	0.0938	BR09 PKP
13	0.0964	SLR0709 PKP
14	0.1000	BR04 OP
15	0.1063	BLR0709 PKP
16	0.1115	SLR1009 PKP
17	0.1115	SLR1409 PKP
18	0.1115	SLR0409 PKP
19	0.1224	BLR1009 PKP
20	0.1224	BLR1409 PKP
21	0.1224	BLR0409 PKP
22	0.1401	BR09 OP

Based on the SCADA and additional digital protective relay data, the estimated fault sections are listed in Table 11.

Table 11 Estimated Fault Sections based on SCADA and Digital Protective Relay DATA for Case 2

No.	Fault Section	Truth Degree Value
1	B04	0.882
2	B09	0.882
3	L0409	0.618

Besides the buses B04 and B09, on which faults actually occur, the transmission line L0409, which has no fault, is included in the candidate set. The transmission line L0409 has a far small truth degree value than the other two candidates, which indicates very small possibility of fault occurrence.

Case 3:

A permanent fault occurred on the transmission line L1314 at 0.05 s. A second permanent fault occurred on the bus B13 at 0.11 s. The circuit breakers CB1312 and CB1306 failed to open. The BR13 TRIP signal should be observed but it was not observed. The observed SCADA data are listed in Table 6, and the observed digital protective relay data are listed in Table 12.

Table 12 Digital Protective Relay Data for Case 3

Sequence No.	Time Stamp (sec)	Observed Signal
1	0.0641	SLR1314 PKP
2	0.0651	SLR1413 PKP
3	0.0683	BLR0904 PKP
4	0.0688	BLR0204 PKP
5	0.0693	SLR0504 PKP
6	0.0698	MLR0704 PKP
7	0.0698	MLR0704 PKP
8	0.0703	SLR0904 PKP
9	0.0703	SLR0204 PKP
10	0.0740	MLR0504 PKP
11	0.0740	MLR0304 PKP
12	0.1141	BR13 PKP
13	0.1193	SLR0613 PKP
14	0.1204	SLR1213 PKP
15	0.1271	BLR0613 PKP
16	0.1297	BLR1213 PKP
17	0.1605	BR13 OP
18	0.2433	BLR0613 OP
19	0.2459	BLR1213 OP

Based on the SCADA data and additional digital protective relay data, the estimated fault sections are listed in Table 13.

Table 13 Estimated Fault Sections based on SCADA and Digital Protective Relay DATA for Case 3

No.	Fault Section	Truth Degree Value
1	L1314	0.882
2	B13	0.854

The transmission line L1314 and bus B13 faults are correctly identified and included in the candidate set. The use of DPR data increases the truth degree values for all candidates. It should be noted that in the previous case 3 in Section 3 with SCADA data only, B13 fault only has a truth degree value of 0.729 due to the missing and false data, and now it increases to 0.854 which is a more convincing result.

4.5 Summary

This Section discusses the performance characteristics of the substation IED data measurement chain by focusing on industry standards for the instruments used. It also focuses how efficiently substation IED data along with the traditional SCADA data and other available data can be integrated to enhance certain power system functions by automatically retrieving information from substation database.

It can be concluded that major enhancements in performance of FRPN model can be achieved by integrating digital protective relay data even with missing or false alarm signals.

5. RELIABILITY AND LIFE CYCLE ANALYSIS OF CIRCUIT BREAKER

5.1 Introduction

After the discussion of the implementation of the Fuzzy Reasoning Petri-nets model in the fault section estimation module, it is noted that the accuracy of the input data plays a vital role in the overall analyzing procedure. It is almost evitable that protection devices sometimes may fail to operate normally, which means for instance, a circuit breaker keeps opening/closing when it is supposed to close/open, or a relay fails to trip when it is supposed to do so. Though the FRPN model has the fault-data-tolerant capability to some extent, it would be better if we could correctly identify the reliability index or truth degree value of each individual protection device as an input. And when protection devices failed or are about to fail, we have to initiate a maintenance strategy.

Therefore, how to make decisions to optimally allocate the resources by deciding when to perform maintenance on power apparatus becomes a critical issue, especially with present economic scenario in power industry.

Power industry is gradually changing from scheduled maintenance to "as needed" or "just-in-time" maintenance, which means that it is important not to "over maintain" the equipment. Also, if too little maintenance is done on the equipment, it may fail due to wear and deterioration. Even when maintenance is performed, the inadequate type of maintenance will not improve the condition of the equipment. The attention must be put on the troubled area. Otherwise unnecessary maintenance action is simply a waste of time, effort and money [92].

An effective maintenance that can reduce the frequency of service interruptions and the many undesirable consequences of such interruptions is in great need. Commonly used maintenance strategies are reviewed and reported in [93]. These approaches range from scheduled maintenance to reliability-centered maintenance (RCM) and condition based maintenance (CBM) [94]-[98]. RCM allows modeling the component deterioration process and linking it to the condition of the device [99][100]. These models are further developed for circuit breakers and transformers with objective being determination of the Mean Time to First Failure (MTTFF), estimation of the failure probability and prediction of cost reduction [101]-[103].

In failure models, the deterioration process is represented by a sequence of stages of increasing wear, finally leading to equipment failure. Deterioration is of course a continuous process in time and only for the purposes of easier modeling is it considered in discrete steps. The common way to define deterioration stage is by duration, e.g. the second stage is reached, on average, in three years, the third in six, and so on. The problem with this approach is that the mean time is usually obtained from a large amount of historical data from many circuit breakers that are working under different operation environment, such as temperature, humidity, open/close frequency, different level of rated voltages and current, etc. The deviation among CBs may impede an attempt to determine the stage of deterioration. Since the mean times between the stages are usually uneven, they are selected from performance data or by judgment based on experience.

Under a predictive maintenance model, maintenance is carried out as needed. The need for maintenance is established through condition monitoring which is the ongoing inspection and surveillance of the operation of equipment to ensure proper performance and to detect abnormalities indicative of approaching failure. Reverences [104][105] have proposed a methodology utilizing the control circuit data of CB to define several performance indices. Time instants in the waveforms captured from the control circuit when CB operates (either open or close operation) to reflect the health/condition of various assemblies such as trip coil, close coil, auxiliary contacts etc. are used. The disadvantage of the previous method is that it uses only two maintenance state: healthy and failure. This ignores the possibility that different types of maintenance can be done to correct specific problems. With the inclusion of more than one maintenance state, a maintenance model can be more sufficiently applied to practical situations.

To overcome the deficiency, this Section proposes methodology suitable for practical applications and it can be applied in real time using field measured condition-based data. Though this Section only focuses on circuit breaker monitoring, this approach can be extended to relay, transformer and other devices as well.

5.2 Life Cycle Model using Condition-based Data

5.2.1 Condition-based Data

According to the failure survey conducted by CIGRE Working Group A3.12, majority of CB failures are due to malfunction of operating mechanism and control circuit in that order compared to other CB assemblies [106]. The condition monitoring techniques are relatively easy to develop since the secondary circuit is readily accessible for on-line monitoring. There are portable test devices available on the market to collect and display the control circuit signals which are analog and/or digital waveforms [107]. A low cost circuit breaker monitor (CBM) developed for recording and automated analysis of condition-based data both offline and online is reported in [108]. Signal processing and expert system modules for extracting the exact timings of the signal parameters for both open and close operations are implemented in [109]. The list of events, corresponding definitions and timing parameters are presented in Table 14 [109]. Based on the preliminary research done in [104], only timing parameters t2-t6 are considered in this paper.

Table 14 List of Event and Signal Parameters

Event	Event Description	Signal Parameter
1	Trip of close operation is initiated	t_1
2	Trip coil current picks up	t_2
3	Trip coil current dips after saturation	t_3
4	Trip coil current drops off	t_4
5	B contact breaks or makes (a change of status from low to high or vice vresa)	t_5
6	A contact breaks or makes	t_6
7	Phase current breaks or makes	t_7

5.2.2 Probability Distribution

A normal distribution is assumed for all signal parameters for the purpose of illustration. The probability distribution of signal parameter t_2 is shown in Figure 24. To proceed with the methodology, three bands for each timing parameter are defined: healthy, minor deterioration and major deterioration. If one new value of t_i falls in the “healthy” range, then it indicates that those parts of the breaker which cause the occurrence of time instant t_i operate properly. One new value of t_i falls in the second band means that the associated parts respond with some delays and may be in the minor deterioration. If one new value of t_i falls in the third range that suggests that the associated parts can’t respond in time and may be in the major deterioration stage. To be more specific, for instance, if t_2 falls out all of three ranges, it means that there is some problem associated with the close coil. These limits are specific to each circuit breaker and can be determined once and for all.

