DELHI TECHNOLOGICAL UNIVERSITY

DEPARTMENT OF ELECTRICAL ENGINEERING

CERTIFICATE

This is to certify that the dissertation entitled "**FAULT LOCATION ON A HIGH VOLTAGE SERIES COMPENSATED TRANSMISSION NETWORK** is an authentic report of the project done by **RACHNA** in the partial fulfillment of the requirement for the award of degree of Master of Technology in Power Systems by the Delhi Technological University during the year 2012-13.

Project Guide	**Head of the Department**
Dr. RACHANA GARG	**Prof. Madhusudan Singh**
Associate Professor	**Head of the Dept**
Dept. of Electrical Engineering	**Dept. of Electrical Engineering**
DTU, Delhi	**DTU, Delhi**

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ABSTRACT

The demand for electrical energy is increasing exponentially and along with this, the size and complexity of the power system is increasing. This requires more compact and flexible equipment to increase the stability

In order to minimize the overall cost and to enhance the power transfer limit, series compensation has been a fast growing area since earlier eighties. The obvious fact is that series device helps in achieving steady state limit by damping power oscillations. In addition, the series compensation device compensates for VAR losses by reducing the effective reactance resulting into better efficiency. The series compensation is configured as a fixed capacitor located in series with the line. The capacitor is protected by a connecting a MOV across it. MOV bypasses the capacitor during high voltage conditions protecting the capacitor. The MOV conducts immediately after the voltage drop across capacitor exceeds a certain voltage level (V_{ref}). Due to being non linear in nature, MOV bring instabilities in the system. Also addition of such devices results in inaccuracy in determining the fault location.

In this work, the fault and analysis on a high voltage series compensated line is carried out and the data obtained during fault analysis is utilized in determining the fault location

The simulation for system under study is carried out on MATLAB/SIMULINK. A two end transmission system with a series compensation unit at the centre is taken and fault analysis on this system is carried out and MOV behavior is studied. Results are evaluated for different types of faults. To overcome the problems associated with series compensated lines, an algorithm is applied on the line to achieve accuracy in fault location. The data obtained during fault analysis is utilized in determining the fault location.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER-1

INTRODUCTION

INTRODUCTION

Electrical power demand in India is growing at tremendous rate causing a large mismatch between generation and demand. To meet this increase in demand, power system has to be largely interconnected. As interconnections grew, networks became more complex, increasing the impacts of system on each other [1]. This presented ever increasing difficulties in analysis of the transmission network. Hence the system is becoming less secure due to increased complexities leading to several power outages. It may results in large reactive power flow, dynamic swings and thus threatening power system security and reliability.

Reconstruction of the electricity market and increased system size has made the analysis required to survive a transient contingency complex. Interconnected system with greater interdependence among its members, heavier transmission loadings and the concentration of some large generation units at light loads has further complicated it [2]. With the advent of competitive market structure and flexibility to control power across the transmission network, several technical issues regarding the network's capability to transfer power arise. These issues involve the physical capability of the network to handle power flows maintaining reliability and security. For controlling power and enhancing the usable capacity, the flexibility of the system needs to be improved. In this view FACTS devices came into existence.

FACTS devices are used extensively to increase the operational efficiency of interconnected power systems. FACTS devices are capable of controlling the network condition in a very fast manner and this unique feature of FACTS devices can be employed to improve the transient stability of a system [3,4], provided they are optimally placed. Reactive power compensation is an important issue in electrical power systems and FACTS devices play an important role in controlling the reactive power flow and hence reducing the system voltage fluctuations and in improving transient stability. These aspects are playing a major role in the operation and control of the deregulated electricity market. With the growing stress on today's power systems, many utilities are constantly facing the threat of transient stability problems [5]. For large power systems, more than one compensator may be required to achieve the desired performance. So there is need to analyze the effect of application of compensator in different locations of a system. Previous works suggest that shunt FACTS devices assist stabilized voltage support when sited at the mid-point of the transmission line [6].

With the increase in electrical power demand, the need to increase the transmission capability of the existing line is felt. The transmission capability of the line can be increased by compensating the reactance of the line either by series or shunt compensation. In the present work, capacitor bank is used in series with the line. But the problem with series capacitor is its protection and hence MOV is used for the protection of series capacitor. The presence of series capacitor alters the behavior of line by reducing the effective reactance of the line.

Series-compensated lines are very important links associated with power generation and energy consumption regions. All the advantages relevant for the series capacitor compensation [7] are the primary reasons for increased use of such the transmission links. However, installation of series capacitors (SCs), equipped with nonlinear Metal-Oxide Varistors (MOVs) for overvoltage protection, on transmission lines causes certain problems for protective relaying and fault location [SAHA]. Accurate fault location requires to offset the series compensation effect and the problems associated with MOV has been developed [8].

It is not practical to design and build electrical equipment or networks so as to completely eliminate the possibility of failure in service. It is therefore an everyday fact of life that different types of faults occur on electrical systems, however infrequently, and at random locations. Existing power system has created an excellent record in detecting and isolating most of the faults and fast restoring of the system but problem arises when it comes to networks with wide configurations [7] where fault location becomes extremely difficult due to presence of non linearities.

