RELIABILITY ANALYSIS OF SMART ELECTRICAL TRANSMISISON SYSTEM AND MODELING THROUGH DYNAMIC FLOWGRAPH METHODOLOGY

by

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ABSTRACT

Reliability assessment methods allow the evaluation of the reliability of systems and provide important information on how to improve a system's life to reduce risk and hazards. With the advancement in technology, the existing methods were extended and new methods were adopted. The advancement from mechanical to numerical and analog to digital system in many applications, and deregulation of energy sector brought the need to further modify the reliability analysis methods. The scope of this research is to demonstrate the advancement of the Dynamic Flowgraph Methodology (DFM) to reliability modeling of Smart Electrical Transmission System. The reason behind this is the successful operation of electric power under a deregulated electricity market depends on transmission system reliability management. Besides this, analog electro-mechanical systems in existing power system are aging and becoming obsolete. This thesis also illustrates how the electrical transmission system can be renovated into smart electrical transmission system and evaluates the reliability measures.

Keywords: dynamic flowgraph methodology, smart electrical power transmission system, reliability modelling.

DEDICATION

To my parents Abdul Razzaq and Shafiqa Razzaq who taught me the meaning of endurance in the journey of life and diligence in work.

ACKNOWLEDGMENTS

قُلْ إِنَّ صَلاتِي وَنُسُكِي وَمَحْيَايَ وَمَمَاتِي لِلَّهِ رَبِّ الْعَالَمِينَ (١٦٢) لاَ شَرِيكَ لَهُ وَبِذَلِكَ أُمِرْتُ
وَأَنَاْ أَوَّلُ الْمُسْلِمِينَ (١٦٣)

سورة الأنعام: ١٦٢–١٦٣

"Verily, my prayer, my sacrifice, my living, and my dying are for Allah, the Lord of all that exists." (6:163) "He has no partner. And of this I have been commanded, and I am the first of the Muslims." (6:164) Qur’an (Surah Al-An’am)

I would like to begin by thanking Allah, Most Strong, All Almighty, for providing me the strength and perseverance required to achieve this work. I would like to express my deep gratitude to my supervisor Dr. Lixuan Lu for providing me guidance and support throughout the course of my master’s degree. It would not have been possible for me to achieve this work without her crucial guidance. Besides this, I would like to thank my supervisory committee member, Dr. Ahmad Barari. I would also like to thank my parents and my siblings for their steadfast support and encouragement, their care and love has been indispensable at all times in my entire life. I would like to thank my wife Sarah, the love of my life, for her wonderful support and encouragement. I am thankful to all my friends and colleagues at UOIT for providing me wonderful and pleasant learning environment. Finally, I would like to thank all professors and staff at UOIT for their tremendous effort that made it possible for me to conduct my research and make the utmost benefit from the time I spent in the program.

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Abbreviations

DFM	Dynamic flowgraph Methodology
PSA	Probabilistic Safety Assessment
TTN	Time Transition Network
CN	Causality Network
FMEA	Failure Mode And Effect Analysis
FTA	Fault Tree Analysis
HAZOP	Hazard and Operability Analysis
MVL	Multi-Valued Logic
PI	Prime Implicants
TFT	Time Fault Tree
P&C	Protection and control
PLC	Programmable Logic control
SETS	Smart Electrical Transmission System
SEPS	Smart Electrical Power System
GPS	Global Positioning System
AC	Alternating Current
DC	Direct Current
FACTS	Flexible AC Transmission System
HVDC	High voltage Direct Current
RTU	Remote Terminal unit
PMU	Phasor Measurement Unit

CT	Current Transformer
PT	Potential Transformer
LAN	Local Area Network
SPS	Special Protection Scheme
UPS	Uninterruptable Power Supply
SCADA	Supervisory Control And Data Acquisition
GIS	Geographical Information System
QoS	Quality of Service
KV	Kilo volt
MV	Mega Volt
MVAR	Mega Volt Ampere Resistance
MW	Mega Watt
ROW	Right Of Way
IEEE RTS-96	Institute of Electrical and Electronics Engineer Reliability Test System-96

INTRODUCTION

Reliability assessment methods allow the evaluation of the reliability of systems. The methods provide important information on how to improve a system's life to reduce safety risk and hazards. Several reliability assessment methods were defined and used over the past decades [1, 2]. With the advancement in technology, the existing methods were extended and new methods were adopted. The advancement from mechanical to numerical and analog to digital system in many applications, and deregulation of energy sector brought the need to further modify the existing reliability assessment methods. The deployment of digital system and changing from analog system dictates the use of dynamic reliability assessment methods with special features, such as time dependency and multistate representation [3].

Due to the deregulation of energy sector, operators are inventing and introducing techniques to make their system reliable and smarter. For that purpose, digital control system is taking place of analog system and introducing modeling techniques for their system behaviour. Development in the capabilities for sensors and digital control technologies and improved communication of digital data and information has opened a large range of new options for both the transmission and distribution segments of the industry. Smart electrical transmission system is an advance or modified form of present electrical transmission system with advance features. In addition, communication system has been introduced to control the flow and amount of electricity. Most of the equipments and techniques are available to make our electrical system smarter but the implementation in a right direction is required.

Utilities understand their business of delivery of electricity to end user and are justifiably proud of the achievements they have made in the field of reliable power. But problems can be occurs at the back end when the whole reliable distribution system will be collapse when generation and transmission system will not reliable and working on digital system or not synchronized with the distribution system. Operators and utility companies are working on smart grid features which are about electrical distribution system. They are not touching the complete electrical power system like generation, transmission, distribution system. There are lot of work has been presented about the smart grids but no work has been done about the reliable transmission system which can be claimed as smart.

This smart system is necessary because if some fault happens at the high voltage transmission system, then the smart communication system and digital system will guide the rest of the system to shift the load. In addition, make some necessary measure to make the system safe and protect from any major black out.

Objectives of the Thesis

The scope of this research is to demonstrate the advancement of the Dynamic Flowgraph Methodology (DFM) to reliability modeling of Smart Electrical Power Transmission System. This issue has become the utmost importance as deregulation and competition is invading the power industry. The reason is that the successful operation of electric power under a deregulated electricity market depends on transmission system reliability management. Analog and electro-mechanical systems in existing power system are aging and becoming obsolete. Software-based digital electronic systems for instrumentation and control are part of the design of advanced and smart electrical power system. They are being introduced more slowly into existing electrical system. This thesis also illustrates how the electrical transmission system can be modernized into smart electrical system and how we can check the reliability measures of the system. The modeling is performed subsequent to defining the configuration of new digital systems, and discussing the behavior of power flow and the architecture of smart electrical power transmission system.

Organization of the Thesis

In this thesis, reliability modeling of smart electrical transmission system is discussed and investigates the behavior of transmission system due to changes of load, power interruptions, and failure of components or aging components. After a literature review about the reliability modeling through dynamic flowgraph methodology, reliability of electrical power system in chapter 2 has been discussed. Chapter 3 is devoted for the detail components and features of smart electrical transmission system and chapter 4 explains the methodology of reliability modeling of smart electrical transmission system, its simulation and results. Chapter 5 concludes the thesis work and present recommendations for future works.

CHAPTER 1

LITERATURE REVIEW

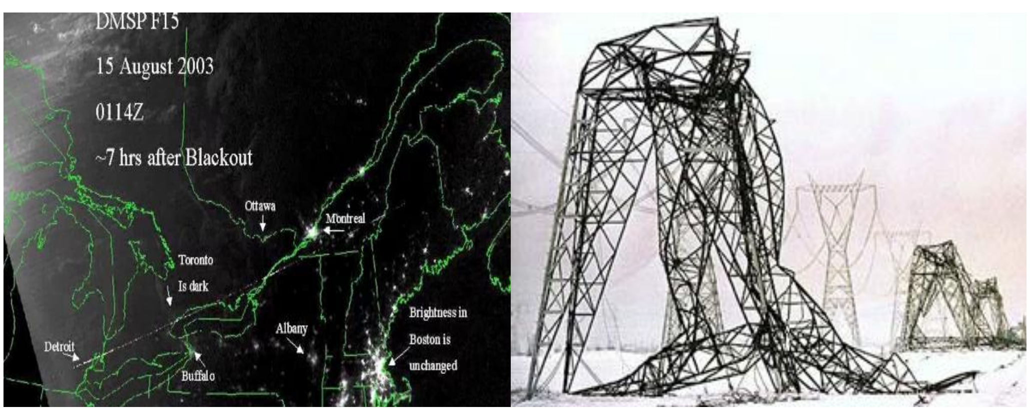
This chapter presents a review of the results found in literature in the areas of electrical power transmission system, and reliability assessment and modeling. The failure and performance degradation of the system can lead to system instability [4]. Thus, the reliability assessment is an essential feature for the electrical transmission system. The failure of control components i.e., hardware, software and communication networks high voltage breaker, transmission line breakdown, electrical component aging, system over loading, relay malfunctioning, relay disorder) is discussed herein. Methods for reliability assessment and modelling are compared. The dynamic flowgraph methodology is introduced and the reliability modelling of smart electrical power transmission system is discussed.

1.1 Electrical Power Transmission System

Continued global competitiveness and quality of life depend on a reliable power system and high-quality supply of electricity. It is also known that there is a direct correlation between economic growth and energy consumption and reliability [5]. Meanwhile after deregulation of energy sector, the utility network operator tends to focus their attention on improving the return on investment in their assets while power consumption is increasing and power delivery infrastructures are aging. In addition, shortcomings in capacity, reliability, power quality and security cost a lot of money to the economy and national security.

These considerable operational constraints have increased the amount of operators are encountering while more and more blackouts have happened in the world over the past decades. It is therefore of no surprise that automation elements and strong communication link have become increasingly important in utility investments for improving the global reliability, stability and availability of the network. A single incident might affect the performance of the entire power grid and hence thousands or millions consumers.

Much of the north-eastern United States of America and part of Canada were plunged into darkness in August 2003 when a disruption in the electric grid's complicated balance caused a massive blackout with substantial economic consequences. The North American ice storm of 1998 is a perfect example for natural disasters which vulnerable the electric grids. It caused massive damage to trees and power lines throughout the area, leading to widespread long term power outages. Figure 1.1 (a) and (b) shows the results of these incidents [6].



(a) (b)

Fig. 1.1 (a) Blackout in North America in August 2003 (b) freezing rain in Quebec, Canada, 1998

The collapse of the grid was caused in this case by a combination of human errors and technical challenges [7]. Following are some of the causes that can affect the performance of the entire electric grid.

1. Generation outages
2. Overextended controllers
3. Transmission line failures
4. Overloading of substation
5. Overloading of transmission lines
6. Voltage instability
7. The overheating of alternate transmission lines causing lines to sag into trees
8. An insufficient ability to repair or replace sensors and relays quickly
9. Poor maintenance of control room alarms
10. Poor communications between load dispatchers and power plant operators
11. Insufficient understanding of transmission system interdependencies

1.2 Reliability Assessment of Electrical Power Transmission System:

Modern society depends on uninterrupted electricity supply for sustainable development. Reliability of electricity supply, therefore, becomes a paramount element in a country's ability to organize its commerce and industry capabilities [8]. Today, industrial and commercial customers of an electric utility compete in the global market place. The customer's ability to compete in an intense free-market environment is influenced by the ability of its electricity suppliers to provide services that are of high reliability and cost effective. Increasingly, utility, industrial, and commercial customers are going to look for an electricity service that balances cost, product support, and reliability in a manner that best satisfies their individual requirements. In an electric power transmission network, a fault occurring on any one of its components sometimes causes an active event as a result of interaction between the power system and its protection system. An outage of sections adjacent to the faulted one for a small duration is characteristic of these events [9].

The reliability of an electric utility transmission system is a measure of its ability to continuously meet the demands of all its customers (i.e., points of delivery). Enhancing the supply reliability is one of planning and design targets of any utility within the constraints of capital investments, intense free-market competition, variable and higher level of customer preferences, and safety and environmental considerations [10]. The utilization of transmission system facilities is changing from its traditional role in this new deregulated era and raising significant concerns about the possible erosion of the reliability of utility transmission facilities. It has been recognized that, with the movement toward a deregulated and competitive electricity market, decisions to improve reliability will be heavily influenced by industrial and commercial customer preferences requiring service level benchmarks to be defined.

1.2.1 Definition of Reliability of Power system

The function of an electric power system is to satisfy the system load requirement with a reasonable assurance of continuity and quality. The ability of the system to provide an adequate supply of electrical energy is usually designated by the term of reliability. The concept of power-system reliability is extremely broad and covers all aspects of the ability of the system to satisfy the customer requirements. There is a reasonable subdivision of the concern designated as “system reliability”, which is shown in Figure 1.2 [11].

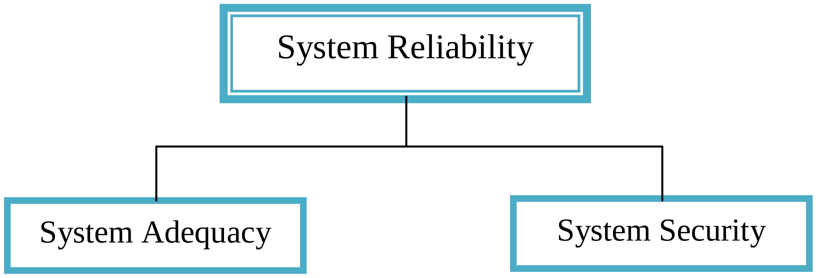


Figure 1.2 subdivision of system reliability

Figure 1.2 represents two basic aspects of a power system: system adequacy and security. Adequacy relates to the existence of sufficient facilities within the system to satisfy the consumer load demand. These include the facilities necessary to generate sufficient energy and the associated transmission and distribution facilities required to transport the energy to the actual consumer load points. Security relates to the ability of the system to respond to disturbances arising within that system. Most of the probabilistic techniques presently available for power-system reliability evaluation are in the domain of adequacy assessment.

1.2.2 Reliability issues in present utility environment

In developing countries with highly developed electrical power systems, electric power utilities are undergoing considerable change in regard to structure, operation and regulation. Normally, vertically integrated utility structure consisting of generation, transmission and distribution operational zones has in many cases been unbundling into separate and distinct utilities in which each perform a single function in the overall electrical energy delivery system [12]. It has created an environment in which the overall responsibility for serving the electrical energy needs of the individual consumer does not reside in a single utility and is difficult to assign.

In this environment, the electricity consumers will also select their supplier based on cost-effectiveness and reliability. Deregulation of energy sector does not mean that every operator will make their own complete network like, transmission line, substations and power house but they can get an energy from the existing power house or they can built their own small power house to full fill the customer demand. Requests for use of the transmission network by third parties are extending the traditional analysis of transmission capability far beyond traditional institutional boundaries. Given these significant policy shifts, the electric utility industry is moving to new planning criteria where broader engineering considerations of transmission access and risks must be explicitly addressed. In general, the new reliability related planning criteria should address the following issues:

- Uncertainties associated with deregulation, wheeling and transmission access, and disintegration of the distribution systems
- Integrated generation and transmission system modeling
- Maintaining service reliability with the planned load growth while being financially solvent
- Electrical transmission system is connected with generation and distribution and behave according to the system demand response
- Augmentation of electrical transmission is necessary in this deregulated environment according to the smart electrical transmission system
- Assessment of transmission bottlenecks
- Assessment of Information Technology (IT) in electrical transmission system for smart grid development
- Real time load flow studies for better electrical transmission system operation.

The electric power utility environment will become increasingly competitive in the future. Traditional reliability criteria based on deterministic considerations will become increasingly difficult to apply as the traditional utility functions are unbundled. This is particularly true in the system operation domain where security constraints are deterministically based. In order to appreciate the reliability issues arising in the present electric power utility environment, it is necessary to recognize the forces and actions which are shaping this environment. However, in spite of the progress over the past decades in studying the reliability of electrical transmission system, there are many areas that need to be established.

1.2.3 Methods of Reliability Modeling and Assessment

There are several methods that can be used to model and assess the reliability of systems. The choice of the method depends on the several modelling requirements. The most commonly used methods are:

- Dynamic fault trees
- Markov models
- Petri nets

Dynamic fault tree: Dynamic fault trees use timed house events or functional dependency gates to represent the time-varying dependencies between basic events. Quantification of dynamic fault trees is performed using time-dependent Boolean logic or markov models. Application of dynamic fault trees mostly includes computer-based systems, including mission avionic systems. Dynamic fault tree are able to model the sequencing of events in system evolution and have been used to model fault tolerance systems. However it is not clear that they can be used to model differences in system behaviour that depend on the exact timing of failure events [13].

Markov models: It is a well established method for modelling systems and has been used by the process industry to model digital systems. It has been used in modeling non-digital systems at NPPs, but its integration with existing PRA models may not be straight forward. It is suitable for modeling digital system features, such as fault detection, recovery, and reconfiguration, by assuming that software works perfectly [14]. Its capability to capture the contribution of software failures to system reliability is limited.

Perti-Nets: The Perti-Net method has been used as a modelling method for the behaviour of software. The advantage of Petri-Net is its case of modelling the behaviour of a dynamic system. A petri-net model can be analyzed to show the presence or absence of safety properties, such as hazardous conditions, system deadlock, or unreachable states. The method has been used as a tool for an FMEA to identify failure and their effects. It has not been commonly used by the nuclear industry but has been used for reliability modelling of computer-based system.

Current Probabilistic Safety Assessment (PSA) analytical tools that assess the safety of safety-critical systems typically involve fault tree analysis, often in combination with other methods such as event trees, Markov models and reliability block diagrams [15, 16]. Due to the deregulation of energy sector, the capability and reliability related issues of PSA tool are in hot water. This is due to the facts that the improvement of present transmission system, authorities or operator should do some development or move towards smart electrical transmission system then the question is either this PSA tools will full fill the requirement for reliability assessment or system will demands some other method. Hence, smart electrical transmission system is going to be new shape of present system must be able to interface with the current PSA tools which dictate the finding of methods to address system reliability with the current PSA tools. Smart electrical transmission system will be more complicated and integrated with renewable energy resource, which needs more reliability and safety measures.