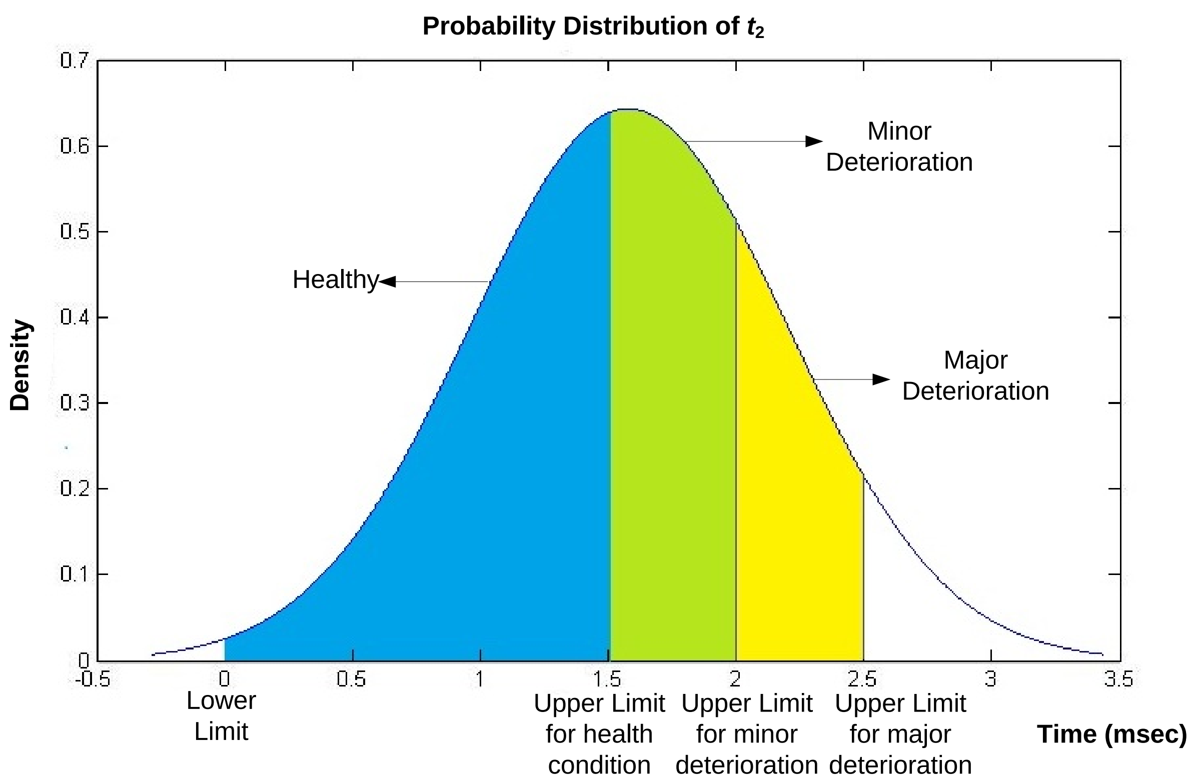

Figure 24 Probability distribution of parameter t_2

In general, probability that breaker operates correctly with respect to t_i is defined as $p(t_i^1) = \Pr(l_i \le t_i \le u_i^1)$, $p(t_i^2) = \Pr(u_i^1 \le t_i \le u_i^2)$, $p(t_i^3) = \Pr(u_i^2 \le t_i \le u_i^3)$, where l_i is the lower limit and u_i is the upper limit, superscript 1,2,3 denotes the three stages: healthy condition, minor deterioration and major deterioration respectively. Those probabilities are used to define performance indices for various part assemblies of circuit breaker.

5.2.3 Condition Assessment

Reference [104] has listed five part assemblies.

- Performance of trip and close coils

A sample representation of trip coil current is shown in Figure 25. After the trip initiate is active, the coil current makes a gradual transition to a nonzero value at time 't_2'. The time instant 't_3' corresponds the time at which the operating mechanism starts moving with the help of trip coil energy. The coil current starts dropping down to zero at time 't_4'. The trip coil current signals should be fairly smooth except for the dips at the beginning and end of the waveform.

Possible abnormalities associated with trip coil include: pick up delayed, dip delayed, drop-off delayed, etc. In worst case, these abnormalities may result in breaker not opening when it is supposed to. These abnormalities can be addressed by probabilities $p(t_2)$, $p(t_3)$ and $p(t_4)$ corresponding to the timing parameter t_2, t_3 and t_4. These time instants should occur within the tolerance limits to assure proper operation of trip coils. The performance index related to trip coil is defined as the probability that trip coil fails to operate properly,

$$p_f(TC) = 1 - p(t_2)p(t_3)p(t_4) \tag{5.1}$$

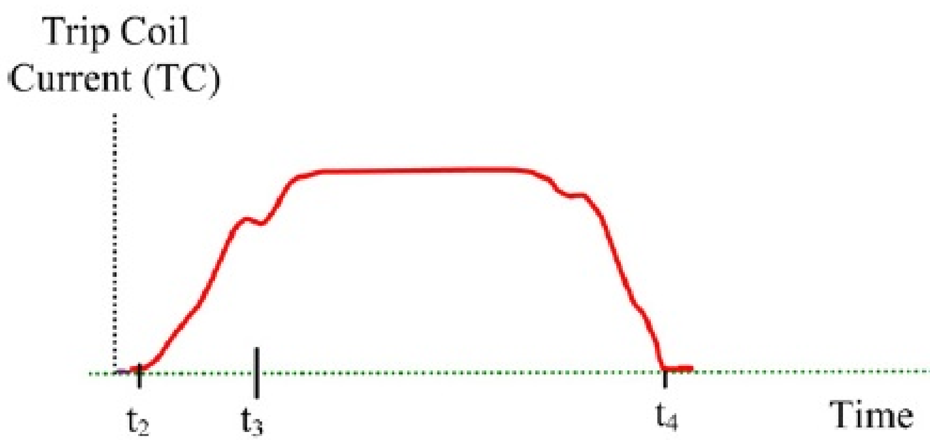

Figure 25 Trip coil current during openning

- Performance of auxiliary contacts

As the breaker opens its main contacts, it also changes the status of the auxiliary 'a' and 'b' contacts as shown in Figure 26. Some possible abnormalities associated with operation of 'a' and 'b' contacts are: delay in transition, premature transition, unstable contacts, noise and contacts bounce. If the timings t_5 and t_6 fall within their tolerance limits, we can say the auxiliary contacts operate normally. The performance index related to auxiliary contacts can be defined as, the probability that auxiliary contacts fails to operate properly,

$$p_f(AB) = 1 - p(t_5)p(t_6) \tag{5.2}$$

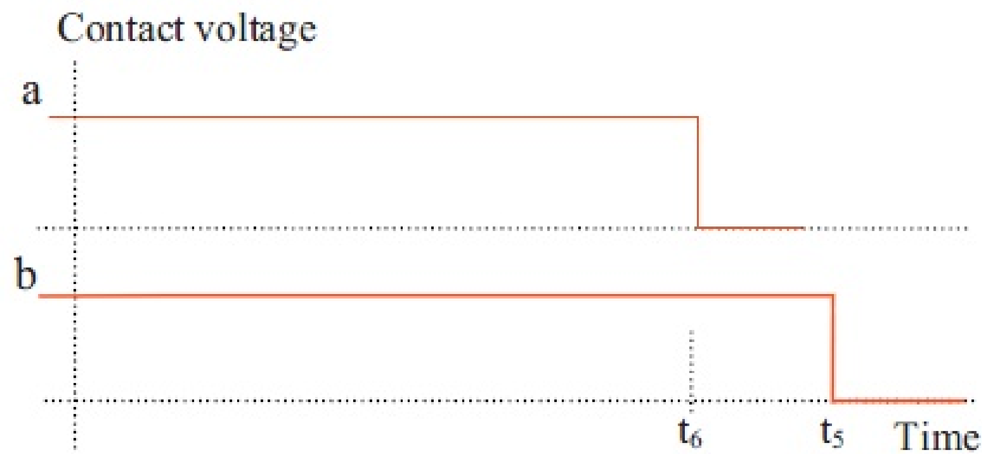

Figure 26 ‘a’ and ‘b’ contacts transistion during close operation

- Performance of operating mechanism

The time period between the instant at which the TC rises (t_2) and the instant at which the dip occurs (t_3) is the ‘free travel time’ that equals to $|t_3 - t_2|$. This free travel time reflects the performance of the trip latch mechanism. The timings t_2 and t_3 need to fall in the tolerance limits for the breaker to have normal free travel time. Any violation reflects an improper operation of trip latch mechanism. The corresponding performance index is defined as the probability that free travel time is abnormal,

$$p_f(FT) = 1 - p(t_2)p(t_3) \tag{5.3}$$

The coil current also needs to correlate with the event of ‘a’ or ‘b’ contact changes. The time period between the dip and the change of ‘a’ for opening is the mechanism travel time which is equal to $|t_6 - t_3|$ for opening [110]. For normal ‘mechanism travel time’, the timings t_5 and t_6 need to fall in corresponding tolerance limits. Any violation of these timings can be reported as abnormal operation of breaker. The corresponding performance index is defined as the probability that the mechanism travel time is abnormal,

$$p_f(MT) = 1 - p(t_3)p(t_6) \tag{5.4}$$

- Performance of breaker

In addition to the performance of individual components of breaker, an overall performance of the breaker may be assessed. If none of the timings t_2 to t_6 is violated, we can say that breaker operates properly. If any of these timings falls out the corresponding tolerance limits, we can say that the breaker fails to operate properly. This quantity can be defined as probability that the breaker does not operate properly and is estimated as,

$$p_f(Br) = 1 - \prod_{i=2}^{6} p(t_i) \tag{5.5}$$

A summary of all performance indices for CB opening is given below in Table 15.

Table 15 CB Opening Performance Indices

Operation	Performance index	Performance
Open	$p_f(TC)$	Trip coil
	$p_f(AB)$	Auxiliary ‘a’ and ‘b’ contacts
	$p_f(FT)$	Trip latch mechanism
	$p_f(MT)$	Operating mechanism
	$p_f(Br)$	Breaker as a whole

5.3 Model Development

5.3.1 Assumptions

The proposed model is built based on the following assumptions:

1) Only if all the time instants are within the health condition range, the associated component is considered being in the health stage.
2) If one or more time instants are within the minor deterioration range, the associated component is considered being in the minor deterioration stage.
3) If one or more time instants are within the major deterioration range, the associated component is considered being in the major deterioration stage.
4) If one or more time instants are in the fault range, the associated component is considered being in the failure stage. If one component or the breaker as a whole is in a failure stage, it may respond very slowly or it may get stuck.
5) The component will not recover to the previous stage automatically without proper maintenance.