Also when faults occur on a transmission network equipped with some compensation device, then also conventional methods are not suitable. The very obvious reason is that these devices introduce non linearities [7] and hence the available methods till now are no longer valid.

In a large power system network, occurrence of faults are more likely, so it is very essential to detect the fault in that area and isolating it as quickly as possible or else security of system becomes a critical issue [8]. Power system faults can be broadly categorized into a no of types. Some of the faults are easily detectable using the existing protective equipments. Symmetrical faults come under this category. But there is a category of faults which are not characterized by enough current to be measurable. This type of fault includes High impedance fault comes under this category. HIF's cannot be cleared by normal protective relays. Hence new techniques have been proposed which are utilized in detecting faults and to estimate the phasors of the voltage and current signals, essential for transmission line distance protection [9].

1.2 FAULTS IN POWER SYSTEM

A fault on a power system is an abnormal condition which involves an electrical failure of power system equipment operating at one of the primary voltages within the system.

Faults usually occur in a power system due to either insulation failure, flashover, physical damage or human error. These faults may either be three phase in nature involving all three phases in a symmetrical manner, or may be asymmetrical where usually only one or two phases may be involved [10]. Faults may also be caused by either short-circuits to earth or between live conductors, or may be caused by broken conductors in one or more phases.

Sometimes simultaneous faults may occur involving both short-circuit and broken conductor faults (also known as open-circuit faults).

The faults can be broadly classified as:

i. Short circuit faults
ii. Open circuit faults

1.2.1 SHORT CIRCUIT FAULTS

Short-circuit faults can occur between phases, or between phases and earth, or both. Short circuits may be one-phase to earth, phase to phase, two-phase to earth, three-phase clear of earth and three-phase to earth. These are further categorized as :

i. Symmetrical faults
ii. Unsymmetrical faults

SYMMETRICAL FAULTS

A three phase fault is called a symmetrical type of fault. In a three phase fault, all the three phases are short circuited. The three-phase fault symmetrically affects the three phases of a three-phase circuit [11]. It is the only balanced fault whereas all the other faults are unbalanced. There may be two situations- all the three phases may be short circuited to the ground or they may be short circuited without involving the ground. A three phase short circuit is generally treated as standard fault to determine the system fault level.

UNSYMMETRICAL FAULTS

Single phase to ground, two phase to ground short circuits, single phase open circuit and two phase open circuit are unsymmetrical types of fault.

In order to fault analysis to be done on a network, fault currents voltages data are required during a part of or entire fault duration, which is highly, dependent on the fault network and its configuration. Depending on the number of phases involved with the fault and how the faulty lines are connected to the earth, five types of faults can be identified as follows:

i. Single line to ground fault (L-G)
ii. Line to line fault (L-L)
iii. Double line to ground fault (L-L-G)
iv. Three phase to earth fault (LLLG)

L-G Fault

A one-phase to earth short-circuit fault in a high impedance earthed distribution system may cause a sufficient voltage rise on a healthy phase elsewhere in the system that a flashover and short-circuit fault occurs.

L-L Fault

When two phases are involved, it is said to be L-L fault

L-L-G Fault

Most faults do not change in type during the fault period but some faults do change and evolve from say a one-phase to earth short circuit to evolve into a second phase where it changes to a two-phase to earth short circuit fault. This can occur on overhead lines or in substations where the flashover arc of the faulted phase spreads to other healthy phases.

L-L-L-G Fault

This fault involves all the three phases and it is most severe type of fault

1.2.2 OPEN CIRCUIT FAULTS AND HIGH IMPEDANCE FAULTS

Fault levels are generally determined by the intensity of current flow during unhealthy conditions. Sometimes current is large enough to be easily determined by protective devices but sometimes it is not detected due to abnormal current signature.

A high impedance fault (HIF) results when an energized primary conductor comes in contact with a partially-insulating object such as a tree, structure or equipment, or falls to the ground

When the phase wire unintentionally touches or falls on ground without contacting the neutral, then “high impedance fault” is said to be occurred. And it is followed by very high impedance resulting in a very low current which makes it hard to be located by protective devices.

1.3 FAULT LOCATION ALGORITHM

Many research efforts have been undertaken on fast and accurate fault location algorithms for single-circuit, double-circuit and series-compensated transmission lines. They can be classified into the following four categories: phasor based, time-domain based, traveling-wave based, and others.

Phasor based algorithms take terminal voltage and/or current phasors as input. The method comprises one-terminal, two-terminal and multi-terminal algorithms.

The one end algorithm is the simplest and dispenses with synchronized data communications with the other ends of the transmission network. However, accuracy of such algorithm is adversely affected by the fault resistance, series compensation devices and fault in feed from remote ends.

In order to estimate the fault locations using multi ends algorithms knowledge of the fault resistance is not needed. In contrast, these algorithms require accurate synchronisation of sending and remote ends fault data in the computation of distance to fault. If the fault information of the remote ends is available, several algorithms have been developed using both synchronized and unsynchronised sample data.