1.2.4 Requirement of Reliability Modeling

The modelling methodology is chosen based on specified requirements. The requirements specified for modelling electrical transmission systems are listed as follows [17]; Requirements:

1. The model must be able to predict future failure well.
2. The model must account for the relevant feature of the system under consideration.
3. The model must make valid and plausible assumptions.
4. The model must quantitatively be able to represent dependencies between failure events accurately.
5. The model must be designed so it s not hard for an analyst to learn the concept and it is not hard to implement.
6. The data used in quantification process must be credible to a significant portion of the technical community.
7. The model must be able to differentiate between a state that fails one safety check and those that fail multiple ones.
8. The model must be able to differentiate between faults that cause function failures

and intermittent failures.

9. The model must have the ability to provide relevant information to users, including cut sets, probabilities of failure, and uncertainties associated with the results.
10. The methodology must be able to model the digital system portions of accident scenarios to such a level of detail and completeness that non digital system portions of the scenarios can be properly analyzed and practical decision can be formulated and analyzed.
11. The model should not required highly time-dependent or continuous plant state information.

1.2.5 Comparison of Different Modeling Methodologies

Table 1.1 provides details on the satisfaction of the requirements mentioned above when applying some of the methods for reliability modelling of electrical transmission system and smart electrical transmission system [18].

Methodology/Requirement	1	2	3	4	5	6	7	8	9	10	11
Continuous event Trees	X	X	X	X	O	?	?	X	?	?	O
Dynamics Event Trees	X	X	X	?	X	?	?	?	X	X	O
Markov Models	X	X	X	X	O	?	X	X	X	X	O
Petri Nets	X	X	X	X	O	?	?	?	X	X	O
Dynamic Fault Trees	X	?	?	?	X	?	X	?	X	?	X
Dynamic Flowgraph Methodology	X	X	X	?	X	?	?	?	X	X	X
Event Sequence diagram	X	X	X	X	O	?	?	?	X	X	O
GO-FLOW	X	?	X	?	O	?	?	?	X	X	X

Table 1.1 Reliability Modeling Methodologies and Requirements

In the table 1.1, ‘X’ indicates that model comply with the requirement, ‘O’ indicates that model is not fulfilling the requirement and ‘?’ indicates that it is not clear or further research is required to confirm about that feature. As can be noted, no single method satisfies all requirements. Each method is associated with its own advantages and disadvantages. The methods that rank as top three with most positive features and least negative or uncertain features are the dynamic flowgraph methodology, dynamic event tree approach or Markov approach and event sequence diagram [19].

Although fault trees and reliability blocks diagrams are the easiest and most often techniques which are in use of complex systems reliability assessment. These techniques are Boolean models and thus their aim is to show how a binary system’s two states depends on the binary states of the systems components. In additions, those methods assume components independence and hence they are not suited to modelling systems in which there are dependencies between components [20]. As many researchers have refined the static techniques for use in various industries, including aerospace, medical, and nuclear, efforts must be made to modify the dynamic techniques for integration in the current probabilistic safety assessment tools.

1.3 Reliability Modeling of Electrical Power Transmission System:

Due to the different perspectives that traditional and electric power systems maintain with regard to system reliability evaluation, this research has devoted research efforts to develop electric power reliability models for any configuration as long as the failures for the system are specified. There are different types of failure categories; some of them are permanent, switching and transient system failures. The present work focuses on the reliability modeling of permanent and switching system failures of electricity transmission systems. Importance measures are important tools to evaluate and rank the impact of individual components within a system. For electricity transmission systems, previously developed measures do not meet all user needs. For this reason, there is a need for criticality measures that evaluate, in a more accurate way, the reliability modeling of electricity transmission systems. In the present research, we are developing new criticality measures that can be used in this type of reliability assessment modelling.

1.4 The Dynamic Flowgraph Methodology (DFM)

The dynamic flowgraph methodology is a digraph or directed graph based approach to model and analyze the behaviour and interaction of software and hardware within an embedded system for the purpose of safety and reliability assessment and verification [21, 22]. The dynamic flowgraph methodology has been mainly applied in modelling software driven control systems. It was also presented as an approach to model an operating team, where the performance of individuals in the team and their interaction with the system hardware was modeled [23]. In the DFM approach, system models are developed in terms of causal relationships between physical variables and temporal characteristics of the execution of software modules. The DFM model can also capture time dependent behaviour and switching logic. When modelling a digital control system, both the controlling software and the system being controlled can be represented in the DFM model [24]. The methodology has two fundamental goals [25]:

- To provide an integrated hardware/software model of the system
- To identify how certain critical events of interest may occur

Although DFM is based on digraphs, it shares more similarities with the state machine approach. Instead of using static models with continuous partial derivates to model the relationships between process variables, the system state is dynamic and state transitions are expressed using decisions tables. The difference is that DFM also models the system hardware (including failure behaviour) and operating environment in addition to software [26].

1.4.1 Model elements

The DFM uses a set of basic modeling elements to represent the system parameters and their relationships as described and shown in Figure 1.3 below.

1. Process variable and conditioning nodes,
2. Causality and conditioning edges,
3. Transfer and transition boxes,

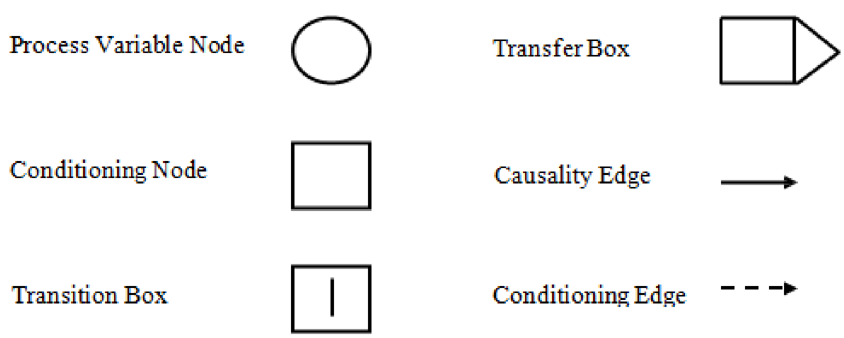


Figure 1.3 DFM Modelling Elements

Through use of directed graphs, with relations of causality and conditional switching actions represented by edges that connect nodes and operators in the diagrams, a DFM model integrates three types of network. The Time-Transition Network (TTN) describes the sequence in which software modules i.e. subroutines are executed, the Causality Network (CN) shows the functional relationships among key hardware and software parameters, and the conditioning network models discrete software behavior caused by conditional branching or discontinuous hardware performance due to components failure. The building blocks of these networks include process variable nodes, condition nodes, causality edges, condition edges, transfer boxes, transition boxes and their associated decision tables.

Process variable nodes are used to represent essential physical or hardware variables of the digital system. Like process variable nodes, condition nodes represent physical or software parameters that identify components failures, changes of process operation regimes and modes, or software conditional branching. Condition nodes can be associated with transition for this purpose. Causality edges are employed to connect process variables nodes which have a cause-and-effect relationship between the variables. Condition edges are used to model discrete behavior of the system. They think parameters nodes to transfer boxes, showing the possibility of using a different transfer function to map input variable states to output variable states. A transfer box models a transfer function between process variables nodes. In spite of indicating a cause-and-effect relationship similar to that of a transfer Box, a transition box differ from a transfer box in that a time delay for the transition is assumed to exist between the time when the input variable states become true and the time when the corresponding output variable states are reached. As an extension of a truth table, a decision table allows each variable to be represented by any number of states, instead of being limited to the binary logic of 0 (false) and 1 (true). The decision table is constructed from empirical knowledge, physical equations, logic relations, software, or pseudo code.

1.4.2 Model Construction

The modelling strategy is a two step process: construction of a model and analysis of the constructed DFM model. The construction of DFM models is performed using a detailed multi-state representation of the cause-and-effect and time-varying relationships that exist between key system parameters. The nodes represent the system parameters, components or variables. They are discretized into a finite number of states and therefore represent more than just an operative or failed scenario. For example, a node can represent a range of operating pressure reading. The process variable nodes are used to represent physical or software parameters. The condition nodes are used to identify component failure states, software switching actions and changes of process operation modes [27]. The edges are used to visually represent the type of relationships that exists between parameters (i.e., cause-and-effect or conditioning relationship). Transition boxes and transfer boxes are used to express the detailed representation of the function and temporal relationships that exist among parameters states. Transition boxes differ from transfer boxes in that a time lag is assumed to occur between the times when the input variable states become true and the time when the output variable states are reached [28]. The boxes contain decision tables that are used to incorporate a multi-state representation of the relationships that exist among the parameters. Decision tables are a mapping between possible combinations of the input states and output process variable nodes. They can be implemented from empirical knowledge of the system, physical equations that describe the behaviour of the system, or software code and/or pseudo code [29].

A model is always a compromise between faithfulness and simplicity. A model can be very detailed to represent all the system behaviour and dynamics, yet at the same time, can be intractable. Thus, assumptions should be made to simplify the model, while leaving it relatively faithful and tractable [30]. In other words, careful selection of the number of states should be made while maintaining sufficient amount of information in order to capture more details of the behaviour of the system.

1.4.3 Model Analysis

The second step involves the analysis of the constructed model. Once the model is set up, one can use the DFM analysis engine to automatically search for prime implicants of a given top event. A typical execution of a DFM analysis is a two-step process. The two basic steps are:

Step 1 Build a model of the system for which a safety analysis is required. The model consists of both the controlling software and the entities being controlled. Multi-valued logic relations are used to discretized continuous domain quantities, including time;

Step 2 Use the model development in step 1 to systematically search for the prime implicants of a top event, describe or undesirable, depending on the objectives of the analysis.

This allows for identification of the modes by which specific system and process failure states can take place. An implemented DFM model can be analyzed by tracing sequences of events inductively and/or deductively through the model structure. This identifies the paths by which combinations of basic events can propagate through the system to result in system events of interest, whether desirable or undesirable. The DFM Software Toolset allows for performing the deductive and inductive analysis of an implemented DFM model.

The inductive DFM analysis follows a bottom-up approach. It is performed by specifying a set of component states and then investigating the propagation through the system and finding the influence on the system state level of interest. The deductive DFM analysis follows a top-down approach. It is performed by specifying a state of interest and finding the combination and sequences of parameters that lead to the specified state. When performing deductive analysis, timed prime implicants can be found. A prime implicant is defined as a conjunction of primary events which are sufficient to cause the top event and which does not contain any shorter conjunction of the same events which is also sufficient to cause the top event [31]. Prime implicants can be helpful in identifying unknown systems hazards, prioritize the disposition of known systems hazards, and guide lower-level design decisions to eliminate or mitigate known hazards [19]. In addition, timed fault trees can be derived for any top event to visually represent the combination and sequences of events that lead to the occurrence of the specified top event. In the inductive and deductive DFM analysis, the model is analyzed by automated forward- and back-tracking procedures, respectively. The analysis can be continued for several steps forward or backward in time. The information associated with each step is presented in the form of intermediate transition tables. Transition tables are logically equivalent to gates in a time-dependent fault tree. The deductive DFM analysis shares key conceptual features with traditional fault tree analysis. However, DFM uses a multi-state and time dependent representation of system and parameter conditions. In addition, timed fault trees, derived using DFM deductive analysis, systematically and formally account for the timing relations between system and parameter states. DFM is reported to offer major advantages over conventional safety and reliability methods. It represents the capabilities of FMEA, FTA and HAZOP in one tool [32]. Only one DFM model is needed to capture the complete behaviour of a system. A model can be used for performing failure analysis, verifying design requirements and defining test cases. In addition, a model provides the capability of executing the equivalent of a large number of fault tree derivations for different possible top events of interest. Thus, it is not necessary to perform separate model construction for each system's state of interest. The DFM approach provides a documented model of the system behaviour and interactions as well as a framework to model and analyze time-dependent behaviour [33].

1.5 Chapter Summary

The chapter provided literature review of electrical transmission systems and their reliability assessment. Methods for reliability assessment transmission system were compared. The dynamic flowgraph methodology was introduced and the advantages of the method were discussed. In addition, the features that should be provided by reliability assessment methods were listed. The following chapter demonstrates the extension of the dynamic flowgraph methodology to modelling of smart electrical transmission systems.

CHAPTER 2

DESCRIPTION OF METHODOLOGY

Modern power system is required to become smarter in order to provide an affordable, reliable and sustainable supply of electricity. Under such circumstances, considerable activities have been carried out in the world to formulate and promote a vision for the development of the future smart power grid [34]. However, the majority of these activities only placed emphasis on the distribution grid and demand side; while the big picture of the transmission system in the context of smart grid is still unclear and need a lot of explanation and work. This smarter grid is the integration of new technologies that allow utilities and manufacturers to rethink the design and operation of electrical power systems which can be then called as smart electrical power system.

We are giving a name of Smart Electrical Power System (SEPS) which is one step ahead of smart grid due to the reason that it has generation, transmission, distribution and load end. These systems transmit electricity directly from producers to consumers by combining digital technology incorporated into the entire smart electrical power system, and this, from generation to transmission via distribution, while improving efficiency, quality and reliability services and reducing costs through the use of smart components and equipments designed to optimize power consumption.

Figure 2.1 (a) shows a present electrical network with a centralized and unidirectional flow of electricity. Figure 2.1 (b) and (c) shows fault after power generation and transmission station. There will be no power after these fault points if some fault happened on these points. In addition, this fault can also affect the source of the system, because fault always travels back. At that time, the Protection and Control (P&C) of the system should be strong enough and control coordination should be in perfect state.

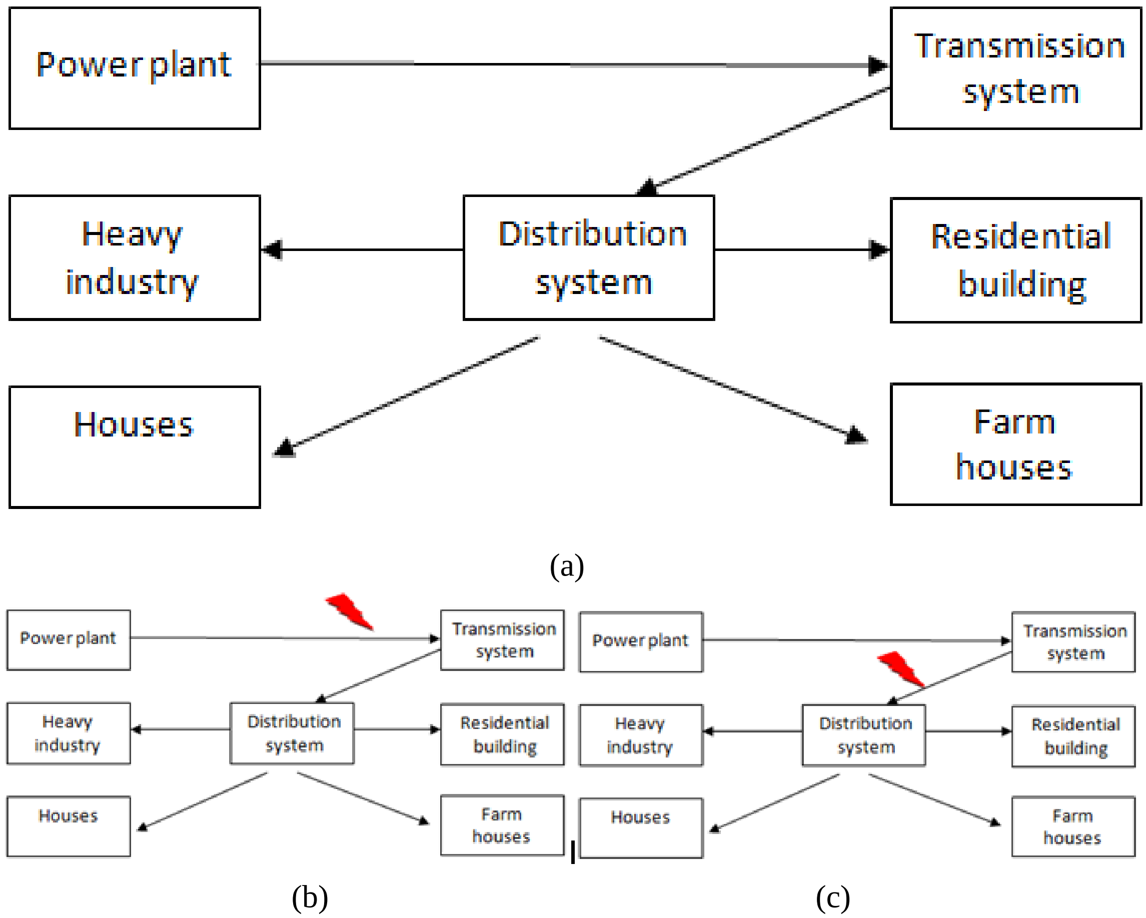


Figure 2.1 (a) Present unidirectional centralized electricity networks, (b) and (c) fault indication in present unidirectional network.

Figure 2.2 present a bidirectional network with integrated dynamic power flow and data management with a need for information in real time. Yellow lines shows flow of electricity and blue solid lines represented a strong communication link to make a smart system. This creates the need to develop and implement new tools and equipment to help operators to improve the operation and safety of their electrical systems. If we updated our 21st century power grid with 21st century technology then this advancement will be called as smart electrical power system. Figure 2.1 (a) and 2.2 differentiate the conventional electrical power system and smart electrical power system which is a strong communication link between every component from generation to end user.

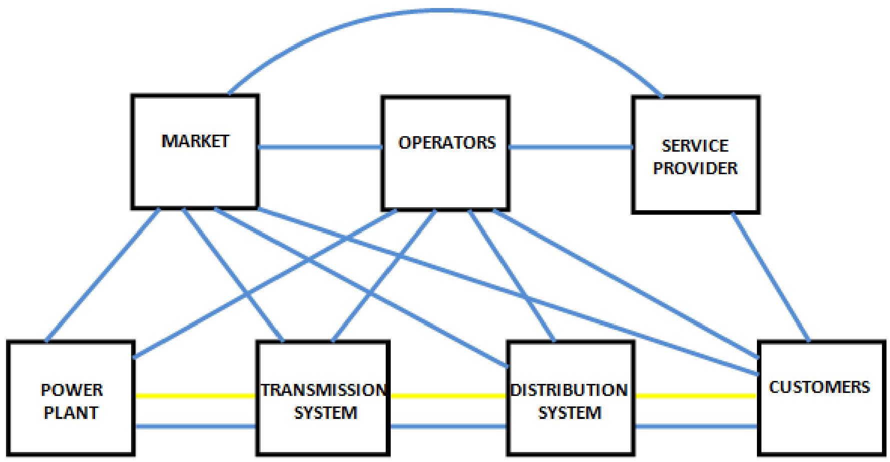


Figure 2.2 Future bi-directional dynamic flows of energy and data

2.1 Smart Electrical Transmission System (SETS):

This vision of the smart electrical transmission system is built on the existing electric transmission infrastructure. However, the emergence of new technologies, including advanced materials, power electronics, sensing, communication, signal processing, and computing will increase the utilization, efficiency, quality, and security of existing systems and enable the development of a new architecture for transmission networks. This electrical transmission network has a capability of bidirectional network integrating dynamic power flow and data management with a need for information in real time. This creates the need to develop and implement new tools and equipment to help operators to improve the operation, safety, and reliability of their electrical systems. This can only be realistic and possible to implement with the assistance of new technologies such as

Global Positioning System (GPS), high speed communications e.g. wireless, Ethernet, Power Line Communication (PLC), etc.