Therefore, to determine the life cycle stage of specific part assemblies, equations (5.1)-(5.5) can be extended as:

Trip coil:

$$p_f(TC^f) = 1 - \sum_{j=1}^{3} p(t_2^j) \cdot \sum_{j=1}^{3} p(t_3^j) \cdot \sum_{j=1}^{3} p(t_4^j) \tag{5.6.1}$$

$$p_f(TC^3) = \left(1 - p_f(TC^f)\right) - \sum_{j=1}^{2} p(t_2^j) \cdot \sum_{j=1}^{2} p(t_3^j) \cdot \sum_{j=1}^{2} p(t_4^j) \tag{5.6.2}$$

$$p_f(TC^2) = \left(1 - p_f(TC^f) - p_f(TC^3)\right) - p(t_2^1) \cdot p(t_3^1) \cdot p(t_4^1) \tag{5.6.3}$$

$$p_f(TC^1) = p(t_2^1) \cdot p(t_3^1) \cdot p(t_4^1) \tag{5.6.4}$$

Auxiliary contacts:

$$p_f(AB^f) = 1 - \sum_{j=1}^{3} p(t_5^j) \cdot \sum_{j=1}^{3} p(t_6^j) \tag{5.7.1}$$

$$p_f(AB^3) = (1 - p_f(AB^f)) - \sum_{j=1}^{2} p(t_5^j) \cdot \sum_{j=1}^{2} p(t_6^j) \tag{5.7.2}$$

$$p_f(AB^2) = \left(1 - p_f(AB^f) - p_f(AB^3)\right) - p(t_5^1) \cdot p(t_6^1) \tag{5.7.3}$$

$$p_f(AB^1) = p(t_5^1) \cdot p(t_6^1) \tag{5.7.4}$$

Trip latch mechanism:

$$p_f(FT^f) = 1 - \sum_{j=1}^{3} p(t_2^j) \cdot \sum_{j=1}^{3} p(t_3^j) \tag{5.8.1}$$

$$p_f(FT^3) = (1 - p_f(FT^f)) - \sum_{j=1}^{2} p(t_2^j) \cdot \sum_{j=1}^{2} p(t_3^j) \tag{5.8.2}$$

$$p_f\left(FT^2\right) = \left(1 - p_f(FT^f) - p_f(FT^3)\right) - p(t_2^1) \cdot p(t_3^1) \tag{5.8.3}$$

$$p_f(FT^1) = p(t_2^1) \cdot p(t_3^1) \tag{5.8.4}$$

Operating mechanism:

$$p_f(MT^f) = 1 - \sum_{j=1}^{3} p(t_3^j) \cdot \sum_{j=1}^{3} p(t_6^j) \tag{5.9.1}$$

$$p_f(MT^3) = (1 - p_f(MT^f)) - \sum_{j=1}^{2} p(t_3^j) \cdot \sum_{j=1}^{2} p(t_6^j) \tag{5.9.2}$$

$$p_f(MT^2) = \left(1 - p_f(MT^f) - p_f(MT^3)\right) - p(t_3^1) \cdot p(t_6^1) \tag{5.9.3}$$

$$p_f(MT^1) = p(t_3^1) \cdot p(t_6^1) \tag{5.9.4}$$

Breaker as a whole:

$$p_f(Br^f) = 1 - \sum_{j=1}^{3} p(t_2^j) \cdot \sum_{j=1}^{3} p(t_3^j) \cdot \sum_{j=1}^{3} p(t_4^j) \cdot \sum_{j=1}^{3} p(t_5^j) \cdot \sum_{j=1}^{3} p(t_6^j) \tag{5.10.1}$$

$$p_f(Br^3) = \left(1 - p_f(Br^f)\right) - \sum_{j=1}^{2} p(t_2^j) \cdot \sum_{j=1}^{2} p(t_3^j) \cdot \sum_{j=1}^{2} p(t_4^j) \cdot \sum_{j=1}^{3} p(t_5^j) \cdot \sum_{j=1}^{3} p(t_6^j) \quad (5.10.2)$$

$$p_f(Br^2) = \left(1 - p_f(Br^f) - p_f(Br^3)\right) - p(t_2^1) \cdot p(t_3^1) \cdot p(t_4^1) \cdot p(t_5^1) \cdot p(t_6^1) \quad (5.10.3)$$

$$p_f(Br^1) = p(t_2^1) \cdot p(t_3^1) \cdot p(t_4^1) \cdot p(t_5^1) \cdot p(t_6^1) \quad (5.10.4)$$

where the superscript *f* denotes the failure stage and the other superscripts 1,2,3 denotes the three stages of healthy condition, minor deterioration and major deterioration respectively.

5.3.2 Development Steps

The general model development has the following steps:

1) Capture history of CB control signal changes and extract timings of each signal parameter using signal processing module.
2) Analyze the relationship between the parameters and fit a probability distribution to each parameter.
3) Define performance indices using these distributions to assess the conditions (health, minor/major deterioration, failure) of the breaker.
4) As the new data arrives, update the distribution and performance indices.

In the last step, since the normal distribution is selected to fit all the signal parameters, the distribution is updated by updating the mean and variance of the time instances. We write:

$$X \sim N(\mu, \sigma^2) \qquad (5.11.1)$$

or

$$f(x; \mu, \sigma^2) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{\frac{-(x-\mu)^2}{2\sigma^2}}, \text{ for } x = t_2, t_3, t_4, t_5, t_6 \qquad (5.11.2)$$

The flowchart of the CB assessing model is shown in Figure 27.

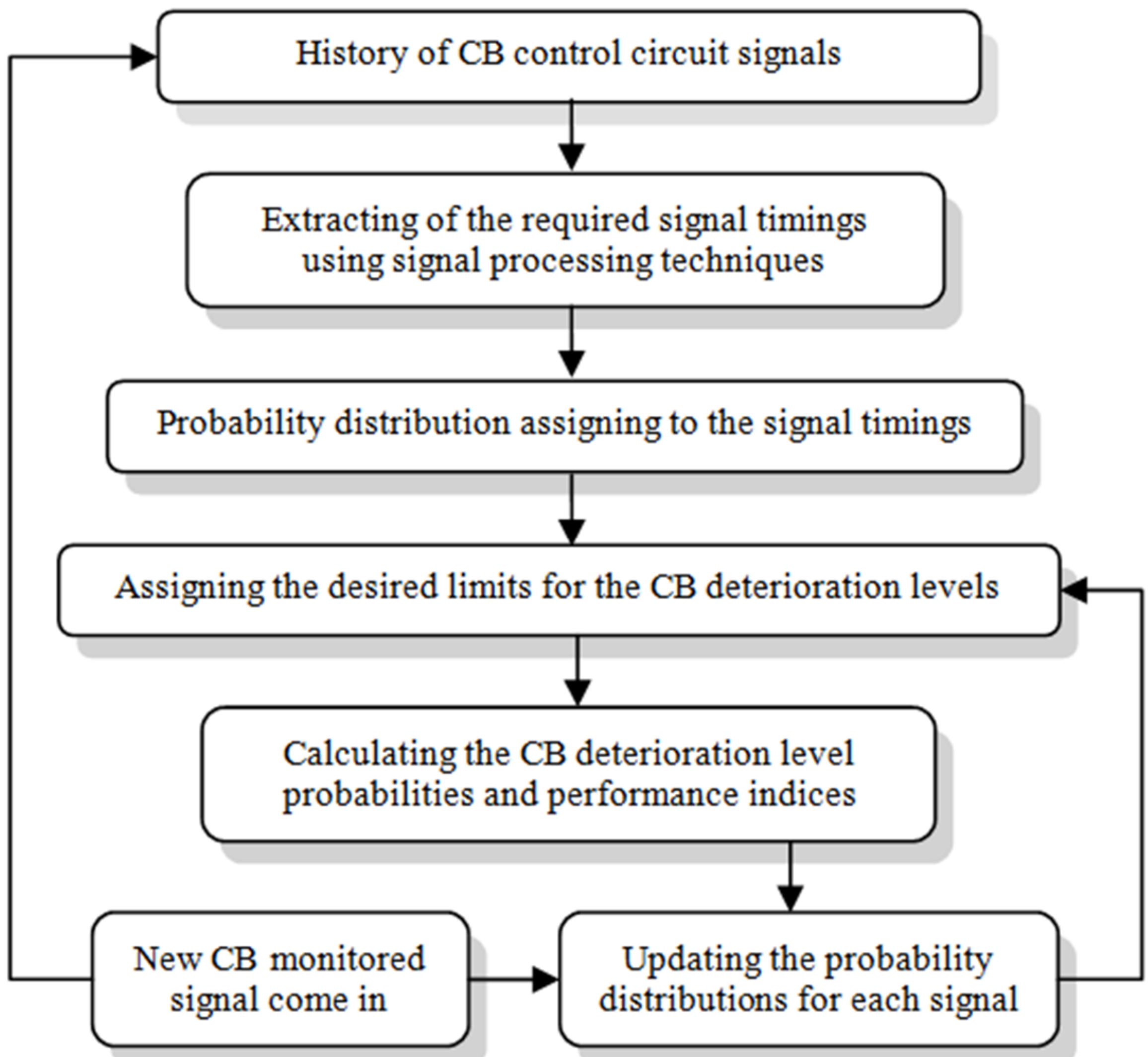

Figure 27 Model flowchart for assessing the CB conditions

5.4 Case Study

To illustrate the proposed methodology, history of each signal parameter is developed using the waveforms taken from control circuit of a GE circuit breaker. Detailed data sets can be found in the Appendix A. The tolerance limits for operation in [109] have been further divided into three bands, as shown in Table 16.

Table 16 Tolerance Limits for CB Open Operation

Event (ms)	**Lower limit**	**Upper limit for health condition**	**Upper limit for minor deterioration**	**Upper limit for major deterioration**
t_2	0.00	1.00	1.50	2.00
t_3	13.6	16.1	17.4	18.6
t_4	26.4	30.9	33.2	35.4
t_5	28.7	33.7	36.3	38.7
t_6	22.4	27.4	29.9	32.4

The computed performance indices are shown in the Figure 28 to Figure 32.