Figure 2.3 shows a communication network of generation, substation, transmission system, and control centers. There are three major units of smart electrical transmission system;

1. Smart electrical power transmission network
2. Smart transmission substation
3. Smart transmission control center

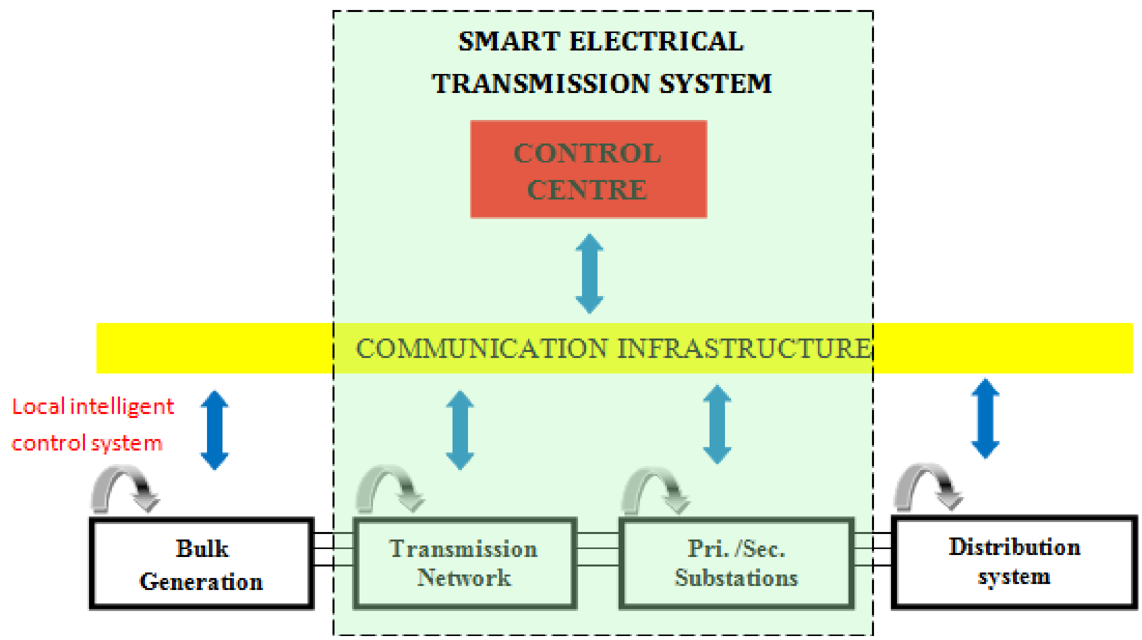


Figure 2.3 Centralized network having communication sources for SETS

2.1.1 Smart Electrical Power Transmission Network

Smart transmission network is a basic component of smart electrical power system and this smartness comes with the integration of advanced communication technologies, modern electrical equipments, best sensing products, high quality power electronics devices, and computing system which enhance the efficiency, quality and security of the present system and allow the operators to develops a new architecture for smart transmission network. This transmission network should have the following feature to become a smart transmission network;

High quality and efficient transmission network: Smart transmission networks will be enabling to interconnect extra high-voltages, high-capacity transmission corridors. This will be done for balancing electric supply and demand on a national basis. Within each regional interconnection, long-distance transmission is accomplished by using controllable high-capacity AC and DC facilities. In smart transmission network, underground cables will be use where difficult to transmission power through overhead bare conductor like sea span or urban area. Good quality having high-temperature composite conductors for overhead transmission and high-temperature superconducting cables, needed to be widely used for electricity transmission. These conductors have the properties of greater current-carrying capacity, lower voltage drops, reduced line losses, lighter weight, and greater controllability. In addition, new transmission line configurations, e.g., 6- or 12-phase transmission line configurations, allow for greater power transmission in a particular right-of-way with reduced electromagnetic fields due to greater phase cancellation.

Transmission Reliability and Controllability: The advanced Flexible AC Transmission Systems (FACTS), High-Voltage DC (HVDC) devices, and other power electronics-based devices can be facilitating the transmission network for flexibility and reliability. FACTS devices can improve the dynamic performance and stability of the transmission network. By the addition of these devices in transmission network, we can enable to increase power transfer levels without new transmission lines [35, 36]. Through the utilization of power electronics advance technologies the future smart transmission grids should be able to maximally relieve transmission congestions, and with the trend of increasing penetration of large-scale renewable/alternative energy resources, the future smart transmission grids should be able to enable full integration of these resources.

HVDC lines are widely used to provide an economic and controllable alternative to AC lines for long distance and high-capacity power transmission and integration of large wind farms. Solid-state transformers are used to replace traditional electromagnetic transformers to provide flexible and efficient transformation between different voltage levels [37]. Solid-state circuit breakers are used to replace traditional mechanical breakers. These solid-state devices are free from arcing and switching, and offer reliability and longer lifetimes as well as much faster switching times [38].

Maintenance of Transmission facilities: In the smart transmission networks, reliability, flexibility and controllability of system is a major issue. For that purpose, live-line maintenance can be used to clean and melt conductors, clean and lubricate moving parts that open and close, replace spacer/dampers, disconnect/connect breakers, tighten or replace bolts, and install sensors and measuring devices. This reduces disastrous failures and maintenance costs, and improves the overall reliability of the transmission system.

Robust Transmission and self healing system: Smart transmission networks will extensively incorporate advanced sensing, signal processing, and communication technologies to monitor operating conditions of transmission lines, transformers, and circuit breakers in real time [39]. A cost-effective distributed power line condition monitoring system, based on a distributed power line wireless sensor net in which each distributed intelligent sensor module incorporates with advanced signal processing and communication functions, is able to continuously measure line parameters and monitor line status in the immediate vicinity of the sensor [40]. They are critical for line operation and utilization, including measurement of overhead conductor sags, estimation of conductor temperature profile, estimation of line dynamic thermal capacity, detection of vegetation in proximity to the power line, detection of ice on lines, detection of galloping lines, estimation of mechanical strength of towers, prediction of incipient failure of insulators and towers, identification of the critical span limiting line capacity, and identification of the fault location of the line. Besides the present protection system of power transformers, a sophisticated transformer monitoring system is able to monitor health and efficiency, measure dissolved gases-in-oil, and load tap changers of transformers in real time. A circuit breaker monitoring system is able to measure the number of operations since last maintenance, oil or gas insulation levels, and breaker mechanism signatures, and monitor the health and operation of circuit breakers in real time. Based on the parameters and operating conditions of transmission facilities, it can automatically detect, analyze, and respond to emerging problems before they impact service; make protective relaying to be the last line of defense, not the only defense as it is today; quickly restore the faulty, damaged, or compromised sections of the system during an emergency; and therefore enhance dynamic and static utilization and maintain the reliability and security of the transmission system.

2.1.2 Smart Electrical Substation

The smart electrical substation idea is built on the existing widespread automation technologies of substations. It should enable more reliable and efficient monitoring, operation, control, protection, and maintenance of the equipment and apparatus installed in the substations. To achieve these goals, the major characteristics of a smart substation shall include the following.

Smart Sensing and Measurement: The smart substation provides a unique and compatible platform for fast and reliable sensing, measurement, communication, control, protection, and maintenance of all the equipment and apparatus installed in a variety of substations. All measurement signals will be time stamped with high accuracy by using a Global Positioning System (GPS) signal. The Remote Terminal Unit (RTU) function will be replaced by a Phasor Measurement Unit (PMU) in the future. The traditional electromechanical Current Transformer (CT) and Potential Transformer (PT) will be replaced by an optical or electronic CT and PT whose advantages include wide bandwidth, high accuracy of measurement, and low maintenance costs [41].

Communication system: The operation of the smart substation does not depend upon the control centers and other substations, but they can communicate with each other to increase the efficiency, stability, and reliability of power transmission. Within a substation, the operation of individual components and devices is also autonomous to ensure fast and reliable response, especially under emergency conditions. Each smart electrical substation has its own high-speed Local Area Network (LAN) which ties all measurement units and local applications together.

Control coordination and Adaptive Protection system: The smart substation should be ready and find it easy to communicate and coordinate with other substations and control centers. Adaption of protection and control schemes should be achieved under coordination of control centers to improve the security of the whole power grid. One important step is that the settings of protective relays can be remotely modified in real time which helps the smart substation to serve as an intelligent unit of Special Protective Schemes (SPS) to improve the reliability of the power grid [42, 43].

Monitoring and alarm/indication system: Advancement in communications enables remote operators to be informed immediately of equipment status changes and trips. Traditionally, these common devices, such as battery chargers, UPS systems, and fire alarm systems, alarm a fault condition locally; but unless a substation visit is performed, the fault may go undetected for extended periods. Ignoring these faults could cause more disastrous failures to occur. An increasing amount of data about failures in system is gathered which helps to develop a more secure operational schemes and help to find the root causes of the faults.

Self healing: The smart substation is able to reconfigure itself dynamically to recover from attacks, natural disasters, blackouts, or network component failures. A smart substation should be based on a self-healing communication network to significantly improve the reliability of monitoring and control of substations.

Advance Interfaces: Smart electrical substations should provide advanced power electronics and control interfaces for renewable energy and demand response resources so that they can be integrated into the power grid on a large scale at the subtransmission level. By incorporating microgrids, the substation can deliver quality power to customers in a manner that the power supply degrades gracefully after a major commercial outage, as opposed to a tragic loss of power, allowing other installations to continue operations. Smart electrical substations should have the capability to operate in the islanding mode taking into account the transmission capacity, load demand, and stability limit, and provide mechanisms for seamlessly transitioning to islanding operation.

2.1.3 Smart Electrical Control Center

The vision of the future smart electrical control centers is built on the existing control centers originally developed approximately a half-century ago. The expected new functions, such as monitoring/ visualization, analytical capability, and controllability of the future control centers, are discussed in this section.

Monitoring and Visualization system: The present monitoring system in a control center depends on state estimators, which are based on data collected via *Supervisory Control And Data Acquisition* (SCADA) systems and Remote Terminal Units (RTUs). In the smart control center, the system-level information will be obtained from the state measurement modules based on Phasor Measurement Units (PMUs) [44]. The PMU-based state measurement is expected to be more efficient than the present state estimation since synchronized phasor signals provide the state variables, in particular, voltage angles. As a comparison, the present state estimation demands additional running time and is less robust, since the data collected from the RTUs is not synchronized and significant effort must be made for topology checking and bad data detection.

The present visualization technology displays the system configuration with one-line diagrams that can illustrate which buses are connected with a specific bus. However, it is not exactly matched to the geographic location. In addition, it is typical that only buses in the control area, together with some boundary buses, are displayed in the monitoring system. In the future, the results from state measurement shall be combined with a wide-area Geographical Information System (GIS) for visual display on the screens of the control center. The wide-area GIS shall cover a broad region including the control center's own service territory as well as all interconnected areas. Since the future visualization and monitoring technology will cover a much broader scope, an increased information exchange is needed. In smart control center, the communication channels are expected to be more dedicated such as employing a fiber optic network for communications with Quality of Service (QoS) implemented. Not surprisingly, this also demands a unified protocol for better communications among different control areas. Wide-area GIS data based monitoring system will help to monitor voltage stability margin and frequency wave on the top of the actual map in real time. Another noteworthy technology can be the alarming system. The present technology typically presents alarming signals without priority. The smart control centers should be able to provide the root cause of possible problems to enable the operators to provide closer monitoring.

Protection and control system: In the present control centers, the ultimate control action, such as separation, is taken based on offline studies. In the smart control center schemes, the system separation will be performed in real time to better utilize the dynamic system condition. Similarly, the present restoration plan based on offline studies should be replaced with online restorative plans. Presently, the protection and control settings are configured as fixed values based on offline studies. In the smart control schemes, these settings should be configured in real time in a proactive and adaptive approach to better utilize the generation and transmission asset when the system is not stressed and to better protect the system under extremely stressed conditions. The present technology lacks the sufficient coordination of protection and control systems. Each component takes actions based on its own decision. This uncoordinated control could lead to an overreaction under the present contingency plan. The smart control centers shall have the capability to coordinate multiple control devices distributed in the system such that optimal coordination can be achieved simultaneously for better controllability.

Analytical Capability: The present online analytic tool in control centers typically performs steady-state contingency analysis. Each credible contingency event is analyzed using contingency power flow studies allowing line flow violations to be identified. In the smart control center, it is expected that online time-domain-based analysis, such as voltage stability and transient angular stability [45], should be available. In addition, online small-signal stability analysis is expected. The present analysis is based on predefined generator and transmission models. This does not represent the real-time dynamic characteristics of the system. Therefore, the online analysis in the control center shall perform dynamic model update and validation. The updated and validated data will be used for the online stability analysis previously mentioned. The present technology is for the online security analysis for the next operational time interval, such as every 5 min. In smart control center, online analysis is expected to have look-ahead simulation capability so that future system conditions will be considered. Then, possible short- to midterm strategic actions can be considered. Several other factors should be addressed. For instance, the present technology generally applies N-1 contingency in a deterministic approach. In the future control centers, credible N-x or cascading failures should be considered with a probabilistic approach for security risk analysis.

Architecture and Data flow Process: The data flows required to perform real-time control at a Control Centre location are shown in Figure 2.4. The data which is stored in the control centre location vary from location to location but portions of the data must be made available to the connecting stations.

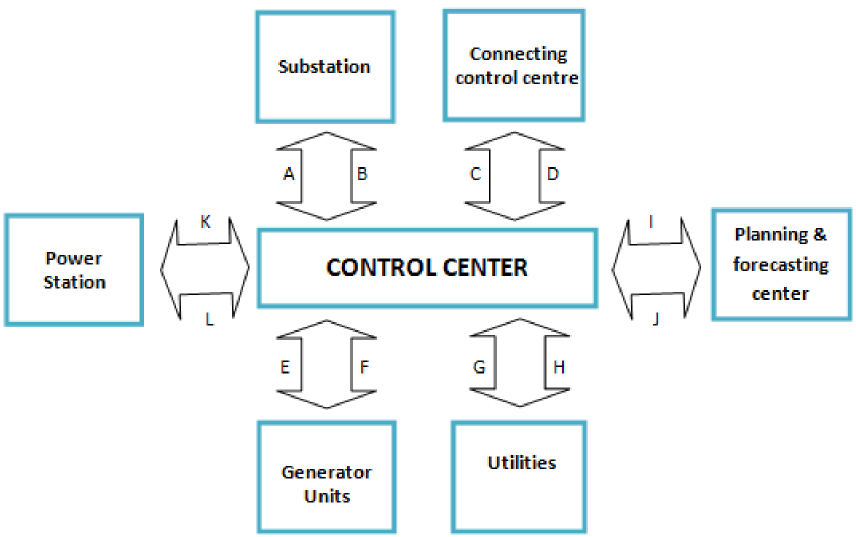


Figure 2.4 Architecture and data flow model of smart control center

In the above model, A to L shows their functions that these stations are performing. For example; A is a list of data that substation has to send to the control centre and B is a list of data that control center need to send, in a response of A or in a routine matter. Here is a list of some communication of data from substation and control center;

A) Line substations to the control center

1. Line flow at each tie line metered with pulse accumulator (MWH).
2. Voltage level at substation (KV)
3. Circuit breaker positions at substation (Open/closed)
4. Substation and communication system alarms (Various)
5. Power flow data of each transmission line at substation (MV/ MVAR)

B) Control center to line substations

1. Command to change a tap position of transformer (N/R/F)
2. Commands to open/close a circuit breaker or switch (Open/Close).
3. Recording of data of transmission line and substation

C) Connecting Control Center to (Main) Control Center

1. Hourly Load flow data, system information (MW/MV/MVAR).

D) (Main) control center to connecting control center

1. Hourly projection for next hour/day from load and contingency hazards (MW/MV/MVAR)
2. Emergency assistance request to reserve sharing system (MW)
3. Verification of network interchange schedule (Time, MW)
4. Establish short/long notice revised schedule (MW, Time)

E) Generator Units to Control center

1. Generator unit output (MW and MVAR).
2. Generator unit auxiliary loads (MW).
3. Substation and communication system alarms (Various)
4. Problem notification (date/Time, MVAR, MW)

5. Maintenance schedule notification (Date/Time)

F) Control center to Generator unit

1. Recording of hourly/daily data (MW,MVAR, Date/Time)
2. Preparation and scheduling for backup power from other units in case of shutdown of units for maintenance (MW, MVAR)
3. Notification of utilities, substations (Date/Time, MW, MVAR)
4. Action on problem and make a alternate arrangement if necessary

G) Utilities to control center

1. Hourly load forecast for the next day (MW, Hours, Location)
2. Hourly generation unit dispatch for next time (Unit, MW, MVAR)
3. Schedules for approved interchange transaction (MW, Date/Time)
4. Schedule for maintenance work (Date, Time)
5. Increase/Decrease of demand (MW, MVAR)
6. Voltage variation problem (KV, locations)

H) Control center to Utilities

1. Recording of load forecast and make a schedule for next day (MW, Hours, Location)
2. Approval and notification for interchange transaction (MW, Date, Time, Location)
3. Make an arrangement for increase demand (MW, MVAR)
4. Command to the tap changer of specific substation for voltage (N/R/F)

I) Planning and forecasting department to control center

1. Request of data for next month/year planning (MW, MVAR)

2. Scheduled maintenance outage plans for generation resources (Unit, MW, Date/Time).
3. Scheduled maintenance outage plans for transmission facilities (Line, Date/Time).

J) Control center to P&F department

1. Exchange of data (MW,MVAR)
2. Command to the specific area about the schedule (Unit, Date, Time)

K) Power station to Control Area control center

1. Voltage level at substation (KV)
2. Circuit breaker positions at substation (Open/closed)
3. Substation and communication system alarms (Various)
4. Power flow data of each transmission line at substation (MV/ MVAR)

L) Control Area control center to bulk power substation

1. Command to change a tap position of transformer (N/R/F)
2. Commands to open/close a circuit breaker or switch (Open/Close).
3. Recording of data of transmission line and substation

2.2 Challenges of Smart Electrical Power System

The electrical power transmission grid has been progressively developed for over a century and it was the development of human society and economic needs that continuously drove the revolution of transmission grids stage by stage with the aids of the innovative technologies. As the backbone to deliver energy from generation to end user, the need of transmission grid revolution has been highly recognized to deal with more diversified challenges than ever before.

2.2.1 Infrastructure Challenges

The existing infrastructure for electricity transmission has been suffering of aging components and insufficient investments. With the pressure of increasing load demands, the network congestion is becoming worse. The fast online analysis tools, wide-area monitoring, measurement and control, and fast and accurate protections are highly needed to improve the reliability of the networks and demand of SETS. Increasing competition in power market requests highly transparency and liberty, which needs the technical supports of the transmission grid operation, mature market regulation and policies. Customer satisfaction with high quality/price ratio and freedom to interact with the grid in electricity consumption becomes more important.

On one hand, the innovative technologies, including new materials, advanced power electronics, communication technologies, etc, are not yet mature or commercially available for the revolution of transmission grids; on the other hand, the existing grids lack enough compatibility to accommodate the implementation of spear-point technologies in the practical networks.

2.2.2 Technical Challenges

Power transmission systems also suffer from the fact that intelligence is only applied locally by protection systems and by central control. In some cases, the central control system is too slow, and the protection systems are limited to protection of specific components only. To add intelligence to an electric power transmission system, we need to have independent processors in each component and at each substation and power plant. These processors must have a robust operating system and be able to act as independent agents that can communicate and cooperate with others, forming a large distributed computing platform. Each agent must be connected to sensors associated with its own component or its own substation so that it can assess its own operating conditions and report them to its neighboring agents via the communications paths. Thus, for example, a processor associated with a circuit breaker would have the ability to communicate with sensors built into the breaker and communicate those sensor values using high-bandwidth fiber communications connected to other such processor agents.

2.2.3 Environmental Challenges

Traditional electric power production, as the largest man-created emission source, must be changed to mitigate the climate change [46]. Also, a shortage of fossil energy resources has been foreseen in the next few decades. Natural catastrophes, such as hurricanes, earthquakes, and tornados can destroy the transmission grids easily. Finally, the available and suitable space for the future expansion of transmission grids has decreased dramatically. Policy makers are facing difficulties regarding integration of electrical grid and making policies about smart transformation of electrical system. In modern electrical power system, all generating unit will connect with each other and demand will be cleared out through combined source. Penetration of solar energy wind energy, hydel energy etc have many problems to move straight forward towards smart system. If we need an electricity demand in an area where there is no source or not enough sources of wind, solar, or hydel then operator have to construct a long costly line up to their customer. On the other side, there is lot of wind, solar, nuclear, hydel source in an area but not enough customers to full fill the cost of the power plant then it will be an expensive issue.

2.3 Chapter Summary

This chapter explains in detail about the smart electrical transmission system. We have divided this smart electrical system into three part; smart power transmission network, sub-station, and control centre and explain their details. In addition, also mentioned some challenges with this transmission system. The following chapter demonstrates the reliability analysis of smart electrical transmission system and modelling by using dynamic flowgraph methodology.

CHAPTER 3

RELIABILITY ANALYSIS AND MODELLING OF SMART ELECTRICAL TRANSMISSION SYSTEM

The starting point of any analysis of power system is the computation of complex voltages at all the busses. Once the complex voltages have been computed the power coming out of a bus and the power flowing in all the transmission lines can be calculated. Load flow analysis is a computational tool for this purpose. Load flow is normally used in planning studies when a power network is being laid or when a power network is undergoing expansion. Before doing load flow analysis, we need to model the entire network with all the generators, loads, and transmission lines. A power network is composed of transmission lines (conductor/cable), transformers, reactors, loads and generators. In smart electrical transmission system, communication network is also a major component.

Reliability is one of the most important criteria which must be taken into account during the design and planning phases of a power system. This need has resulted in the development of comprehensive reliability evaluation and modelling techniques [47]. A major issue in reliability modelling is how to compose hardware reliability, software reliability and timely correctness to arrive at a reasonable system's reliability model [48]. Reliability modelling of systems using the dynamic flowgraph methodology offers many advantages over other reliability modelling methods. The use of DFM allows modelling of systems as a whole. The method can be used to capture the behaviour and interactions of the hardware and software components of systems. It allows the incorporation of multistate systems and time dependency into the analysis. One DFM model can be used to study different events of interests. The modelling technique provides the following capabilities:

- Modeling of system behaviour
- The ability to deal with the dynamic aspects of the system; since the time transition are often present in the software and hardware of the embedded system;
- Investigation of the effect of components reliability
- The ability to identify and represent the continuous physical and the discontinuous logic influences present in the system, i.e., use of multi-valued logic.

This chapter is giving us a demonstration about the extension of the methodology to the modelling of smart electrical transmission system. Figure 3.1 shows the schematic of a Smart Electrical Transmission System (SETS). The system consists of a control centre, generating station, sub-station, transmission network, and distribution system. They are arranged and programmed to operate according to their set values. They are also communicating with each other through a communication network.

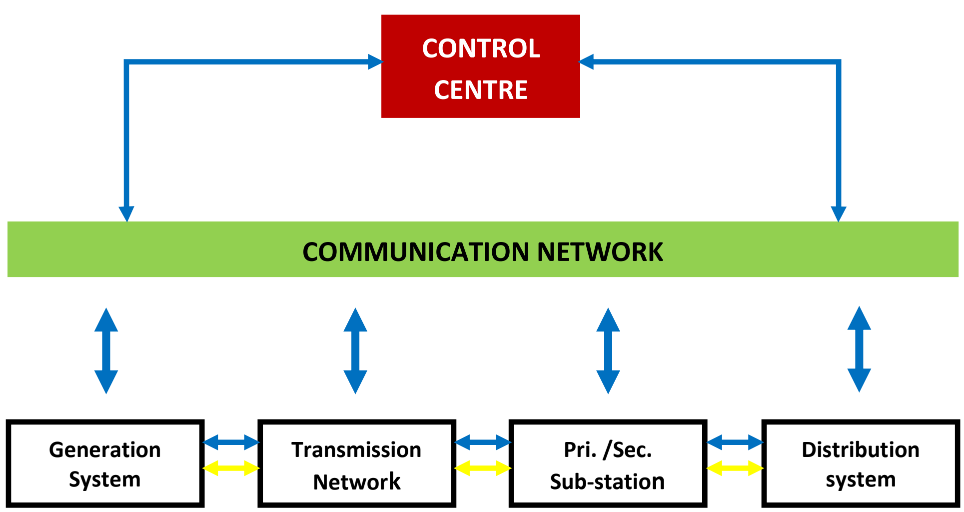


Figure 3.1 A schematic of Smart Electrical Transmission System

The control centre send and receives information from several measurement devices and, once processed, generates the required and appropriate command for the relevant control devices for operation i.e. transformer control unit for tap changing, transmission line control unit for tripping/reclosing, breaker of any electrical equipment etc [49]. The centralized controller received information from the network, from various points through any medium. The SETS is a network of different computers and power infrastructures that examine and manage energy usage. Each utility company maintains operational centers that receive usage information from collector devices placed throughout the served area [50]. For transmission line, communication capability is one of the potential benefits for computer/digital relays, which communicate not only with a center, but with each other too. This in turn will facilitate the overall system-wide protection and control philosophy.

In this system, the reliable and self managing transmission system is seen as the future of protection and control system which is an important factor. It is an automated system of monitoring and control that improves the reliability of the transmission network by preventing wide-spread break-ups [51]. The communication is possible through the use of a shared communication network. The reliability of the transmission network influences signals transmission between the communicating points. For example, in Figure 3.1, if communication link is available, then message will be transmitted on time which may helps to prevent any wide area blackout. This is modelled by allowing the control centre to communicate with control devices to use the current transmitted message. Otherwise, if communication is not available, the control centre will not receive the transmission signal. Consequently, it will use the present transmission line control device data.

3.1 IEEE Reliability Test System (RTS)-96

The standard IEEE Reliability Test System (RTS)-96 is used for the detailed analysis and modeling of system behaviour. Figure 3.2 is a model of IEEE RTS-96.

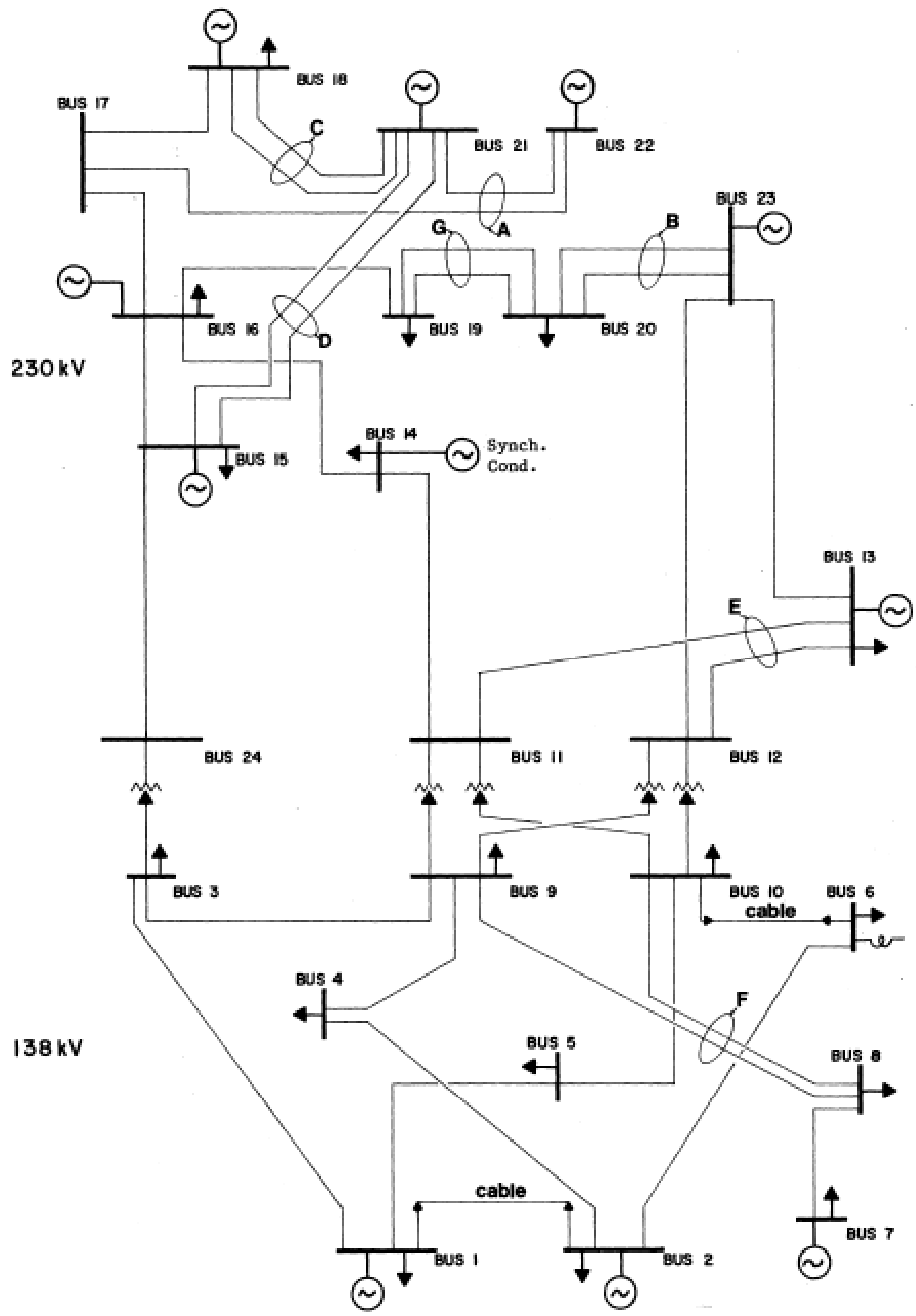


Fig. 3.2 IEEE Reliability Test system (RTS) [48]

IEEE RTS-96 was developed with the objective of assessing different reliability modeling and evaluation methodologies. The advantage of RTS-96 lies in the fact that it presented the system reliability indices derived through the use of rigorous solution techniques without any approximations in the evaluation process. These exact indices serve to compare with results obtained from other methods.

The IEEE Reliability Test System (RTS)-96 is a basis of a grid model of electrical test system with maximum electrical power system requirements. The RTS-96 has the following main features [53];

- It has 24-bus system;
- 32 generation units located at 10 of the buses and ranging from 12 to 400MW.
- The buses are connected with 38 transmission lines.
- Two voltage levels; 138KV (Bus 1 to Bus 10), 230KV (Bus 11 to Bus 24).
- 17 Load buses
- 5 Transformers
- Both over head transmission lines and underground cable connections are used.
- There are several lines which are assumed to be on a common right of way (ROW) or common tower.
- Extensive operating conditions are defined for the RTS including weekly peak load, daily peak load, and hourly peak load conditions; transmission line impedance and rating data; forced outage rates and duration; and generation unit operating parameters.

3.2 Modelling of Smart Electrical Transmission System

This subsection demonstrates the modelling of smart network's behavior in the SETS using the dynamic flowgraph methodology. It is well known that in order to ensure a protection system of transmission system will perform as expected; it must be tested under realistic power system conditions. The main component of this smart electrical transmission system is a communication network but we must ensure our electrical systems reliability. To ensure safe and predictable operation the components of the transmission system are controlled with generators, switches, circuit breakers and loads. The voltage, power, frequency, load factor, and reliability capabilities of the transmission system are designed to provide cost effective performance for the customers. Fault-sensing protective devices, data measuring devices at each end of the line, transformer must communicate to monitor the flow of power into and out of section so that faulted conductors or equipment can be quickly de-energized and the balance of the system restored. Protection of the transmission line from short circuits and other faults is usually so critical that common carrier telecommunications are insufficiently reliable, and in remote areas a common carrier may not be available. In this situation a reliable communication network is necessary for dynamic working capabilities of smart electrical transmission network.

3.2.1 The philosophy of Electrical Power System Protection

It is usually a concept about an electric power system in terms of its more impressive parts, the big generating stations, transformers, high-voltage lines, etc. While these are some of the basic elements, there are many other necessary and fascinating components. Protective relaying/device are one of these. The role of protective relaying in electric-power-system design and operation is explained by a brief examination of the over-all background. There are three aspects of a power system that will serve the purposes of this examination. These aspects are as follows:

A. Normal operation

B. Prevention of electrical failure

C. Mitigation of the effects of electrical failure

The term normal operation assumes no failures of equipment, no mistakes of personnel, or no acts of God. It involves the minimum requirements for supplying the existing load and a certain amount of anticipated future load. Some of the considerations are:

A. Choice between hydro, steam, or other sources of power

B. Location of generating stations

C. Transmission of power to the load

D. Study of the load characteristics and planning for its future growth

E. Metering

F. Voltage and frequency regulation

G. System operation

E. Normal maintenance

The provisions for normal operation involve the major expense for equipment and operation, but a system designed according to this aspect alone could not possibly meet present-day requirements. Electrical equipment failures would cause intolerable outages. There must be additional provisions to minimize damage to equipment and interruptions to the service when failures occur. This is also comes in the aspects of reliability issues. Two recourses are open: (1) to incorporate features of design aimed at preventing failures, and (2) to include provisions for mitigating the effects of failure when it occurs. Modern power-system design employs varying degrees of both recourses, as dictated by the economics of any particular situation [54]. Notable advances continue to be made toward greater reliability. But also, increasingly greater reliance is being placed on electric power.

Consequently, even though the probability of failure is decreased, the tolerance of the possible harm to the service is also decreased. But it is futile-or at least not economically justifiable-to try to prevent failures completely [55].

The type of electrical failure that causes greatest concern is the short circuit, or fault as it is usually called, but there are other abnormal operating conditions peculiar to certain elements of the system that also require attention. Some of the features of design and operation aimed at preventing electrical failure are:

A. Provision of adequate insulation

B. Coordination of insulation strength with the capabilities of lightning arresters

C. Use of overhead ground wires and low tower-footing resistance

D. Design for mechanical strength to reduce exposure, and to minimize the likelihood of failure causable by animals, birds, insects, dirt, sleet, etc.

E. Proper operation and maintenance practices

Some of the features of design and operation for mitigating the effects of failure are:

A. Features that mitigate the immediate effects of an electrical failure.

1. Design to limit the magnitude of short-circuits current.

a. By avoiding too large concentrations of generating capacity.

b. By using current-limiting impedance.

2. Design to withstand mechanical stresses and heating owing to short-circuit currents.

3. Time-delay under voltage devices on circuit breakers to prevent dropping loads during momentary voltage dips.

4. Ground-fault neutralizers (Petersen coils).

B. Features for promptly disconnecting the faulty element.

1. Protective relaying.

2. Circuit breakers with sufficient interrupting capacity.

3. Fuses.

C. Features that mitigate the loss of the faulty element.

1. Alternate circuits.

2. Reserve generator and transformer capacity.

3. Automatic reclosing.

D. Features that operate throughout the period from the inception of the fault until after its removal, to maintain voltage and stability.

1. Automatic voltage regulation.

2. Stability characteristics of generators.

E. Means for observing the electiveness of the foregoing features.

1. Automatic oscillographs.

2. Efficient human observation and record keeping.

F. Frequent surveys as system changes or additions are made, to be sure that the foregoing features are still adequate.

Thus, protective relaying is one of several features of system design concerned with minimizing damage to equipment and interruptions to service when electrical failures occur. When we say that relays "protect" we mean that, together with other equipment, the relays help to minimize damage and improve service. It will be evident that all the mitigation features are dependent on one another for successfully minimizing the effects of failure. Therefore, the capabilities and the application requirements of protective-relaying equipments should be considered concurrently with the other features. This statement is emphasized because there is sometimes a tendency to think of the protective-relaying or devices after all other design considerations are irrevocably settled. Within economic limits, an electric power system should be designed so that it can be adequately protected [55].