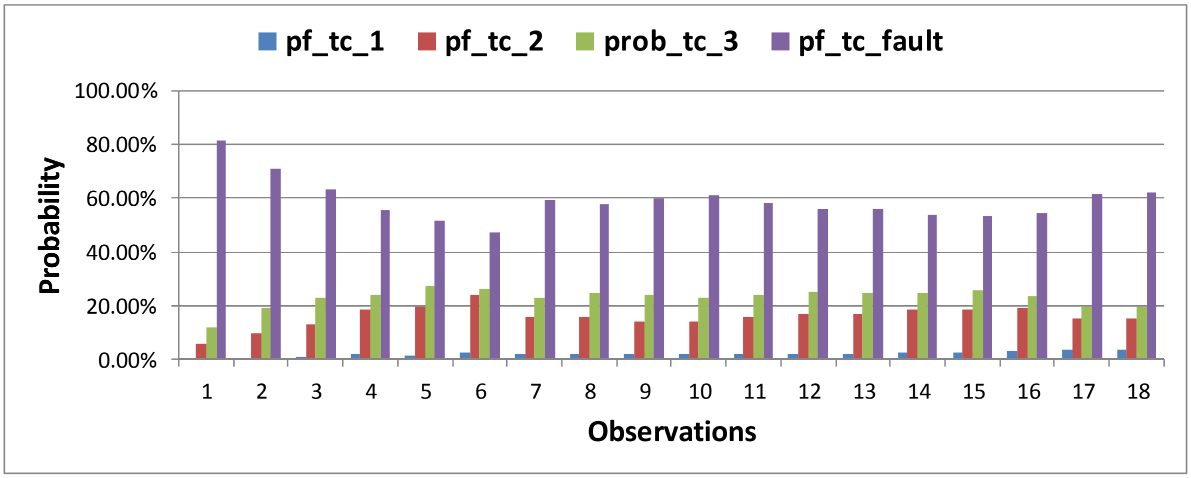

Figure 28 Performance indices for TC

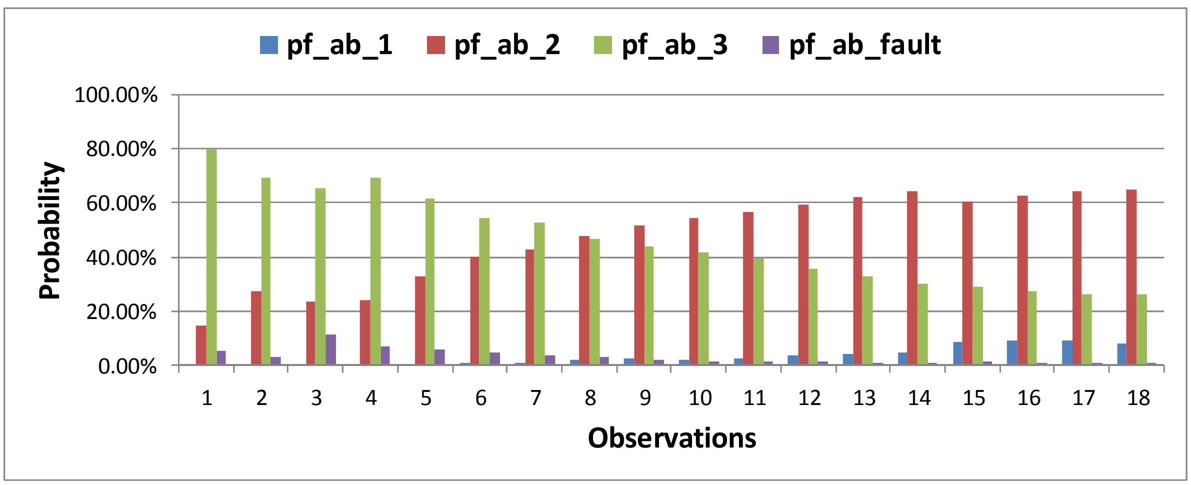

Figure 29 Performance indices for AB

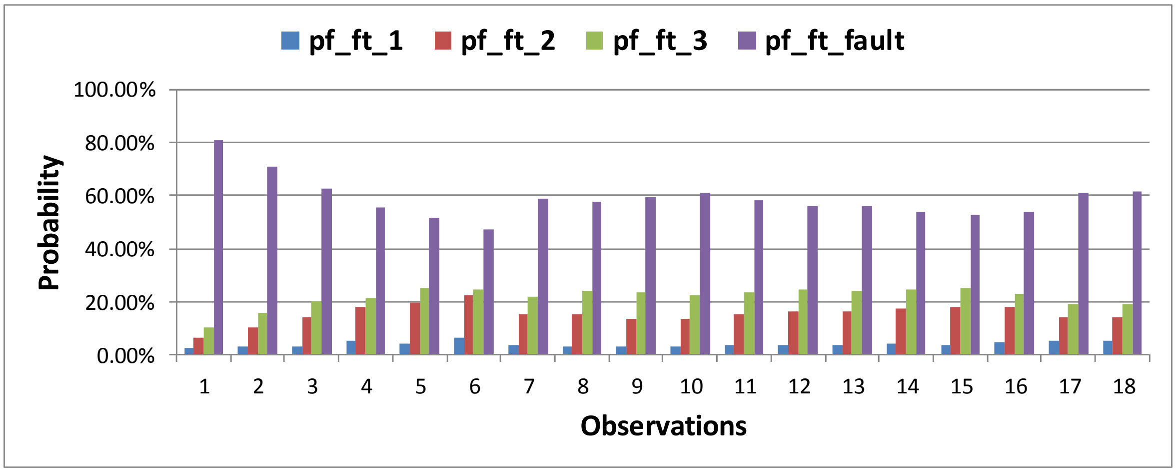

Figure 30 Performance indices for FT

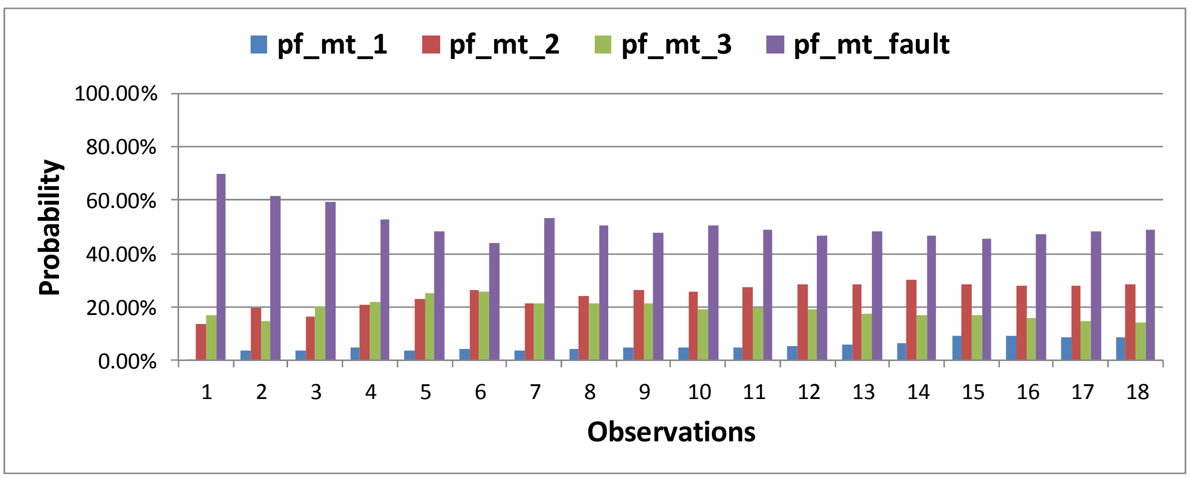

Figure 31 Performance indices for MT

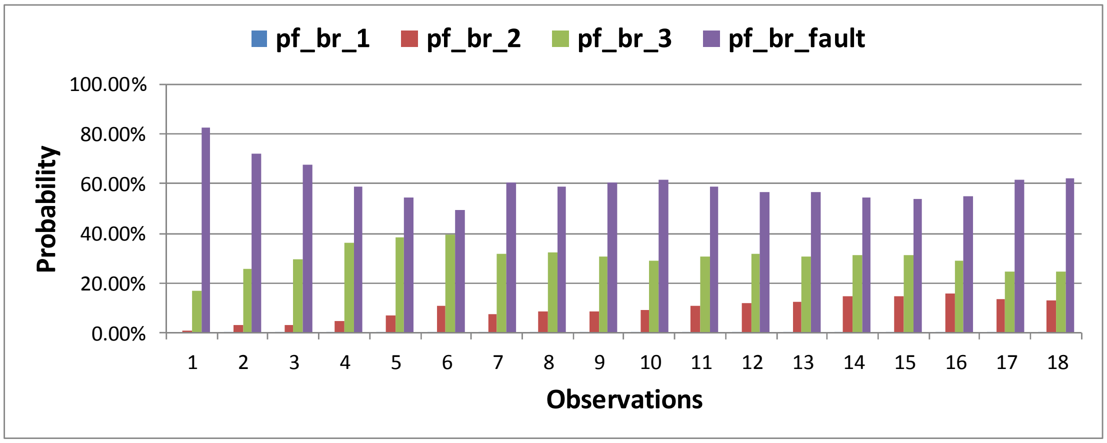

Figure 32 Performance indices for Br

It is observed that only the auxiliary contacts are functioning well and lie in the minor deterioration stage. The performance index p(Br), which depicts the whole breaker is certainly on the edge of failure due to the abnormal operation of trip coil, trip latch and operation mechanism. A major maintenance is in urgent need. Based on these performance probabilities, we get easily apply them to the 'classical' life cycle model, as shown in Figure 33.

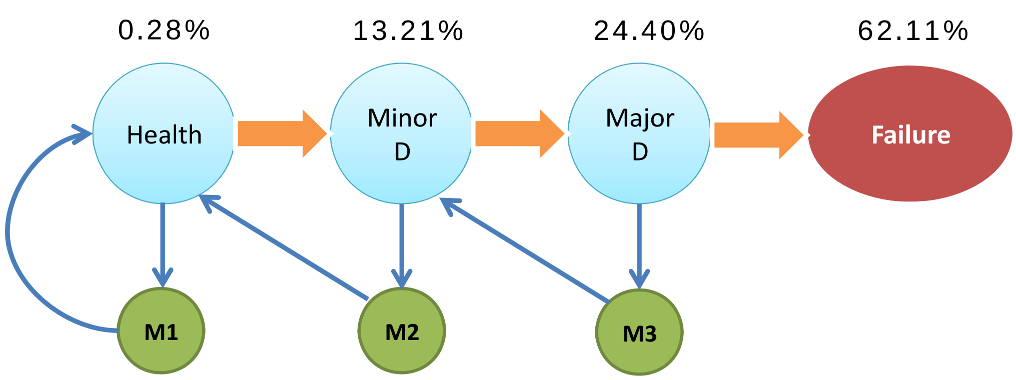

Figure 33 Assessing life cycle stages

The method proposed in this Section uses real-time condition-based monitoring data and provides a probability to each deterioration stage, which is more reliable than the traditional 'mean time' criteria.