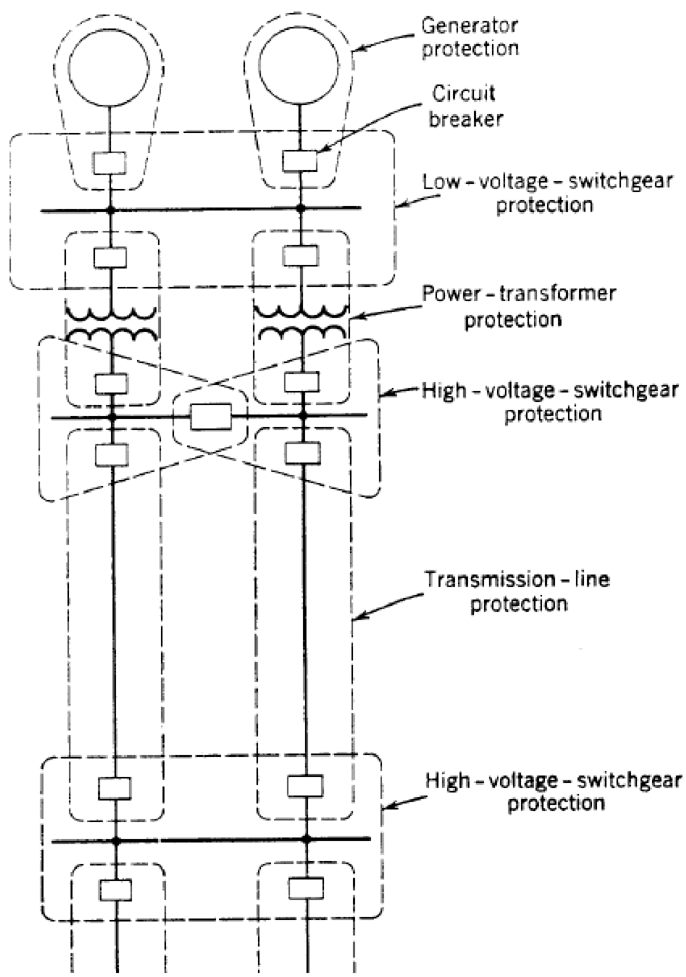


Figure 3.3 Single-line diagram of an electric power system illustrating primary protection

For smart electrical transmission network, manufacturers needs major research and development and try to go beyond limits. Means, they have to go far in feature additions in protective devices. In smart transmission system, protective devices should have an ability to add on system's newly installed equipments and changing by themselves and change their settings accordingly.

Let us consider for the moment only the relaying equipment for the protection against short circuits. There are two groups of such equipment. One which we shall call primary relaying and the other back-up relaying. Primary relaying is the first line of defense, whereas back-up relaying functions only when primary relaying fails. In figure 3.4, the sketch of power system single line diagram with their respective protection devices shows a list of main components and their primary and back-up protective system.

3.2.1.1 Primary Protection

From the above figure 3.4, the first observation is that circuit breakers are located in the connections to each power element. This provision makes it possible to disconnect only a faulty element. Occasionally, a breaker between two adjacent elements may be omitted, in which event both elements must be disconnected for a failure in either one. The second observation is that, without at this time knowing how it is accomplished, a separate zone of protection is established around each system element. The significance of this is that any failure occurring within a given zone will cause the tripping (i.e., opening) of all circuit breakers within that zone, and only those breakers. It will become evident that, for failures within the region where two adjacent protective zones overlap, more breakers will be tripped than the minimum necessary to disconnect the faulty element. But, if there were no overlap, a failure in a region between zones would not lie in either zone, and therefore no breakers would be tripped. The overlap is the lesser of the two evils. The extent of the overlap is relatively small, and the probability of failure in this region is low; consequently, the tripping of too many breakers will be quite infrequent.

Finally, it will be observed that adjacent protective zones overlap around a circuit breaker. This is the preferred practice because, for failures anywhere except in the overlap region, the minimum number of circuit breakers needs to be tripped. When it becomes desirable for economic or space-saving reasons to overlap on one side of a breaker, as is frequently true in metal-clad switchgear the relaying equipment of the zone that overlaps the breaker must be arranged to trip not only the breakers within its zone but also one or more breakers of the adjacent zone, in order to completely disconnect certain faults. This is illustrated in Figure 3.5, where it can be seen that, for a short circuit at X, the circuit breakers of zone B, including breaker C, will be tripped; but, since the short circuit is outside zone A, the relaying equipment of zone B must also trip certain breakers in zone A if that is necessary to interrupt the flow of short circuit current from zone A to the fault. This is not a disadvantage for a fault at X, but the same breakers in zone A will be tripped unnecessarily for other faults in zone B to the right of breaker C. Whether this unnecessary tripping is objectionable will depend on the particular application.

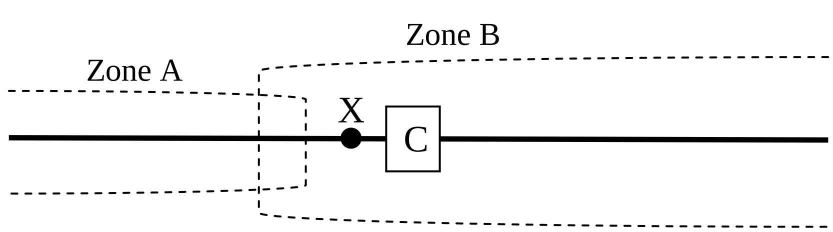


Figure 3.4 Overlapping adjacent protective zones on one side of a circuit breaker

3.2.1.2 Back-up Protection

Back-up protection is only employed against short circuits. Because short circuits are the preponderant type of power failure, there are more opportunities for failure in short primary relaying. Experience has shown that back-up relaying for other than short circuits is not economically justifiable.

A clear understanding of the possible causes of primary-relaying failure is necessary for a better appreciation of the practices involved in back-up relaying. When we say that primary relaying may fail, we mean that any of several things may happen to prevent primary relaying from causing the disconnection of a power-system fault. Primary relaying may fail because of failure in any of the following:

A. Current or voltage supply to the relays.

B. DC tripping-voltage supply.

C. Protective relays.

D. Tripping circuit or breaker mechanism.

E. Circuit breaker.

It is highly desirable that back-up relaying be arranged so that anything that might cause primary relaying to fail will not also cause failure of back-up relaying. It will be evident that this requirement is completely satisfied only if the back-up relays are located so that they do not employ or control anything in common with the primary relays that are to be backed up. So far as possible, the practice is to locate the back-up relays at a different station.

Consider, for example, the back-up relaying for the transmission line section EF of figure 3.6. The back-up relays for this line section are normally arranged to trip breakers A, B, I, and J. Should breaker E fail to trip for a fault on the line section EF, breakers A and B are tripped; breakers A and B and their associated back-up equipment, being physically apart from the equipment that has failed, are not likely to be simultaneously affected as might be the case if breakers C and D were chosen instead.

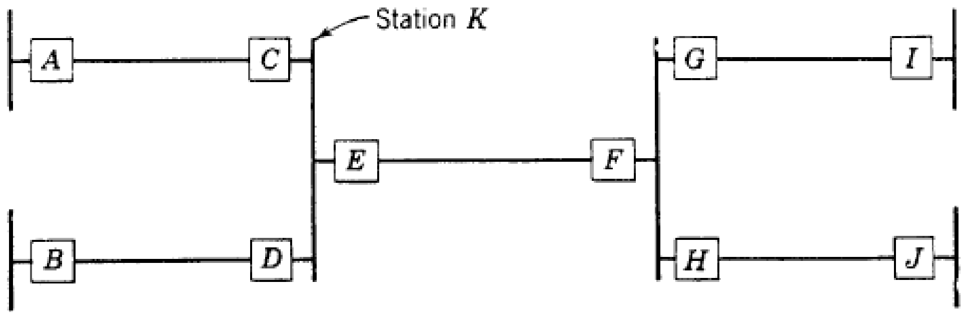


Figure 3.5 Illustration for back-up protection of transmission line section EF.

3.2.1.3 Type of Protective Technologies

In order to fulfill the requirements of protection with the optimum speed for the many different configurations, operating conditions and construction features of power systems, it has been necessary to develop many types of devices that respond to various functions of the power system quantities. For example, observation simply of the magnitude of the fault current suffices in some cases but measurement of power or impedance may be necessary in others. Protective device frequently measure complex functions of the system quantities, which are only readily expressible by mathematical or graphical means. They may be classified according to the technology used:

i) Electromechanical

ii) Static

iii) Digital

iv) Numerical

Every type has somewhat different capabilities, due to the limitations of the technology used.

Protective Devices Technology				
	Electro-mechanical	Static	Digital	Numerical
Basic Timing Error (%)	7.5	5	5	5
Over shoot time (s)	0.05	0.03	0.02	0.02
Safety margin (s)	0.1	0.05	0.03	0.03
Typical overall grading margin	0.4	0.35	0.3	0.3

Table 3.1 Typical standard relays parameter

Overshoot Time: It is defined as the difference between the operating time of a relay at a specified value of input current and the maximum duration of input current, which when suddenly reduced below the relay operating level, is insufficient to cause relay operation.

Grading Margin: The time interval that must be allowed between the operations of two adjacent relays in order to achieve correct discrimination between them is called the grading margin. If a grading margin is not provided, or is insufficient, more than one relay will operate for a fault, leading to difficulties in determining the location of the fault and unnecessary loss of supply to some consumers. The grading margin depends on a number of factors:

i) The fault current interrupting time of the circuit breaker

ii) Relay timing errors

iii) The overshoot time of the relay

iv) CT errors

v) Final margin on completion of operation

Factors (ii) and (iii) above depend to a certain extent on the relay technology used an electromechanical relay, for instance, will have a larger overshoot time than a numerical relay. Grading is initially carried out for the maximum fault level at the relaying point under consideration, but a check is also made that the required grading margin exists for all current levels between relay pick-up current and maximum fault level.

Protective devices are one source of protection and communication between equipment at power house, substation as well as with the transmission lines. Basically these protective devices are controlling transmission lines. They are working according to default parameters that are provided by the programmer or testing engineer according to their system requirement. Smart electrical transmission system requires a system that can handle and acquire these parameters by themselves according to the then present condition of the system. Protective devices should get the data from the control center and change their setting for the system controlling after getting signal or approval from control center.

Figure 3.4 shows that generator, power transformer, and transmission line is the key components of transmission network as well as the addition of communication network. These key components of smart electrical transmission network are modeled here one by one.

3.2.2 Modeling of Transmission line

Transmission line is a major component of SETS and plays a critical role in the electrical power system. Generation unit is worthless without transmission lines because it is a vital connecting link between generation and distribution network. In transmission line, the resistance, inductance and capacitance of overhead transmission lines as well as underground cable, are evenly distributed along the length. In addition, some of the line parameters are also functions of frequency. For steady-state studies, such as load flow and short-circuit studies, the only parameters needed are the positive and zero sequence parameters calculated from tables and simple handbook formulas at the power frequency. For electromagnetic transient studies the parameters calculated from simple formulas are not adequate, and the line parameters must be computed. Figure 3.6 is a basic model for representing various components of system, i.e., Transmission lines, transformers, sources, etc.

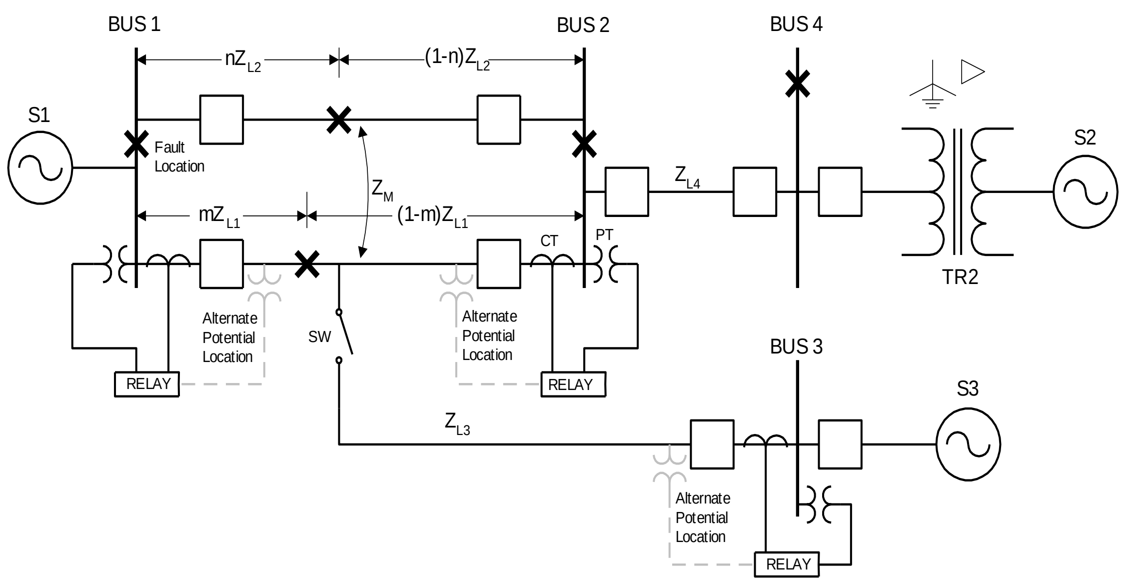


Fig. 3.6 Basic electrical power system model

There are three sources in the network S1, S2 and S3. The source angle can be varied to simulate power flows. The transmission lines consist of one pair of mutually coupled lines (between buses 1 and 2), out of which one is a three terminal line. Intermediate nodes are provided in the line models to enable application of faults at various locations.

Breakers and switches are also included to simulate different configurations. This model can be expanded to include series capacitors, shunt reactors and capacitors etc. As we mentioned earlier that IEEE RTS is a complete package of system components.

3.2.2.1 Transmission Line Models for Steady State Studies

There are a large number of steady state applications where transmission lines need to be modeled correctly and for only one particular frequency. The exact-pi equivalent circuit of a single-phase transmission line is shown in 3.7.

The series impedance and shunt admittance of the exact-pi equivalent circuit of a single-phase line are given below [56] in Equations (1) and (2):

$$\frac{1}{Y_{series}} = (R' + j\omega L') \cdot l \cdot \sinh(\gamma \cdot l) / (\gamma \cdot l) \tag{1}$$

$$Y_{shunt/2} = \frac{(j\omega \cdot C'/2) \cdot l \cdot \tanh(\gamma \cdot l/2)}{(\gamma \cdot l/2)} \tag{2}$$

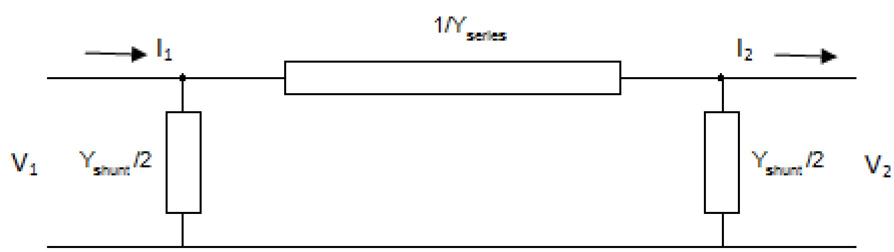


Figure 3.7 Exact-pi Equivalent Circuit.

where, R', L', C' are the resistance, inductance, and capacitance per unit length, l is the line length, and γ is the propagation constant which is equals to equation (3) [56];

$$\gamma = [(R' + j\omega \cdot L') \cdot j\omega \cdot C']^{1/2} \tag{3}$$

Equations (1), (2), and (3), shows that the exact-pi circuit model can represent the line accurately at one specific frequency.

This model is a lumped parameter model and it is good for only one frequency of interest and one particular line length. This model includes the hyperbolic corrections with no approximations involved and is the best model for steady-state solutions and for frequency scans. This model takes into account the skin effect and ground return corrections [56]. It is a multiphase model in the phase domain with constant R, L, C, and G of the line and it is correct for any number of circuits in the same right-of-way. This model is not adequate for transient studies.

Nominal-pi Circuit Model is derived from the exact-pi model described by equation 1 if the frequency or line length is low. For overhead transmission lines this is typically the case if $l \leq 150$ Km at 60 Hz, or $l \leq 15$ Km at 600 Hz. This model takes into account the skin effect and ground return corrections. It is a multiphase model in phase domain with constant R, L, C, and G of the line and it is correct for any number of circuits in the same right-of-way. The line is automatically represented as untransposed, and could model particular transposition schemes in great detail by cascaded connection of nominal-pi circuit models [57].

This model has the same limitations as the exact-pi model in addition to being limited for short lines i.e., less than 150 kilometers at 60 Hz and less than 5 kilometers at 2 kHz. It cannot represent frequency dependence of line parameters in frequency scans, and it cannot be used for “electrically long” lines. This model is not good for transient studies.

However, this it has been used for transient studies by connecting a number of cascaded nominal-pi models in series [58].

3.2.2.2 Transmission Line Models for Transient Studies

Distributed and frequency dependent parameter models are best for transient studies. They use traveling wave solutions, which are valid over a much wider frequency range than pi-circuit models.

Nominal-pi model is not a good choice for transient studies. However, it has been used for transient studies by connecting a number of cascaded pi-nominal models, similar to what was done in the past with transient network analyzers. When used as such, this model has a big disadvantage of producing reflections at the cascading points. To adequately represent the line over various frequency ranges, a large number of nominal-pi cascaded sections should be used. As a rule of thumb, one should use one section to represent the line up to 100 Hz, eight sections to extend the range up to 700 Hz and 15-20 sections to extend the range up to 1-2 kHz or keep the section lengths between 5-10 kilometers (2 kilometers for frequency up to 5 kHz).

Constant-parameter distributed line model assumes that the line parameters R', L', and C' are constant. The L' and C' are distributed and the losses $R' \cdot l$ are lumped in three places, which is reasonable as long as $R' \cdot l$ << Zsurge. The above conditions are met for positive sequence parameters to approximately 1-2 kHz, but not for zero sequence parameters. It is a good model only where the zero sequence currents are very small, or oscillate with a frequency close to the one at which the parameters were calculated. This frequency should not be very high to meet the condition $R' \cdot l$ << Zsurge, otherwise the line must be split into smaller sections. The transformation matrix to decouple the propagation modes is taken as real and constant and it is less valid as asymmetry gets stronger. The speed of execution of this model is much faster than the cascaded nominal-pi circuit models and there are no reflections within the line. Shunt losses are ignored in this model [59].

Frequency-dependent distributed line model provides an accurate representation of the distributed nature of all line parameters, as well as their frequency dependence. Therefore, the line parameters for this model are not constant but functions of frequency, i.e., $R(\omega)$, $L(\omega)$, $C(\omega)$ and $G(\omega)$. All parameters are distributed including R' and G'.

Most frequency-dependent models are based on the modal theory where multi-phase line equations are decoupled through modal transformation matrices, so that each mode can be studied separately as a single-phase line. The transformation matrices for untransposed or unbalanced lines are complex and frequency-dependent. It is possible however to obtain a good accuracy by using real and constant transformation matrices. However, this option has a tendency to yield unstable solutions and should be used with diligence. The latest advancement in frequency dependent transmission line models is the frequency-dependent phase domain model. This model does not use the modal transformation matrix and hence does not have the inaccuracies associated with the frequency dependence of the transformation matrix. It provides better accuracy while dealing with asymmetrical lines.

Hence, use of pi-exact model for steady-state analysis is a best choice. For transient analysis use the frequency dependent model for the lines of main interest, and the constant frequency distributed parameter model for lines of secondary interest. Pi-circuit model is not a good choice for transient studies. However, it has been used for transient studies by cascading a number of nominal-pi sections.

3.2.2.3 Fault Locating in Smart Electrical Transmission system:

Fault location of transmission line is also a great reason to do advancement towards smart electrical transmission system. In figure 3.8, a fault location scheme is introduced for fast and reliable communication medium for this main issue.

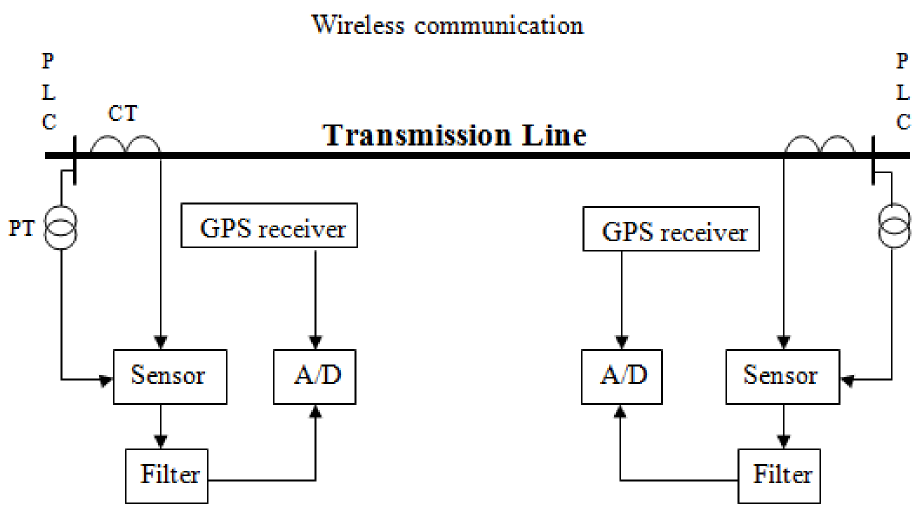


Figure 3.8 Scheme of communication and fault location in Transmission line

Power Line Communication (PLC) is already using on high voltage transmission system for data transmission but for limited purposes. Wired and wireless communication is also necessary for strong link between complete smart electrical transmission systems. GPS/satellite, wireless acts as an ideal synchronous signal which can be collected at different location can be used correctly.

Figure 3.8 illustrated the communication arrangement between two power station i.e. substations or power station to substation. General purpose telecommunications equipment operating over power line carrier, radio or optical fiber media incorporate frequency translating or multiplexing techniques to provide the user with standardized communication channels. They have a nominal bandwidth/channel of 4 KHz and are often referred to as voice frequency channels. Protection signaling equipments operating at voice frequencies exploit the standardization of the communication interface. Where voice frequency channels are not available or suitable, protection signaling may make use of medium or specialized equipment dedicated entirely to the signaling requirements. The communication messages involved may be quite simple, involving instructions for the receiving device to take some defined action like trip, block, restore, etc, or it may be the passing of measured data in some form from one device to another. Various types of communication links are available for protection signaling, for example:

i. Private pilot wires installed by the power authority

ii. Pilot wires or channels rented from a communications company

iii. Carrier channels at high frequencies over the power lines

iv. Radio channels at very high or ultra high frequencies

v. Optical fibers

It is mentioned that whether or not a particular link is used depends on factors such as the availability of an appropriate communication network, the distance between protection relaying points, the terrain over which the power network is constructed, as well as cost.

3.2.3 Modeling of Power Transformer

The transformer is one of the most familiar and well-known pieces of power system electrical apparatus. Despite its simple design, transformer modeling over a wide frequency range still presents substantial difficulties. The transformer inductances are frequency and saturation dependent. The distributed capacitances between turns, between winding segments, and between windings and ground, produce resonances that can affect the terminal and internal transformer voltages.

An ideal transformer has the following physical properties;

1. No Losses
2. No leakage fluxes
3. Magnetic core has infinite permeability

An ideal transformer ignores all leakage by assuming that all the flux is confined in the magnetic core. In addition they neglect magnetization currents by assuming no reluctance in the magnetic material. The saturable transformer model eliminates these two restrictions, by considering that around each individual coil a separate magnetic leakage path exists, and that a finite magnetic reluctance path exists as well. The models based on matrices of mutually coupled coils can represent quite complex coil arrangements but are somewhat more difficult to use.

Usually transformer models are derived considering the behavior of the transformer from its terminals. However, in protection studies, one might be interested in internal power transformer faults. Sometimes, if explicit representation of transformers is not required, the user needs to model the effect of the transformer presence in the power system without the need of any details about the transformer itself [59].

There are basically four different ways in which single-phase transformers are connected into so-called three-phase banks. They may be connected Y-Y, Δ-Y, Y-Δ, or Δ-Δ. All of them, the most favored connection is the Δ-Y with the Y one the high voltage side [60]. The advantages of this connection include the following;

- There is a neutral on the high-voltage side that may be grounded, which helps in short circuiting conditions.
- There is a voltage gain of √3 just by virtue of the connection, in addition to the voltage gain due to the turn’s ratio of the individual single-phase transformers.
- The Δ connection on the primary side serves a useful function as well, with respect to unbalanced operation and/or in the presence of non sinusoidal current or voltage waveforms.
- HV transmission lines are connected in Δ connection, so when they enter to the substation they come on busbar of the line bay and then to the power transformer. A that time, this transmission line requires a transformer with Δ connection on HV side or primary voltage side.

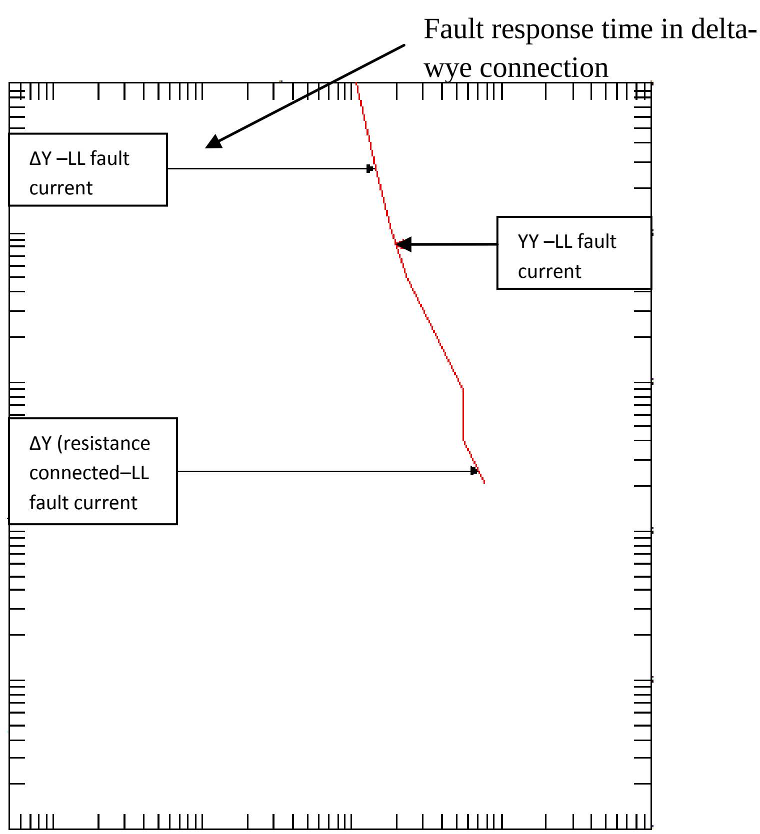


Fig 3.9 Fault response time in line-line fault (Time vs Current Graph)

Figure 3.10 shows the fault current response time in three different types of power transformer connection and Δ-Y connection behaves better than others. Beside this, the advantage of a three-phase transformer is that it is possible to save core material and get a cheaper and more efficient transformer. It is exactly analogous to the saving of wire and energy in a three-phase transmission line versus single phase transmission lines [61].

3.2.4 Modeling of Generator

The following two source models are the most commonly used in the electrical power system studies:

Model 1: Ideal sinusoidal sources behind sub-transient reactances or Thevenin impedances of the system

Model 2: Detailed synchronous machine model

The choice of a specific model in a study depends on system configuration and the objectives of study.

In model 1, Ideal sources with sub-transient reactances model is used for representing large generating stations. The assumption is that the system inertia is infinite and the disturbance under study does not cause system frequency to change. The time frame of interest is small (approximately 10 cycles) and the machine controls such as excitation system and governor have not responded to the disturbance. The model is commonly used in transmission line primary protection system studies [61].

In a large integrated system, the system can be divided into few subsystems. Each subsystem then can be reduced to an ideal three-phase source and equivalent positive and zero sequence Thevenin impedances. These impedances can be calculated using a steady-state 60 Hz fault program by isolating the subsystem from the rest of the system at the common bus between them and then applying a fault at that bus. It is common practice to select the common buses, which are at least one line away from the line terminals where the relaying performance is being evaluated. Again the assumptions in using this representation are the same as those in case of ideal sources with sub-transient reactances. However the main advantage of this model is that the computation requirements are significantly reduced because all components within a subsystem are reduced to a simple representation using an ideal source and equivalent Thevenin impedances. The main disadvantage is that the Thevenin impedance represents the system equivalence at 60 Hz only. The transient response of the system using the reduced model is not as accurate as when the complete system is represented with all lines and sources.

In model 2, The detailed model is mostly used for representing small generating stations in non-integrated systems for applications where the system disturbance is likely to cause change in frequency and the relays are slow in responding to that disturbance. The model requires complete machine data including inertia, sub-transient, transient and steady-state reactances. Models of turbine and excitation system can also be included depending upon the time frame of study and their response time. The detail model represents complete machine behavior from sub-transient to steady-state time frames. Generally, the excitation and governing system are ignored for line relaying studies. The main disadvantage is the model is complex, it requires complete machine data, is computationally inefficient and my not provide any additional accuracy in the simulation. It is therefore not recommended for use in large integrated system. Figure 3.11 shows the speed torque characteristics of the generator. These curves indicate that under normal operating conditions the induction motor should be able to start and pick up the load.

Theoretical torque speed curve for a synchronous machine will be a vertical line located vertical to the synchronous speed at x axis, from starting torque to stalling torque value. This is because theoretically synchronous motors are not self starting. Practically however they start as induction motors and at near synchronous speed the excitation is switched on.

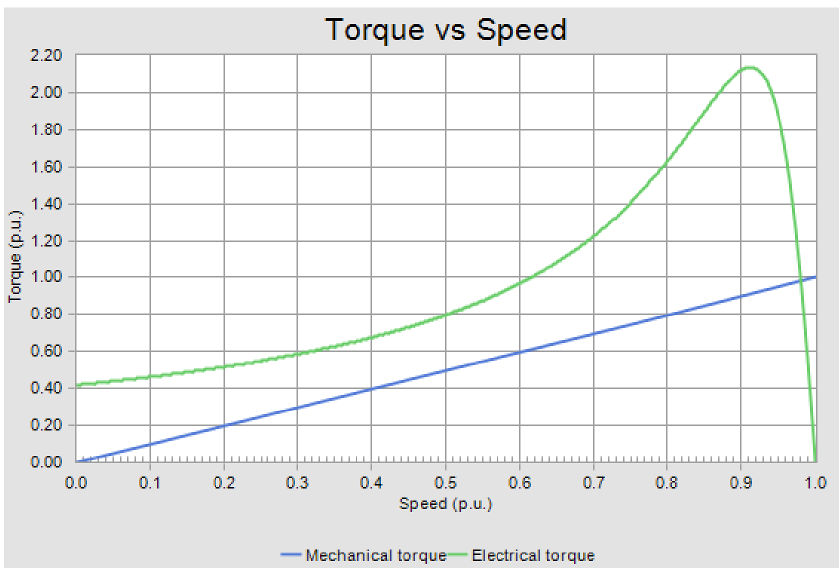


Fig. 3.10 Torque vs. Speed characteristics of the generator

3.2.5 Modeling of Communication Network

Control systems with spatially distributed components have existed for several decades. Examples include chemical processes, power plants, airplanes, etc in such systems the components were connected via point-to-point connections and the systems were designed to bring all information from the sensors to a central location to take a decision on how to act [62]. Physical setups and expanding functionality are pushing the limits of the point-to-point architecture. Hence, such centralized point-to-point control systems are no longer suitable to meet new requirements such as modularity, decentralization of control, integrated diagnostics, quick and easy maintenance, and low cost. Technology advances and the availability of network connectivity have prompted the idea of introducing network facilities to control systems; their sensors, actuators, estimator units, and control units are connected through communication networks. This type of system provides several advantages such as modular and flexible system design, simple and fast implementation, and powerful system diagnosis and maintenance utilities.

The network is made up of two types of components: nodes and communication lines. The nodes typically handle the network protocols and provide switching capabilities. A node is usually itself a computer (general or special) which runs specific network software. The communication lines may take many different shapes and forms, even in the same network. Examples include: copper wire cables, optical fiber, radio channels, and telephone lines. A host is connected to the network by a separate communication line which connects it to one of the nodes. In most cases, more than one host may be connected to the same node. From a host's point of view, the entire network may be viewed as a black box, to which many other hosts are connected. Each host has a unique address allocated to it by the network. For a host to communicate with another host, it needs to know the latter's address. All communication between hosts passes through the nodes, which in turn determine how to route messages across the network, from one point to another.

Modern control theory is largely based on the abstraction that information are transmitted/received along perfect communication channels and that computation is either instantaneous (continuous time) or periodic (discrete time). Future applications of control will be much more information-rich than those of the past and will involve networked communications, distributed computing, and higher levels of logic and decision-making.

A networked control system is shown in Figure 3.12 and its architecture separates the traditional elements of sensing, estimation, control, and actuation for a given system across a network and also allows sharing of information between systems.

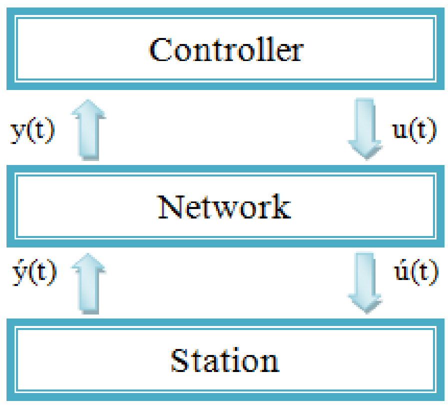


Figure 3.11 Simple model of Communication network

This architecture can be used to model either a single system or multiple systems that interact through the network. The primary advantages of developing a network is reduced system wiring ease of system diagnosis and maintenance, and increased system agility. Because of the network, only the reported output is available to the controller and its prediction processes, similarly, only is available to the actuators on the station. Commonly used local area networks support broadcast, hence is globally known and in such a case the controller itself may be physically distributed. As we have already discussed that nowadays electrical system are modernized with digital and numerical protective devices, it is possible to add control equipment in a protective devices package or add control equipment with them for communication network. Protective relays are mainly for protection of electrical system and also can be modified for communication among equipment, control center and different stations.

IEEE RTS-96 model was used to simulate and tested to determine its reliability behaviour. Data of reliability testing system is used to simulate and compared it with the abnormal (high values) data. We find the following results for transient, harmonics in the simulations.