5.5 Summary

A new methodology to assess the circuit breakers' life cycle using condition-based data is proposed in this paper. In addition to confirming that the case study analysis results are in accordance with the test results in Reference [104], this approach also gives a probability of circuit breaker in each deterioration stage in real time. Another advantage of the proposed failure probability index is that it gives insight into which component of the breaker is causing the problem instead of just reporting the failure rate (number of failures per year). Knowing the CB's exact troubled area and its deterioration stage is very important to making appropriate maintenance strategies since difference maintenance policies' may have different cost that varies a lot.

6. CONTIGENCY-BASED NODAL MARKET OPERATION USING INTELLIGENT ECONOMIC ALARM PROCESSOR*

6.1 Introduction

This Section focuses on the system monitoring and the use of alarm processing for economic decision in the nodal electricity market. The concept of an Intelligent Economic Alarm Processor (IEAP) is proposed to analyze thousands of alarm messages and extract useful information that explains cause-effect sequences associated with the unexpected contingencies. A graphical Fuzzy Reasoning Petri-nets (FRPN) model that uses fuzzy logic parameters to effectively tackle the uncertainties is built. The economic alarm processor module then processes the fault event signal, analyzes the impact on the market activities, and gives recommendations to optimize the total economic impact under fault scenarios.

The independent system operator (ISO) maintains the instantaneous power balance in the system. Its basic responsibilities include monitoring system security functions and re-dispatching generation as necessary to eliminate real-time transmission congestion and maintain system reliability. This includes taking all necessary emergency actions to maintain the system security in both normal and abnormal operating conditions.

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* Part of the material in this section is reprinted from "Contingency-based Nodal Market Operation Using Intelligent Economic Alarm processor," by Yufan Guan, and Mladen Kezunovic, *IEEE Trans. Smart Grid*, Vol. 4, No. 1, pp. 540-548, March 2013. DOI: 10.1109/TSG.2012.2223722 ©2013 IEEE, with permission from IEEE.

Based on the assumption that the system reliability is not immediately threatened when certain fault event occurs in the system, our proposed IEAP model will give operators and other market participants advance notice of an imminent need to serve scheduled loads, find replacement for the transmission transfer capacity, or meet service's needs.

6.2 Integration of Conventional Alarm Processing and Economic Alarms

An alarm, in general, is a mechanism by which a large amount of data is processed in a way that discards the detailed information but retains information to which the operator must attend. The alarms would alert these persons of incipient problematic conditions that may impede effective power market operation. The basic concept is that public information is attainable in providing market participants and operators with alarms based on economic information and trends. It is important to note that system reliability versus system economics is an issue that does not appear to be fully resolved [28].

The concept of power system economic alarms can be defined in two different areas.

- Economic alarms for system operators to augment conventional electric alarms. This type of alarm includes: the identification of operating conditions that limit the effective transfer of power among purchasing and selling entities; conditions such that further contingencies will limit market sales and potentially curtail scheduled transactions; identification of stresses in the bulk transmission network beyond which operators are uncomfortable; and generation and transmission contingencies that may cause degradation of efficient market transactions.

- Economic alarms for all market participants to monitor system state and signal significant changes in trends for LMPs, line loading, and system/bus demands. This type of alarm would rely upon the use of analysis software (load flow studies, contingency analysis, real-time stability analysis and state estimation) to obtain the present economic picture of a power system. Thus near term trends in LMPs, line loading, and bus demands may alert market participants of economic opportunities.

Economic alarms have the potential to alert the operator of electric network economic implications. These economic impacts can range from small value transactions to large scale transmission transactions with concomitant high dollar value. The philosophical base of alarms is the identification of measurement and other data that are "out of range." In power engineering, alarms are usually based on a complex combination of measurement and other data. Identification of the economic impact of events could alter how operators correct the present state of the system so that revenue is optimized, and schedules and power market contracts are effectively implemented.

The Intelligent Economic Alarm Processor (IEAP) proposed in this work can be implemented in a control center to assist the grid operator in rapidly identifying faulted sections and managing market operation. The structure of the application as well as its SCADA support infrastructure is illustrated in Figure 34.

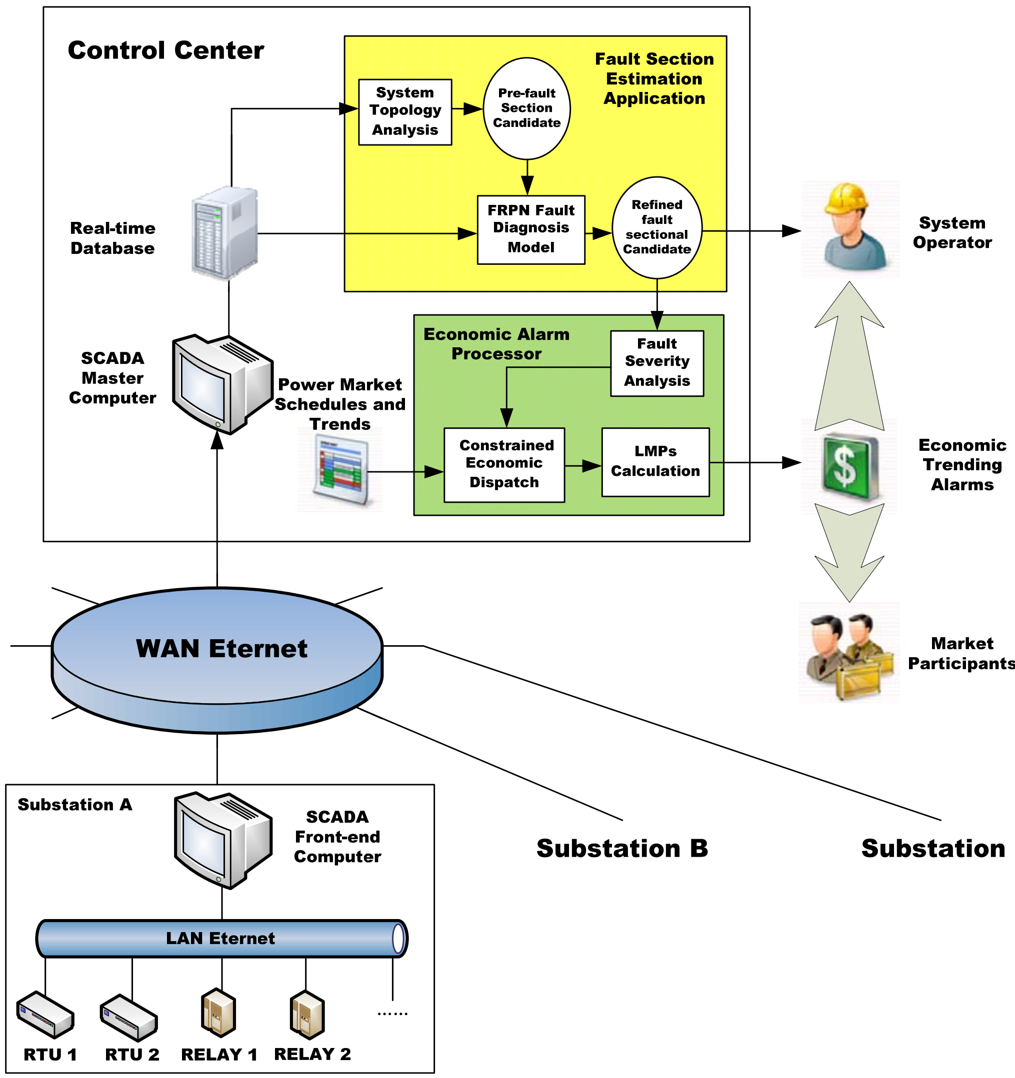

Figure 34 Intelligent economic alarm processor structure

In such a solution, input data such as relay trip signals and circuit breaker status signals are acquired by RTUs of the SCADA system. In the control center, the SCADA master computer puts the input data into a real-time database and keeps updating them at each scan time.

The IEAP application includes two modules, Fault Section Estimation Application and Economic Alarm Processor. In the first module, the Fuzzy Reasoning Petri-net (FRPN) diagnosis model and data in the real-time database corresponding to each section in the rough candidate set are used. Each section is associated with a truth degree value (the possibility of fault occurrence). The section with a truth degree value greater than a certain threshold is included in the refined fault candidate set. Such a refined fault candidate set is presented to the system operator for decision-making.

When market participants receive the system and market data in advance, they make estimation about the system operator's restorative action and their competitors' reaction to it. The general contingency-based strategic bidding model assumes that all the suppliers' and consumers' bids follow a linear function, and will adjust the bidding coefficients of competitors accordingly [112][113].