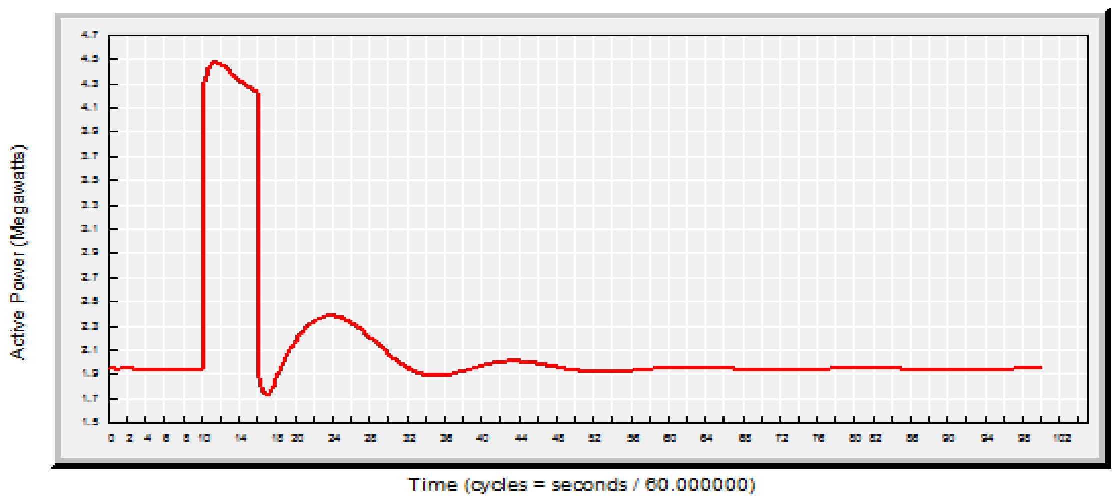


Fig. 3.12 (a) Generator fault due to transient

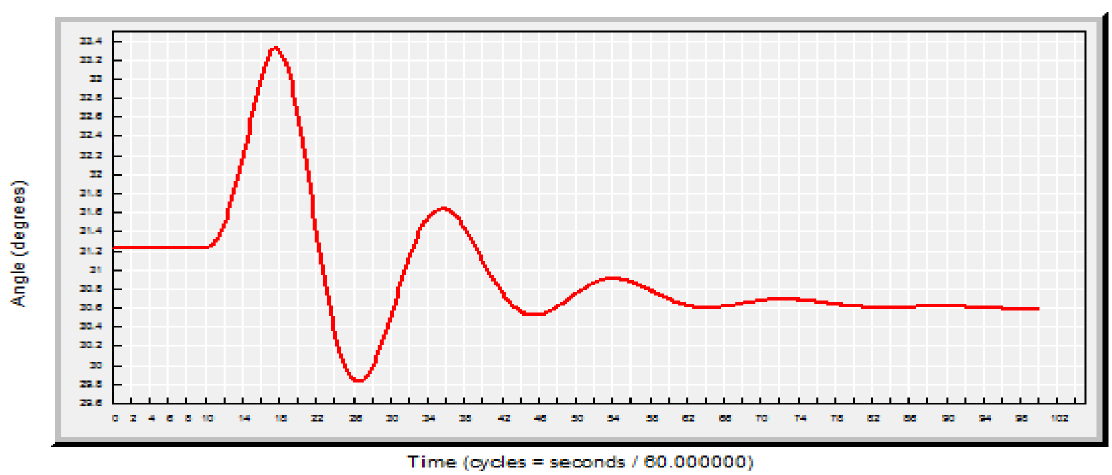
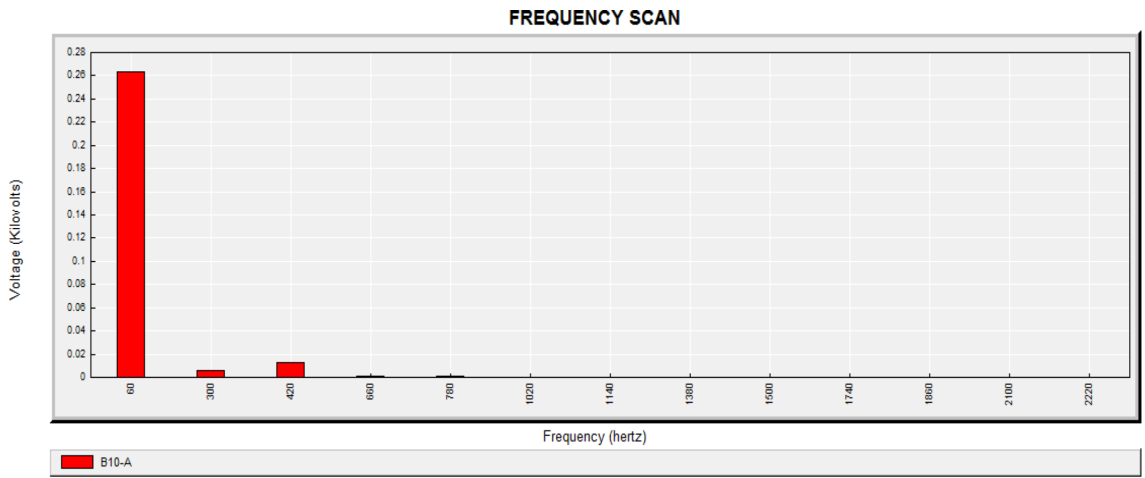


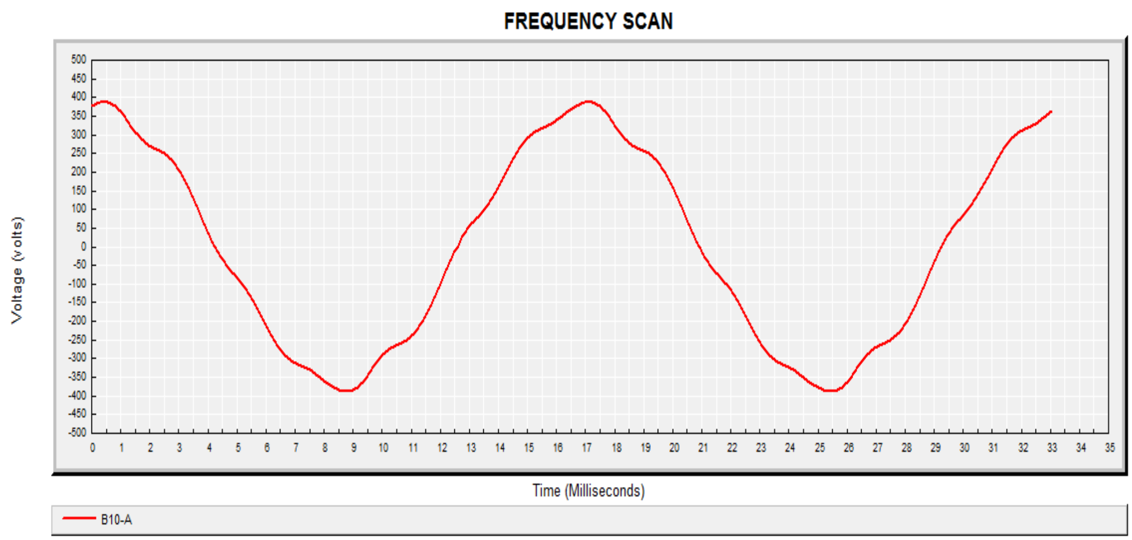
Fig. 3.12 (b) 138KV transmission line faults due to transient

The vast majority of transients are produced within electrical facility. The main problems are with device switching, static discharge, and arcing. Figure 3.12 (a) and (b) shows an oscillatory transient which is also called as a ringing transient. This type of transients is characterized by swings above and below the normal line voltage. This happened when we put an extra line voltage on one phase of a generator. Each time when some device turns on, turn off, load, or unload an inductive device, it produces a transient. Inductive devices are those devices that use magnetic mass to function. Lightning is the most well known of the externally generated transients. Most lightning transients are not actually the result of direct lightning strikes; they are most often induced onto conductors as lightning strikes near the power line. The large electric fields generated during a discharge can couple into the power system, creating induced transients. In figure 13.2 (b) there are transient from time 10 sec @ 31.2 degree, which disturb the transmission line feed. In this situation either system tripped or makes a major distortion in the system voltages which may harm the other system equipment too. But figure shows that system get stables after some time but that transient makes that voltages disturbed.

Harmonic distortion is found in both the voltage and the current waveform. Most current distortion is generated by electronic loads, also called non-linear loads. These non-linear loads might be single phase loads such as point-of-sale terminals, or three-phase as in variable speed drives. As the current distortion is conducted through the normal system wiring, it creates voltage distortion according to Ohm's Law. While current distortion travels only along the power path of the non-linear load, voltage distortion affects all loads connected to that particular bus or phase.



(a)



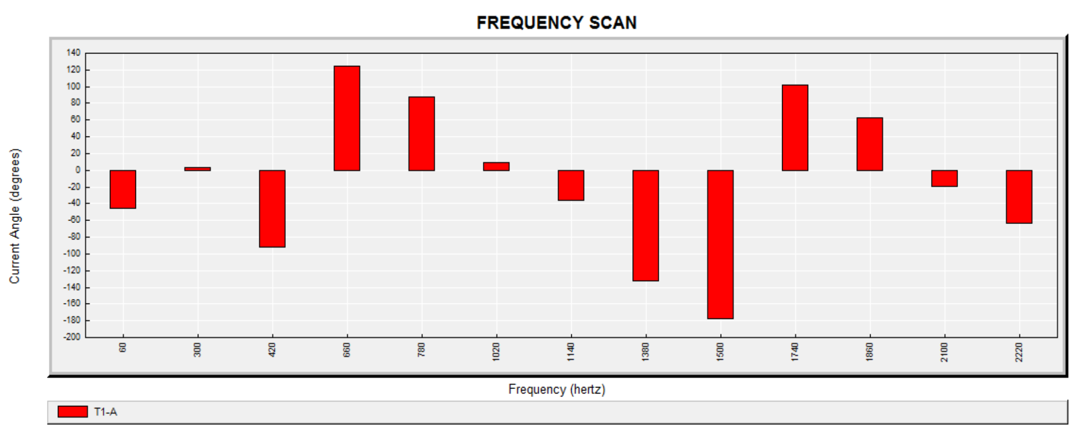
(b)

Fig 3.13 (a) and (b) Harmonics behaviour in a selected bus

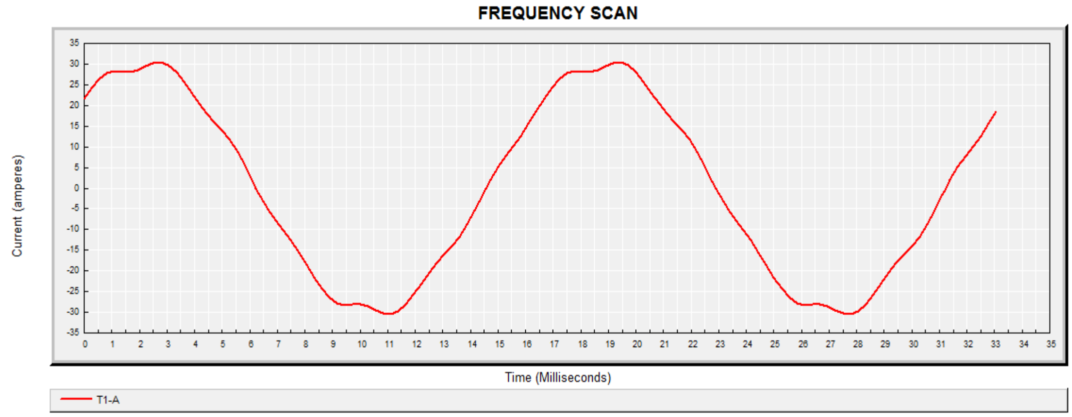
Current distortion affects the power system and distribution equipment. It may directly or indirectly cause the destruction of loads or loss of product. From the direct perspective, current distortion may cause transformers to overheat and fail even though they are not fully loaded. Conductors and conduit systems can also overheat leading to open circuits and downtime. Figure 3.13 (a) and (b) shows a harmonics behaviour in selected buses because PURE SINEWAVE + HARMONICS = HARMONICALLY DISTORTED SINEWAVE. For example, in a 3 phase 4 wire system, the fundamental currents at any instant will always add up to zero in the neutral. However, the third harmonics of each phase is always in phase with those of the other two phases, as a result rather then cancelling each other, they are additive and may well lead to serious neutral loading problem.

Transmission systems around the world are increasingly applying capacitor banks on their transmission systems, primarily to support transmission systems and avoid voltage collapse issues leading to blackouts. Another trend is the utilization of underground cables to obtain right of way in corridors sensitive to overhead lines. These trend both lead to harmonics resonance issues.

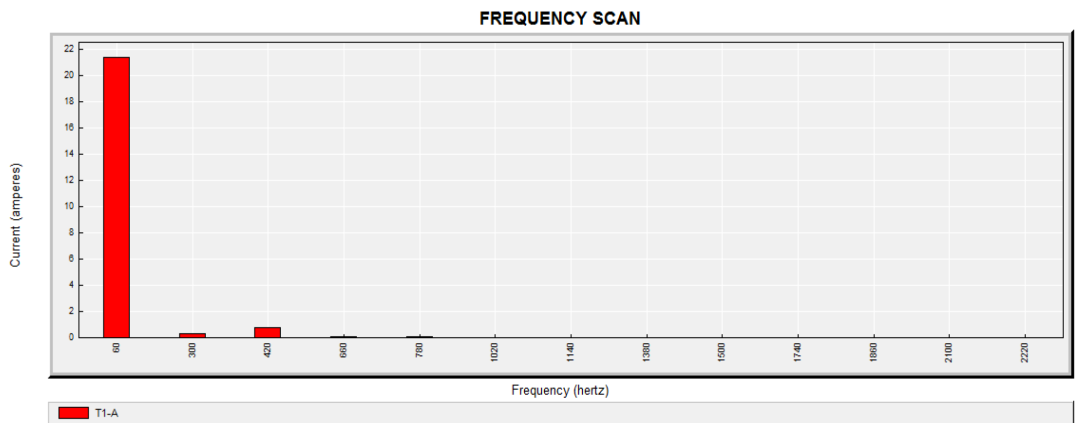
Figure 3.14 (a), (b), (c) represent the behaviour of transmission line with the addition of 3rd harmonics on reactors and underground cables system links.



(a)



(b)



(c)

Fig 3.14 (a), (b), and (c) Harmonics behaviour in a selected transmission line

It shows that with the addition of harmonics in transmission system, there will be major collapse. Mainly protective devices cannot read or sense the fault current properly due to that harmonics in neutral which causes major disturbance in power system.

After simulating the IEEE RTS with the given data and compare results, we have found that we got high values of transient and faults in our system. Due to increase in voltage and frequency from the standard values, system gets collapse. Voltage instability is one of the major causes of system failure; with the stable voltage of the system we can control system behaviour. Beside the above simulations, we also note down the force outages of the system and compared it with the given data of IEEE Reliability test system data.

A multi-national and highly meshed power system grid, are effected by high transit power flow, which are not always scheduled. To ensure safe operation in the light of the high demands and complexities, precise monitoring of the dynamic behaviour has to be provided. Addition of smart transmission features, additional information from the remote ends of transmission corridors can substantially enhance the quality of power system operation, cross border trading could be accompanied by cross border data and even information exchange.

Loss of synchronism means the blackout of a part or the whole system. Moreover, it is accompanied by excess stress on the equipment as a result of over voltages. Without preventive actions, loss of synchronism could therefore result not only in blackouts as such, but in destruction of strategic high-voltage equipment such as transformers, breakers, etc. which at the end will increase unduly the time required for a complete synchronous system restoration. Smart transmission system will helps to indicate the different point in the system which needs preventive maintenance. This will be done with the real time data from different equipments to the control center.

With the provision of smart electrical transmission system, we can avoid different disturbances in the electrical transmission system which can leads to the blackouts or system failures;

- Real time observation of system performance
- Early detection of system disturbance
- Real-time determination of transmission capacities

- Analysis of system behaviour
- Fast remedial measures
- Event analysis to support economical and reliable system operation
- Integration of renewable energy system
- Avoid over loading

3.3 Force outages:

A hardware failure at some point at the generation, transmission, or distribution system that results in interruption of service is called as force outage. Forced outages usually occur due to unexpected component failure or systemic problems such as downed lines or lightning-induced overloads. These outages may or may not affect an end-use customer depending on where they occur. Forced outage rates are used when calculating the overall reliability of an energy delivery system. There are two types of transmission line force outages, one is permanent force outage and second is transient force outages.

3.3.1 Permanent Force outages:

Permanent force outages are those in which some specific time is required to repair, overhaul, maintenance, schedule maintenance of the system which will help to increase the life of the system. Permanent outages are those which require component repair in order to restore the component to service.These are the required force outage and we can decrease the rate with proper maintenance and protection.

3.3.2 Transient Force outages:

Transient force outages are those which are not permanent. They are usually for very short period of time. They are due to the transient, harmonics, surge or some fault of the system. They depend upon geographical location or some other important factors.

Figure 3.15 and 3.16 shows a comparison data of permanent force outages and transient force outages of IEEE RTS-96 and simulated data.

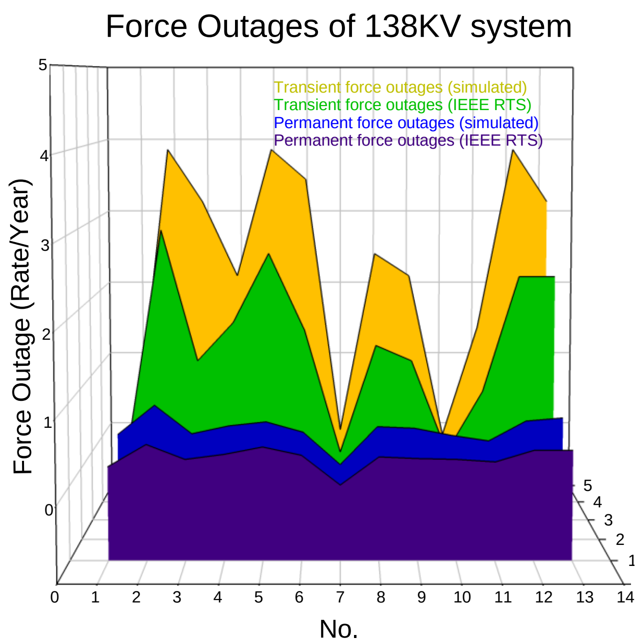


Fig. 3.15 Permanent and transient force outages of 138KV system

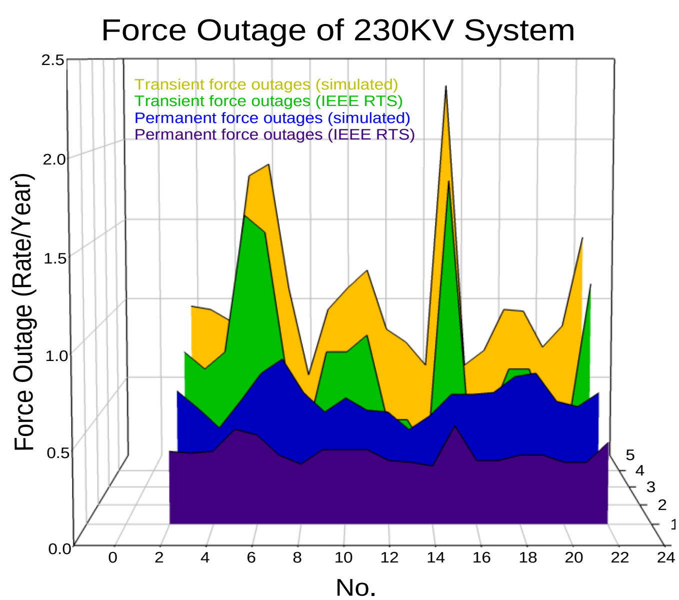


Fig. 3.16 Permanent and transient force outages of 230KV system

We have found that if we increase the voltage of system or give a sudden increase or decrease the system parameters, system will shows more outages either permanent or transient force outages but more chances of transient force outages. Lightning is one of the major adverse weather conditions that can cause frequent transmission line outages in some geographical areas, and this is a best example of transient force outages.