6.3 Economic Alarm Processor Module

As discussed in Section 3 and Section 4, once the fault section estimation module detects a fault in certain region, the economic alarm processor firstly checks if there is any thermal violations and calculates the changes in the LMPs, total generation cost and congestion revenue etc. Then it gives some suggested re-dispatch actions to optimize the whole system. The objective of the module is to minimize the total generation cost. Since the market transactions have already been scheduled prior to the fault event, we may consider the demand is perfectly inelastic, thus minimizing the total cost is the same as maximizing the total social welfare. Therefore, the problem can be written as:

$$
\begin{aligned}
&\min_{P_{Gi}} \sum_{i=1}^{N_G} C_i(P_{Gi}) \\
&s.t. \quad \sum_{i=1}^{N_G} P_{Gi} = \sum_{i=1}^{N_L} P_{Li} \quad \text{(Demandnd = Supply)} \\
&\text{and} \quad P_{Gi}^{\min} \le P_{Gi} \le P_{Gi}^{\max} \ \text{ for } i = 1, \cdots, N_G \\
&\text{and} \quad P_{Lj}^{\min} \le P_{Lj} \le P_{Lj}^{\max} \ \text{ for } j = 1, \cdots, N_L \\
&\text{and} \quad |F_{ij}| \le F_{ij}^{\max} \ \text{ if } \ z_{ij} = 1, \ |F_{ij}| = 0 \ \text{ if } \ z_{ij} = 0
\end{aligned}
\tag{6.1}
$$

P_{Gi} is the generation from generator i, and N_G is the total number of generators. P_{Lj} is the demand for each load j, and N_L is the total number of loads. C_i is the generation cost for generator i, and F_{ij} denotes the power flow from bus i to bus j. z_{ij}=1 when line*ij* is operating normally, z_{ij}=0 when a fault is detected on line*ij*. To simply demonstrate the concept, we assume the following parameters for the same system as in Figure 35 and Table. 17:

Table 17 Test Data for 5-bus Test System

	Reactance x (p.u.)	**Capacity (MW)**
Line 1-3	0.4	200
Line 1-4	0.4	200
Line 2-3	0.4	400
Line 2-4	1.0	400
Line 3-4-1	0.4	50
Line 3-4-2	0.3	200
Line 3-5	0.8	400
Line 4-5	0.4	400
0< P_{G1}<1000 MW, C_1 = 20 P_1\$/hour,0< P_{G2}<1000 MW,C_2 = 15 P_2\$/hour L_3 =275MW L_4 =325MW L_5 =100MW		

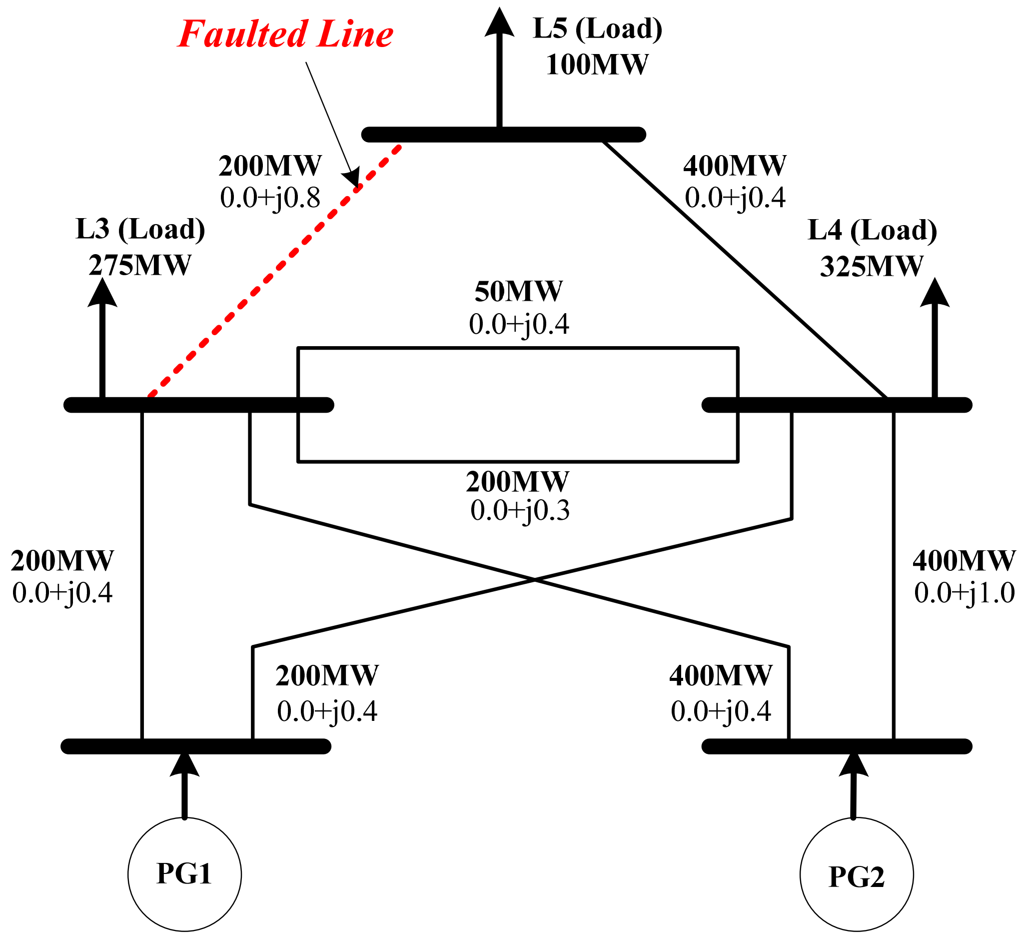

Figure 35 One-line diagram for a 5-bus test system

The economic alarm processor module then sends signal changes including the LMPs, congestions, shadow prices etc. to the system operator and market participants, which allows them to utilize information on a variety of levels:

- To access the short term transmission needs in the system
- To allow for operators to re-dispatch generators based on scheduled transactions and real time market needs

- To assist in making transmission operating decisions optimal for economic efficiency as well as for system reliability.
- To allow market participants to identify trends in LMP, line loading and demand levels in order to find/make transactions in the near future in anticipation of these trends.

The IEAP could be implemented in the control center by ISO directly or by a third party, who would receive system sate and market data from the ISO. Those data may also be available for sale through private companies such as GenScape [111]. However, it is still a question to what extent system's data should be open to the public. The system state data would be valuable to market participants, but the distribution of this data may raises cyber security issues [34].

The IEAP would give the operator an alarm that the line 3-5 is faulted, and the operator has to run the optimal power flow again without the faulted line. The traditional way to run optimal power flow will take all the currently-feasible transmission lines into consideration. . However, it is interested to note that reference [49] raised an idea of "Optimal Transmission Switching". Assumed that taking a "healthy" transmission line out of service will not result in degrading current system reliability, the potential economic savings can be achieved. In the case study presented next, we will also verify this idea by taking the redundant element out to optimize the whole system benefit.

6.4 Case Study

6.4.1 Background

On September 5th 2007, a tornado in the area resulted in the tripping of two 345 kV lines and two generators connected to the same substation. Case data taken from the Supervisory Control and Data Acquisition (SCADA) database of the EMS monitoring the area are used. The first data scan was captured at approximately 07:49 AM, before the event occurred, and the second was captured at approximately 07:54 AM, just after the event occurred.

There were 2125 alarm messages that appeared within only 45 minutes, some a screen shot illustrated in Figure 36. Obviously processing such large number of alarms is beyond the capacity of any operator to handle. Thus, operators may not be able to respond to the unfolding events in time, and even worse, the interpretation by the operators may either be wrong or in conclusive. ERCOT operators also indicated in interviews that the list containing large number of alarms provides little help for them. They normally just make phone calls to look up for the faulted section, which may take 15-20 minutes and even longer.

1	AREA	CATEGORY	TEXT	TIME
850	GENERATN	AGC-MAJOR	STA_LD2 LAAR MW TLM AVAILABLE	9/5/2007 7:42:24 AM
851	GENERATN	AGC-MAJOR	TOPAZSQ1 QSE SCE TLM UNAVAILABLE	9/5/2007 7:42:24 AM
852	ERCOT	69KV<	NVARO CB CB_3290 ST OPEN	9/5/2007 7:42:28 AM
853	ERCOT	LOG2	(05 / 07:42:28 NVARO CB CB_3290) acked by: AutoAck on AlmSe	9/5/2007 7:42:30 AM
854	ERCOT	LOG2	(05 / 07:42:28 NVARO CB CB_3290) deleted by: AutoDelete on Alr	9/5/2007 7:42:30 AM
855	ERCOT	GEN_BRKR	WTCCS CB 7240 ST CLOSED	9/5/2007 7:42:28 AM
856	ERCOT	138KV_BRKR	HORTON DSC DSW_9311 ST OPEN	9/5/2007 7:42:28 AM
857	ERCOT	138KV_BRKR	HORTON DSC DSW_9309 ST OPEN	9/5/2007 7:42:28 AM
858	ERCOT	GEN_BRKR	WCPP CB ST1 ST CLOSED	9/5/2007 7:42:30 AM
859	GENERATN	AGC-MAJOR	STA_LD2 LAAR BKR-REL TLM AVAILABLE	9/5/2007 7:42:28 AM
860	GENERATN	AGC-MAJOR	TOPAZSQ1 QSE SCE TLM AVAILABLE	9/5/2007 7:42:36 AM
861	GENERATN	AGC-MINOR	ERCOT JAGC REQ MW NOT FULLY DISTRIBUTED	9/5/2007 7:42:44 AM
862	ERCOT	69KV<	NVARO CB CB_3290 ST CLOSED	9/5/2007 7:42:48 AM
863	ERCOT	LOG2	(05 / 07:42:48 NVARO CB CB_3290) acked by: AutoAck on AlmSe	9/5/2007 7:42:50 AM
864	ERCOT	LOG2	(05 / 07:42:48 NVARO CB CB_3290) deleted by: AutoDelete on Alr	9/5/2007 7:42:50 AM
865	GENERATN	AGC-MAJOR	STA_LD2 LAAR MW TLM UNAVAIL	9/5/2007 7:42:48 AM

Figure 36 Alarm message in control center

The protection system configuration for this case is shown in Figure 37.

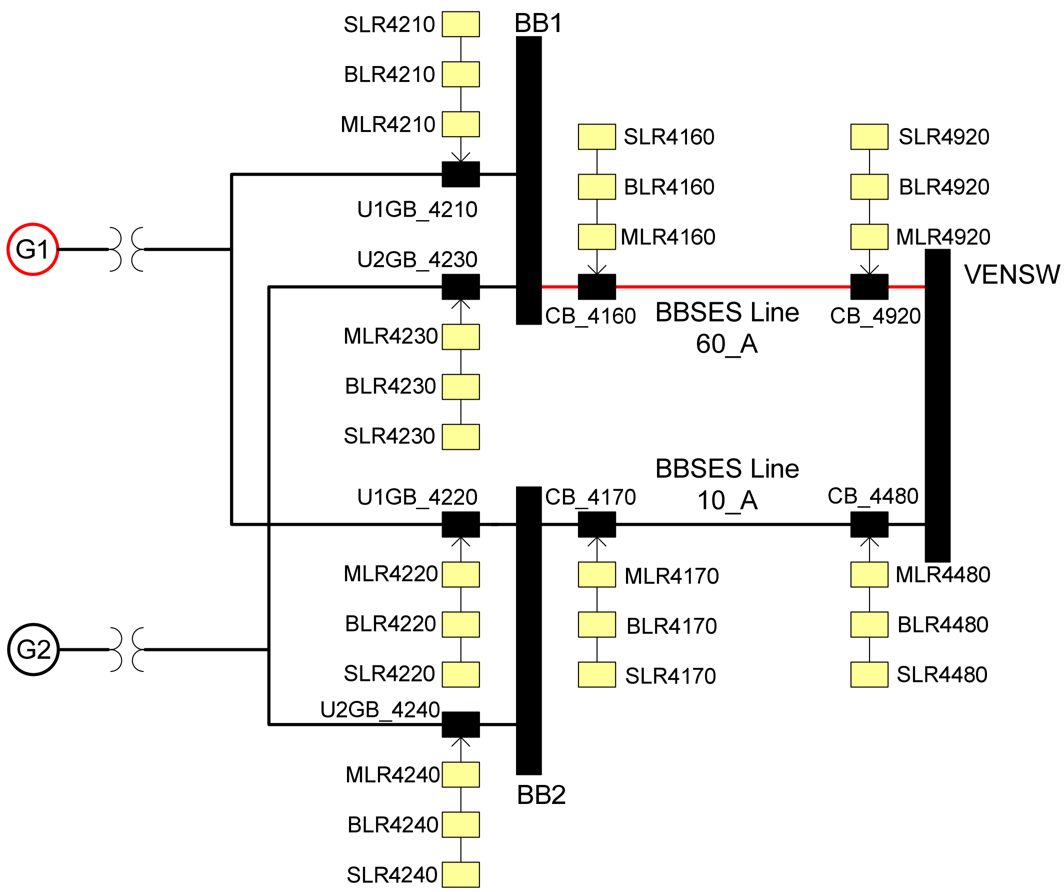

Figure 37 Protection system configuration diagram

The system consists of 9 sections, including 3 buses, 2 generators and4 transmission lines.

6.4.2 Simulation Results

Case 1:

This case assumes the circuit breaker is tripped by the associated relays, thus allowing the relay status to be obtained to validate the fault. The operation of circuit breakers CB4210, CB4220, CB4160, and CB4920 are detected, see in Figure 38.

Diagnosis result: Line BBSES_60A is faulted, and its truth value is 0.8550.

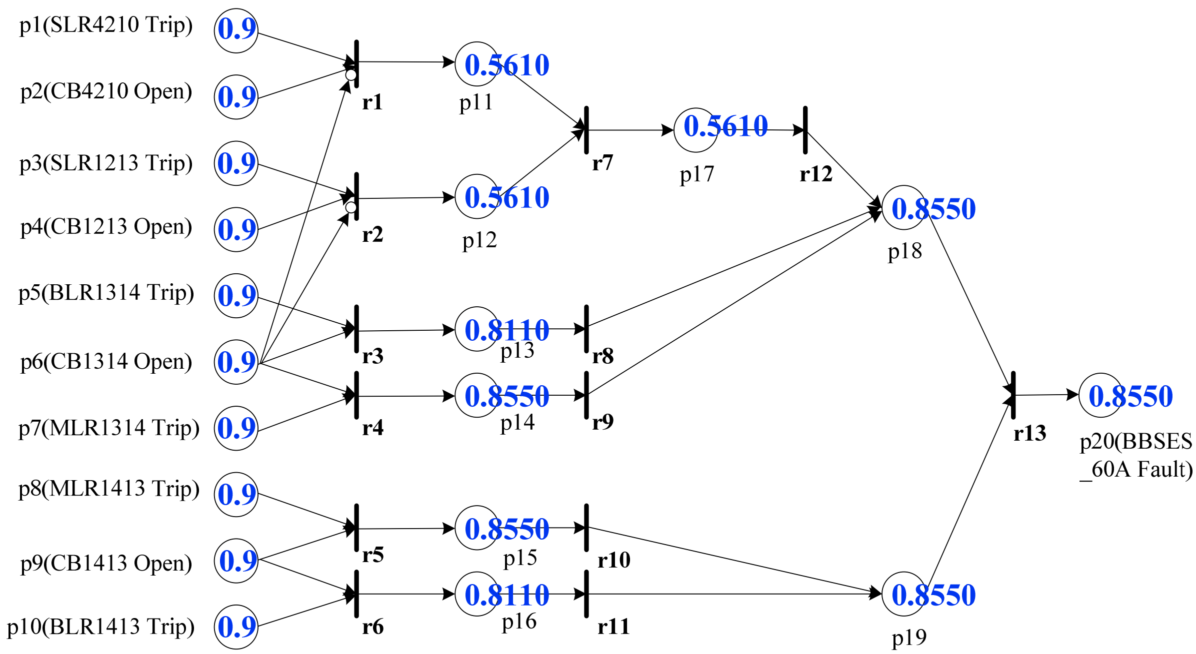

Figure 38 FRPN model analysis procedure for Line BBSES_60A

When the signal designating that BBSES_60A (which is line 3-5) is out of operation is sent to the economic alarm processor module, the current situation is quickly analyzed, and a summary report is shown in Table 18.

In this example, the loss of line 3-5 causes the line 3-4-1 to exceed its thermal capacity. To relieve it from violating the limit, the module gives two suggested actions. The first one is to adjust the generation which results in an increase in the total generation cost. The second option is to take the line 3-4-1 out assuming no other reliability or security standards are violated, and the system total generation cost will remain the same.

Table 18 Economic Alarm Processor Summary Report for Fault BBSES_60A

Before the fault:	
Fault detected?	No
Any thermal violations?	No
Generation 1	300 MW
Generation 2	400 MW
Total Generation Cost	12000 $/hour
After the fault: (if no action is taken)	
Fault detected?	Line 3-5 is out
Any thermal violations?	Line 3-4-1 exceeds the limit by 2MW
Generation 1	300 MW
Generation 2	400 MW
Total Generation Cost	12000 $/hour
Suggested Actions:	
Option 1	Increase P_{G1} and decrease P_{G2}
Fault detected?	Line 3-5 is out
Any thermal violations?	No
Generation 1	330 MW
Generation 2	370 MW
Total Generation Cost	12150 $/hour
Changes in Total Generation Cost	Increased by 150$/hour
Option 2	Taking Line 3-4-1 out.
Fault detected?	Line 3-5 is out
Any thermal violations?	No
Generation 1	300 MW
Generation 2	400 MW
Total Generation Cost	12000 $/hour
Changes in Total Generation Cost	No

Case 2:

This case assumes that no protective relay signals are available. Unit 1 tripped, and operation of circuit breakers CB4210, CB4220, CB4160, CB4170, CB4920 are detected, see in Figure 39.

Diagnosis result: Unit 1 is faulted, and its truth value is 0.8550.

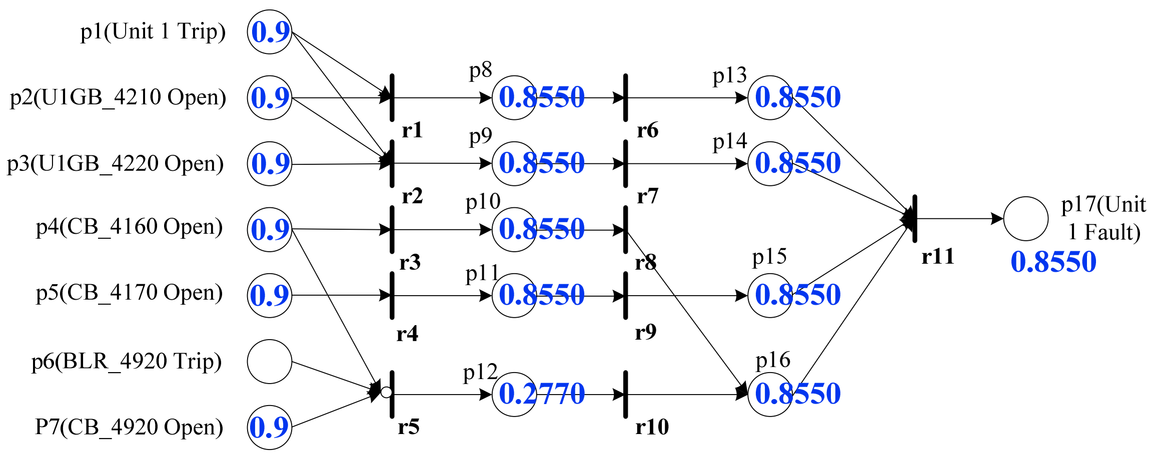

Figure 39 FRPN model analysis procedure for Unit 1

When the signal designating that Unit 1 is lost is sent to the economic alarm processor module, the IEAP will analyze the system state and market data and give a summary report shown in Table 19.

When PG1 is lost, the system is unbalanced and on the edge of collapse. The system operator has to find a solution to restore the system immediately. The easiest and most intuitive way would be increase PG2 by 300 MW. However, two lines would exceed the thermal limits even though the total generation cost decreased. Thus, the operator has to find alternative generation from reserve services or real-time market, which will certainly have a great impact on the market participants' bidding strategies. The last solution would be to cut the load in node 3, 4 or 5, but the system operator has to compensate the customers a lot.