3.4 DFM model:

A dynamic system can be modelled and analyzed for reliability and safety through DFM. In a DFM model, the variables and control systems are represented through a time based logical cause and effect relationship. Figure 3.17 shows a DFM model of IEEE RTS-96.

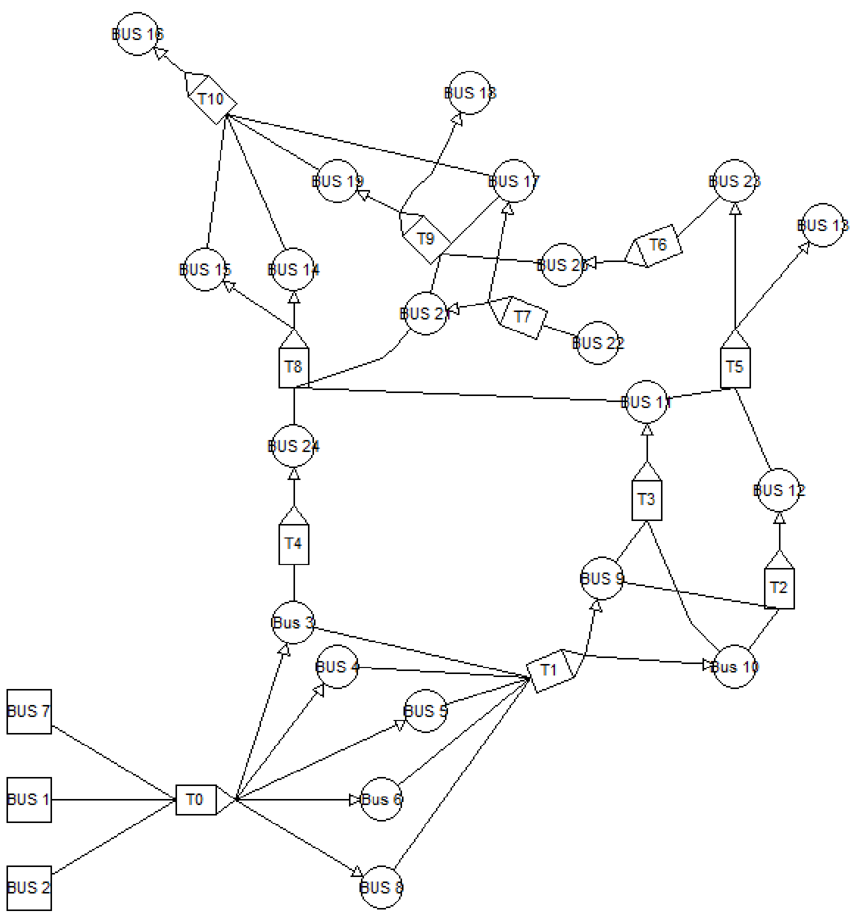


Figure 3.17 DFM model of IEEE RTS-96

The results generated through DFM analysis are multi valued discrete events that can be initial, intermediate, and final events. These sets of events that generate an unanticipated condition due to software logic errors, hardware failures and environmental conditions or can generate anticipated conditions that representing the system behaviour.

A DFM model uses the Multi-Valued Logic (MVL) rules to represent the behavior of the total system by modeling how the sub-systems/components interact with each other. By including the nominal and different failure modes of a sub-system/component, the impact of that particular sub-system/component on the rest of the system can be captured. Once a DFM model is constructed to represent the behavior of the system, automated deductive or inductive algorithms built into DFM can be applied.

Deductive analysis is the backward analysis from effects to causes. The backward analysis finds the set of variables through nodes, edges, transfer and transition boxes that generate a set of prime implicants.

The DFM system model represents both the hardware and software conditions. All the system components in a DFM model have pre-defined conditions. Similarly the software used for system control and monitoring has initial set points. The combination of both the system and the software conditions produce a set of prime implicants. Based on the system knowledge the user can define the system top events. The system top events are normally critical conditions that may lead to system failure. Prime implicants are output of deductive analysis. The shortest way from fault to an initiating event is a DFM model is called a Minimal Cut Set (MCS) which eventually leads to top events that can cause system failure.

Inductive analysis is the forward analysis from cause and effects. For a particular set of inputs, the output can be normal output or may contain errors. The desired states can verify the system requirements whereas the undesired states can verify the system safety behaviour.

We have already discussed that it has six building elements and a decision table is associated with each transfer box. It is used to quantify the relationships between its input and output process variable nodes. This table is a mapping between the possible combinations of the states of the input process variable nodes and the possible states of the output process variable nodes. Decision tables are extension of truth tables in that they allow each variable to be represented by any number of states.

The analysis of a DFM system model constructed according to the rules conducted by tracing sequences of events backward from effects to causes (i.e., "deductively") through the model structure, to identify the paths and the order by which combinations of hardware and/or software conditions can propagate through the system to produce system events of interest.

The DFM model has many states which are discretized according to the nodes of the model. This discretization is shown in the tables mention below. These tables help to understand the DFM model, system, and its different components.

State	Meaning
-2	Very Low voltage
-1	Low voltage
0	Normal
1	High voltage
2	Very high voltage

Table 3.2 Discretization Value of 138KV bus

State	Meaning
-2	Very Low voltage
-1	Low voltage
0	Normal
1	High voltage
2	Very high voltage

Table 3.3 Discretization value of 230KV bus

For 138KV system, the normal voltage is 138KV but low and very low voltage is specified by the system configuration. Normally it is set to be 10% to 15% of the nominal value.

For the figure 3.3, there are transfer boxes and the mapping between the processes variables are shown in the decision table. The decision tables are constructed with logical inputs between process parameters. The decision tables are shown below for T0 to T10.

INPUT			OUTPUT				
BUS1	BUS2	BUS7	BUS3	BUS4	BUS5	BUS6	BUS8
-2	-2	-2	-2	-2	-2	-2	-2
-2	-1	-1	-1	-2	-2	-2	-2
-1	-2	-2	-1	-2	-2	-2	-2
-1	-1	0	0	-1	-1	-1	-1
0	-1	-2	-1	-1	0	-1	-1
0	0	0	0	-1	0	-1	0
1	0	2	0	0	1	1	0
1	2	-2	0	-1	-1	-1	-1
2	-2	-2	0	-2	-1	-1	-1

Table 3.4 Decision table for T0 in IEEE RTS

In the first row of figure 3.4, all the conditions are -2, which means all the conditions have very low voltage value and near to trip the transmission line. In the third row, input have -1, -2 and -2, (low, very low, and very low) and it has -1, -2, -2, -2 and -2 (low, very low, very low, very low, and very low) corresponding value. At the end row, input is 2, -2, and -2 (very high, very low and very low) and output is 0,-2,-1,-1, and -1 (normal, very high, high, high and high)

INPUT					OUTPUT	
BUS3	BUS4	BUS5	BUS6	BUS8	BUS9	BUS10
-2	-2	-2	-2	-2	-	-
-1	-2	-2	-2	-2	-	-
0	-1	-1	-1	-1	-1	-1
-1	-1	0	-1	-1	-1	-1
0	-1	0	-1	0	-1	0
0	0	1	1	0	0	0
0	-1	-1	-1	-1	-1	-2
0	-2	-1	-1	-1	-2	-1
2	-2	-2	0	0	-1	-1

Table 3.5 Decision table for T1 in IEEE RTS

In the above figure 3.5, the output of first row shows BUS9 and BUS10 are tripped (-), which means due to very low voltage at input, the out busses are tripped.

INPUT		OUTPUT
BUS9	BUS10	BUS12
-1	-1	-1
-1	0	-1
0	0	0
-1	-2	-2
0	-2	-1
1	-2	0
1	-1	0
1	2	1

Table 3.6 Decision table for T2 in IEEE RTS

INPUT		OUTPUT
BUS9	BUS10	BUS11
-1	-1	-1
-1	0	-1
0	0	0
-1	-2	-2
0	-2	-1
1	-2	0
1	-1	0
1	2	1

Table 3.7 Decision table for T3 in IEEE RTS

INPUT	OUTPUT
BUS3	BUS24
-2	-
-1	-2
0	0
1	0
2	1

Table 3.8 Decision table for T4 in IEEE RTS

INPUT		OUTPUT	
BUS11	BUS12	BUS13	BUS23
-1	-1	-1	-2
0	0	0	0
-2	-2	-2	-
1	1	1	0
-1	-2	-1	-2
0	-2	-1	-2

Table 3.9 Decision table for T5 in IEEE RTS

INPUT	OUTPUT
BUS23	BUS20
-2	-
-1	-1
0	0
1	1
2	2

Table 3.10Decision table for T6 in IEEE RTS

INPUT	OUTPUT	
BUS22	BUS21	BUS17
-2	-2	-2
-1	-1	-1
0	0	0
1	1	1
2	2	2

Table 3.11 Decision table for T7 in IEEE RTS

INPUT			OUTPUT	
BUS11	BUS21	BUS24	BUS14	BUS15
-1	-2	-	-2	-2
-1	-1	-2	-2	-2
0	0	0	0	0
-2	1	0	-1	-1
-1	2	1	0	-1
0	2	1	1	1
0	1	1	1	1
1	-2	-2	0	1

Table 3.12 Decision table for T8 in IEEE RTS

INPUT			OUTPUT	
BUS21	BUS20	BUS17	BUS18	BUS19
-2	-	-2	-2	-
-1	-1	-1	-1	-2
0	0	0	0	0
1	1	1	1	1
2	2	2	2	2
2	1	-2	0	1
1	-1	-1	0	-1
-2	-2	-2	-	-

Table 3.13 Decision table for T9 in IEEE RTS

INPUT				OUTPUT
BUS14	BUS15	BUS17	BUS19	BUS16
-2	-2	-2	-	-
-2	-2	-1	-2	-
0	0	0	0	0
-1	-1	1	1	0
0	-1	2	2	1
1	1	0	1	1
1	1	0	-1	0
0	1	-	-	0
-1	-1	0	0	0
-2	-1	0	2	0

Table 3.14 Decision table for T10 in IEEE RTS

This kind of DFM analysis thus shares many of the conceptual features of fault tree analysis. A fault tree is a graphical model that represents the combinations of individual component failures which can lead to the occurrence of an overall system failure. We have found that in smart electrical transmission system, voltage instability, harmonics, transient, etc are the major cause of fault. Here are constructing a fault tree by using DFM model for voltage stability. To obtain a timed fault tree from the system model, we have identified different desirable and undesirable states to the model. This system condition is usually expressed in terms of the state(s) of one or more process variable nodes, which are thus taken to be the fault tree "top event(s)." A does not matter table entry is not included in the fault tree since it does not affect the occurrence of events. For analysis, BUS24 = -2 as a top event has been defined as a situation in which the voltage at the specific bus reaches a dangerously low level.

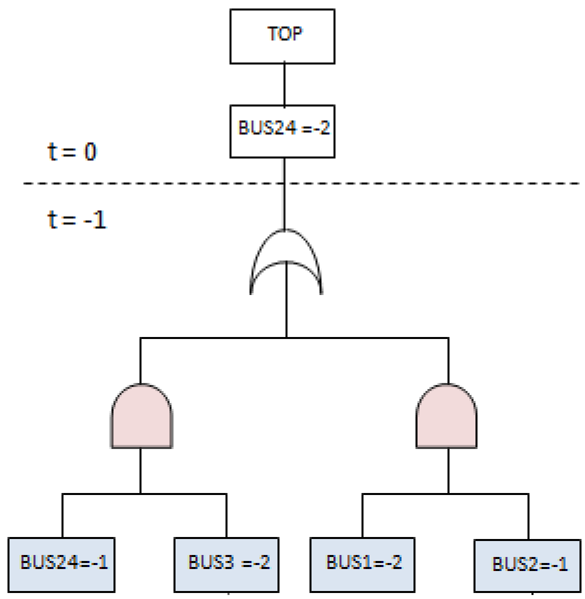


Fig. 3.18 a) Construction of timed fault tree

A dotted line separates the top event and the events at the second level to indicate the presence of a time transition between the events at the two different levels. In figure 3.18 a),

{(BUS24= - 1 @ t = -1)}

AND

{(BUS2 = - 2 @ t = - 1)}

OR

{(BUS1= - 2 @ t = -1)}

AND

{(BUS2 = - 1 @ t = - 1)}

These are found to be the causes and the states of the fault. Note that a dotted line separates the top event and the events at the second level to indicate the presence of a time transition between the events at the two different levels. Now we backtracking the fault and reach to the more deep point of the exact location of origin of fault. Continuation of the backtracking steps on the right most branches produces the structure of the timed fault tree.

For the top event:

At time 0, BUS 24 = -2 (tripped)

There are 4 prime implicants

Prime implicants # 1

At time -1 , BUS 24 = -1 (Low voltage)

Prime implicants # 2

At time -1 , BUS 3 = -2 (Very low voltage)

Prime implicants # 3

At time -1 , BUS 1 = -2 (Very low voltage)

Prime implicants # 4

At time -1 , BUS 2 = -1 (Low voltage)

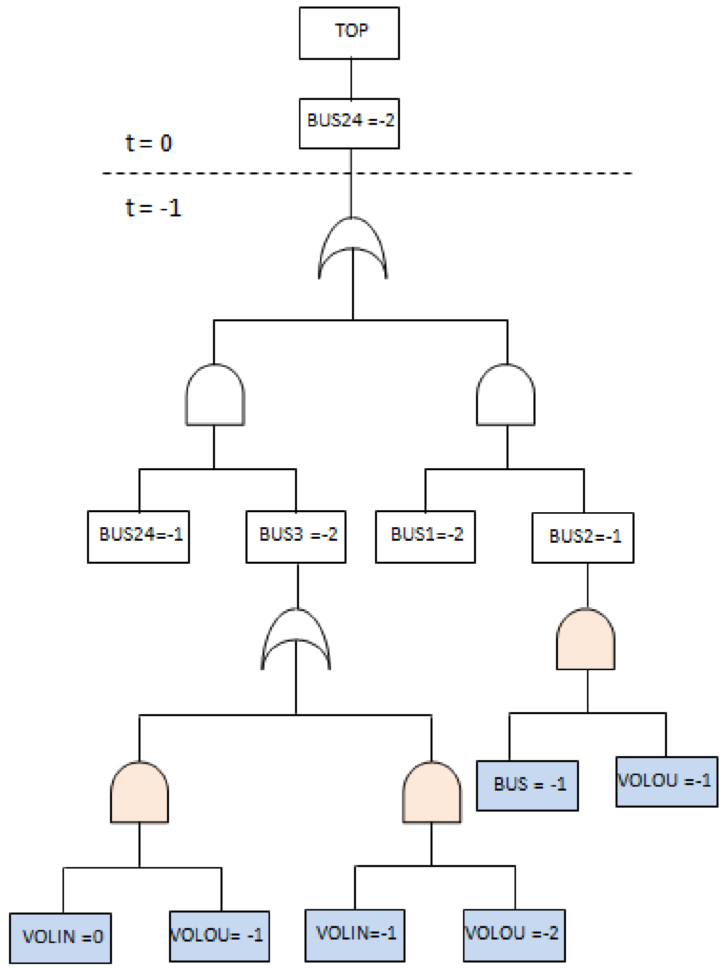


Fig. 3.18 b) Timed fault tree

In this case, BUS14, BUS15, and BUS16 will be off due to no supply from the BUS24. In this scenario, if we consider smart transmission system then at the time of system over loading, the control centre will feed the specific portion of the system from some other side or transfer some load of that over loaded system to other side. This mutual load sharing will helps to avoid the over loading and prevent tripping of the major area of the transmission system.

The backtracking procedure terminates when the basic events are reached. DFM model allows modeling control systems with feedback or feed forward characteristics. When a

DFM model with feedback or feed forward loop is analyzed deductively, a node can be traced back to itself in the fault tree construction. Figure 3.18 b) is a timed fault tree for the fault that is make up with the deductive and inductive analysis of the DFM properties. By this procedure, we can get a root cause of the fault and the path line of the fault and it cause. The main thing is the selection of top event which should be selected correctly.

CHAPTER 4

CONCLUSIONS AND FUTURE RESEARCH

4.1 Conclusions

This thesis investigates the reliability analysis and modelling of smart electrical transmission system where generation, distribution and substations are connected in an electrical power network and enjoying benefits of a complete network. Improvement of the present electrical transmission network has been presented with the addition of communication infrastructure and makes our system smart with the addition of smart electrical equipments. It is presented that dynamic flowgraph methodology can extended to model the behaviour and effect of electrical power network in electrical transmission system. It is useful to model the complete embedded system with the help of dynamic flowgraph methodology which is the best choice. Timed prime implicants and timed fault trees can be generated to analyze the model and to identify areas of improvement. The major contributions of this thesis are as follows;

1. The development of smart electrical transmission system model.
2. The presentation of different features of smart electrical transmission system.
3. The reliability analysis of smart electrical transmission system by using IEEE RTS-96 model.
4. The reliability modeling of electrical transmission system by using dynamic flowgraph methodology.
5. Set a new important topic for the future work.

4.2 Recommendation for the Future Research

It is recommended that future research should investigate the computational capability and scalability of the DFM Software Toolkit as well as its performance when implementing DFM models of complex systems and processes like complete control system of smart electrical transmission system, smart control centre and substation. Future research is also recommended to develop a design of Protection and Control (P&C) system of complete smart electrical power system (generation, transmission and distribution). This includes the selection and configuration of P&C systems for suitable operation of complete system. The availability of a complete system design and specifications allows the finding of reliability data of basic components of the system. This assists in performing detailed reliability analysis. For example, reliability data of basic components can be used in the timed fault trees to measure reliability and occurrence of events of interest. In addition, the control logic and control flow need to be assigned upon completion of system design.

A detailed DFM model to emulate both the behaviour of the smart electrical transmission system and its components and the effect of the communication system need to be constructed. The model construction will become possible when detailed specifications of the smart electrical power system including generation, transmission and distribution systems are available. The detailed model can be used to study the functionality of the system and measure the reliability of the system. It can be used to predict the occurrence of events and identify the corresponding consequences. A prototype of the system should be implemented and this can assist in performing testing and research to obtain actual results and checking system's behaviour. It allows the establishment of a reference for comparison with the DFM model implemented for the system. Also, the knowledge of system behaviour can be used in creating a DFM model with higher accuracy.

We presented that DFM in the field of electrical power system first time, up till now it has been used in control networks of nuclear power plants and control network of space shuttle launching system.

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