Table 19 Economic Alarm Processor Summary Report for Fault Unit 1

Before the fault:	
Fault detected?	No
Any thermal violations?	No
Generation 1	300 MW
Generation 2	400 MW
Total Generation Cost	12000 $/hour
After the fault: (if no action is taken)	
Fault detected?	Unit 1 is out
Any thermal violations?	System is unbalanced
Generation 1	0 MW
Generation 2	400 MW
Total Generation Cost	NA
Suggested Actions:	
Option 1	Increase P_{G2} by 300MW
Fault detected?	Unit 1 is out
Any thermal violations?	Line 2-3 exceeds the limit by 84MW Line 3-4-1 exceeds the limit by 5.5MW
Generation 1	0 MW
Generation 2	700 MW
Total Generation Cost	10500 $/hour
Changes in Total Generation Cost	Decreased by 1500 $/hour
Option 2	Find alternative generations from reserve services or real-time market
Option 3	Cut the load

6.4.3 Impact on Market Participants

Participants are very sensitive to every single event happened in the electricity market. The LMPs are calculated every five minutes in ERCOT's real time market. Market operators from ERCOT admitted that it is possible that EMS (Energy Management System) fails to deliver the latest fault event and topology change information to MMS (Market Management System). Price errors caused from those inaccurate system inputs could be tremendous. And the impacts will arise in varies aspects.

The first impact will be on the “traditional” MPs, such as generation entities and load entities. Take case 1 as an example, since there is congestion after the fault happens. Failure to aware the topology change will result in a LMP differences, which lead to huge economic profits/losses, as shown in Table 20.

Table 20 Impacts of Unaware System Topology Changes

	Real price when retrieve the IEAP report on time	Fail to retrieve the latest fault event information	Differences
LMP 3	8 $/MWh	15 $/MWh	7 $/MWh
LMP 4	28 $/MWh	15 $/MWh	13 $/MWh
LMP 5	28 $/MWh	15 $/MWh	13 $/MWh
Gen 1	Output = 330 MW Revenue = 6600 $/hr	Output = 300 MW Revenue = 6000 $/hr	Revenue loses 600 $/hr
Gen 2	Output = 370 MW Revenue = 5550 $/hr	Output = 400 MW Revenue = 6000 $/hr	Revenue gains 450 $/hr
Load 1	Pays 2200 $/hr	Pays 4125 $/hr	Cost goes up 1925 $/hr
Load 2	Pays 10500 $/hr	Pays 5625 $/hr	Cost goes down 4875 $/hr
Load 3	Pays 2800 $/hr	Pays 1500 $/hr	Cost goes down 1300 $/hr

From the tables above, Generation 1 will lose 600 $/hr, and customers in Load 1 have to suffer a cost increase. On the other hand, Generation 2 and customers in Load 2 and 3 will enjoy an unexpected profit due to the unawareness of the system topology changes.

The second impact is related to the Congestion Revenue Rights (CRR), which will involve many big hedge fund and investment bank participants.

CRR is a purely financial instrument and does not represent a right to receive, or obligation to deliver physical energy. ERCOT allocates a portion of the available CRRs to Non Opt In Entities (NOIEs) as a pre-assigned CRR (PCRR) and auctions the remaining capacity monthly and annually. Most CRRs are tradable in the CRR auction, in the day- s betweahead market, or bilaterally. A typical type of CRRs would be Point-to-Point (PTP) CRR which ien a designated point of injection (source) and point of withdrawal (sink). PTP CRRs might be purchased in the form of PTP option or PTP obligation. The charge and payment are based on the difference in LMPs between source and sink, i.e. the holder of an M megawatt CRR from a to b at time t receives:

$$CRR\ revenue = M * [LMP(a) - LMP(b)]$$

Back to case 1, for instance, if a MP holds 100MW PTP obligation from node 4 to node 3 at the time when fault happens, he would have gained (28-13)*100 = 1500 $/hr profit. However, due to the lack of the timely system information, he receives nothing and loses the obligation payment.

In real market world, the numbers are in millions. Market operators claims that they may correct the price errors after they found the false input data. However, it will take a tedious process and may raise a lot of other problems related to the contracts and protocols.

6.5 Summary

In this Section, it is discussed that one or more faults occurring in the system could trigger numerous alarms, and those alarms will put the system/market operation into alert state. Those alarms will be only sent to the system operator to verify the fault and take appropriate actions to restore the system. The processed information could be distributed to all the market participants for their future strategies in the market.

From the simulation test, we may draw the conclusion that our proposed Intelligent Economic Alarm Processor model works properly for the practical cases, and have the following characteristics compared with those traditional solutions:

- Take electrical grid alarms and power market schedules and trends, such as LMPs and prices, as our inputs
- Have the system operational alarms, fault severity indications and solutions, as well as the impact on the electricity market as our outputs
- Benefit for both system and market operators, and all other market participants.
- Greatly reduce the processing time while increase the accuracy.
- Avoid price errors that will result in unexpected costs and unearned profits.

7. CONCLUSIONS

7.1 Summary of Achievements

The fast development of power system brings more complexities in the system operation and electricity market as there is larger amount of data and more price signals. It also has placed great emphasis on the availability of the grid information, the analysis of this information, and the subsequent decision-making to optimize system operation in a competitive environment. This creates an urgent need for better ways of correlating the market activity with the physical grid operating states in real time and sharing such information among market participants. Choices of command and control actions may result in different financial consequences for market participants and severely impact their profits. Because of this, new solutions have to be implemented toward integrating grid control and market operations taking into account both good engineering practices and appropriate economic incentives.

The main achievements and contributions of this research are summarized as follows:

- *Fault section estimation*

  The Fuzzy Reasoning Petri-nets technique has combined strength of uncertainty processing, rule-based reasoning, symbolic representation, and parallel computing. It makes fault section estimation more accurate, fast and adaptive to system changes. Especially, the reasoning process can be visualized in a form of graphical representation of Petri-nets. The rule base and parameters are saved in matrix forms and the whole reasoning process is implemented by matrix operations. This will significantly facilitates the procedure of rule base building and maintenance.

- *The integration of IED data with SCADA data*

  IED Data are able to reflect the state of power system with a high resolution and wide-area perspective, and hence are more reliable than SCADA data. The proposed approach to combine IED data and SCADA data will further enhance the accuracy of fault section estimation.

- *Reliability and life cycle assessment of protection devices*

  This dissertation proposes a new approach to assess the circuit breaker's life cycle or deterioration stages using its control circuit data. In this approach, the "classical" healthy, minor and major deterioration stages have been mathematically defined by setting up the limits of various performance indices. The model can be automatically updated as the new real-time condition-based data become available to assess the CB's operation performance using probability distributions. The methodology may also be used to quantify the effect of maintenance making use of the defined performance indices, which further helps in developing system-wide risk-based decision approaches for maintenance optimization.

- *Impact of physical grid operating states on real-time market activity*

  The proposed Intelligent Economic Alarm Processor (IEAP) model takes the best aspects of the use of existing artificial intelligent techniques to interpret alarms and extends it for electricity market use. Such approach is able to generate the fault alarm analysis and economic summary report automatically and immediately after the fault occurs with an explanation of the cause-effect relationship associated with the fault and recommendations to optimize the grid's total benefits. The predicated limitations of available transmission capacity (ATC) that is problematic can be identified when caused by a fault and power transfer needs as a consequence of such events can be anticipated.

7.2 Suggestions for Future Work

The following aspects need to be considered in future work:

- *Improvement in the fault section estimation module*

  The weight factors need to be assigned through collaboration of the experienced operators and maintenance staff, who are especially familiar with the importance and expected reliability of each component in the power system of interest. Sensitivity analysis could be performed to better understand the importance of each component in the FRPN model

- *Cost-benefit analysis of the maintenance for the protection devices*

  One notable advantage of the proposed failure probability index is that it gives insight into which component of the breaker is causing the problem instead of just reporting the failure rate (number of failures per year). Knowing the CB's exact troubled area and its deterioration stage is very important to making appropriate maintenance strategies since difference maintenance policies' may have different cost that varies a lot. A cost–benefit analysis with this proposed methodology will be the research focus in the future.

- *Extensive use of Intelligent Economic Alarm Processor*

  The IEAP model takes the best aspects of the use of existing artificial intelligent techniques to interpret alarms and extends it for electricity market use. Other market indices such as Financial Transmission Rights (FTRs) may be added in the summary report for the benefit of the whole system and market participants.

- *Cyber security issue*

  Making the system data available to MPs may raise potential of cyber security breach issues and hence adequate data protection needs to be implemented. An option for the ISO to provide system state data to a third party who would then perform alarm analysis and make the information available to all MPs should be explored. While the system operation data may not be available to all the MPs due to cyber security reasons, a quick and accurate analysis IEAP report will benefit both system and market operators, and all other market participants, to avoid unnecessary price errors that will cause big profits/losses.

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APPENDIX A: PUBLICATIONS

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APPENDIX B

1. Summary of test records taken during the opening operation

Manufacturer and type: GE VIB-15.5-20000-2					
Date	t_2 (ms)	t_3 (ms)	t_4 (ms)	t_5 (ms)	t_6 (ms)
2/12/2002	2.257	17.708	31.076	36.111	30.382
2/13/2002	1.215	9.375	33.333	37.674	29.167
2/13/2002	1.389	14.062	32.639	35.764	27.257
2/19/2002	1.389	14.757	29.514	35.764	32.292
2/21/2002	1.042	15.625	30.382	36.632	28.125
2/21/2002	1.563	18.056	31.250	34.375	29.687
2/21/2002	0.868	16.840	30.382	33.507	28.299
3/05/2002	2.083	23.090	28.646	36.111	27.604
3/05/2002	1.910	15.972	29.687	32.986	27.604
3/05/2002	2.431	14.931	29.167	34.375	28.299
6/10/2002	1.389	10.590	29.861	35.243	27.778
6/10/2002	1.215	15.278	30.208	33.681	29.167
6/10/2002	1.389	15.104	30.035	32.986	27.083
6/10/2002	1.389	11.458	29.514	33.333	27.604
6/11/2002	1.042	15.278	28.993	33.681	27.257
6/11/2002	1.563	14.062	26.910	31.076	25.000
6/11/2002	0.694	11.111	31.944	33.854	27.431
6/11/2002	3.299	11.458	30.729	34.549	28.125
6/11/2002	1.910	12.153	30.903	35.764	28.646