The principle behind the standing wave propagation algorithms is that waves generated at the position where the fault occurs can be monitored from either ends to estimate the fault location. One of the distinctive advantages of this method is that it can be easily applied to long transmission lines with considerable shunt capacitive currents. Since the position of the fault is determined from the measurements of the times between the initial travelling waves set up by the fault and subsequent waves resulting from reflections, time measurements to be precise up to several nanoseconds.

In high-speed tripping applications it is desirable for the fault location to be completed before the current disappears due to relay operations . For phasor-based algorithms the acquisition of high-accuracy phasor estimates needs to obtain at least one cycle of data. Therefore the algorithms in this category are not suitable for high-speed applications. Instead, some time-domain algorithms have been developed for single-circuit networks . The traveling-wave based algorithms use the return time of the reflected waves traveling from the fault point to the line terminal as a measure of distance to the fault. Other algorithms using wavelet techniques artifcial neural networks , and support vector machines have been developed as well.

In general these are the major sources of error in any fault location algorithm:

- Line asymmetry**-** Algorithms developed under the assumption of the transposed lines are applied to untransposed lines, and will introduce errors in consequence.
- Shunt capacitance**-** Most algorithms utilize the lumped parameter model which neglects the charging effect of the lines. However, for long transmission lines an exact representation of the line needs to fully consider shunt capacitance.
- Fault resistance.
- Load current
- Source impedances. In practical power systems the equivalent source impedance of every terminal changes continuously.

1.4 OBJECTIVE OF THE THESIS

Following objectives have been defined for the present work:

- Simulation of High impedance fault
- Use of series capacitor bank for the compensation of line reactance.
- Protection of series capacitor
- Simulation of different faults for the series compensated line
- Fault location using a fault location algorithm.

1.5 OUTLINE OF THE THESIS

Chapter 2 begins with a detailed study of High impedance faults. Because these faults are difficult to be located, protective relays fail to detect it. Wavelet Transformation technique is discussed which utilizes multiresolution analysis to demarcate fault signals and non fault signals.

In chapter 3, transmission line models are briefly discussed. A two end transmission model has been simulated at a later stage. A two end transmission line has been used for fault analysis in later chapter.

In chapter 4, model of a two end transmission network equipped with series compensation device is developed. Different types of faults are simulated and the voltage and current waveforms are observed.

In chapter 5, a fault location algorithm is applied on a two end transmission network equipped with series compensation. This chapter presents the importance of developing an algorithm for detecting faults for modern transmission networks connected with VAR compensating devices. Development of algorithm in time domain space is discussed and tested on a two end transmission network model simulated in MATLAB.

Chapter 6 presents the assessment of results obtained from the algorithm.

Chapter 7 gives the conclusion of the thesis and suggestions for future improvements.

CHAPTER 2

HIGH IMPEDANCE FAULT

INTRODUCTION

Most transmission line faults are caused by lightning strikes on transmission towers and 90% of these are short duration temporary faults. When a fault occurs in a transmission network, it will be first detected by the protective relays which quickly send signals to relevant circuit breakers to isolate the faulty part of the network.

Faults on a distribution system are normally detected by simple over current relays. Faults through a high impedance object such as dry earth or asphalt do not have enough current to operate over current relays and must be cleared manually. Such a high impedance faults may pose a serious threat to the public. Equipments are now commercially available to detect a few percentage of high impedance faults, but use of these equipments bring in operational issues which affect the whole system.

The IEEE Power System Relay Committee working group on High Impedance Fault Detection Technology [12] defines High impedance faults as those that "do not produce enough fault current to be detectable by conventional over current relays or fuses". High impedance fault on distribution systems create distinctive challenges for a power system protection engineer. HIFs do not produce enough currents to be detectable by conventional protective equipments [13]. Due to their abnormal fault signature and difficult detection, these have always been difficult for identification. Another unique feature of high impedance faults is that they exhibit wide fluctuations in current levels.

From the beginning of power distribution, the power system protection engineer has been challenged with the detection of high impedance faults. As such, it should be noted that whereas traditional protection is designed to protect the power system, High impedance protection is primarily focused on the protection of people and property.

A high impedance fault (HIF) results when an energized primary conductor comes in contact with a partially-insulating object such as a tree, structure or equipment, or falls to the ground. The significance of these undesirable faults is that they represent a serious public safety hazard as well as a risk of fire is there. A high impedance fault is characterized by very high impedance [12] such that it is not detected by normal over current protection, such as fuses and over current relays. Unlike low impedance short circuits, which involve relatively large fault currents and can be easily detectable by conventional over current protection, these HIFs represent little threat of danger to power system equipment

A high impedance fault can occur in three ways [14,15]:

i. When conductor breaks and falls on the ground
ii. When conductor doesn't break but comes in contact with insulating objects through insulation failure
iii. A sagging conductor

Fig 2.1 shows condition when conductor breaks down and falls on ground. While in Fig 2.2 arching is shown when a conductor comes in contact with ground (an insulating object).

Fig 2.1: Dropping of conductor on earth [15]

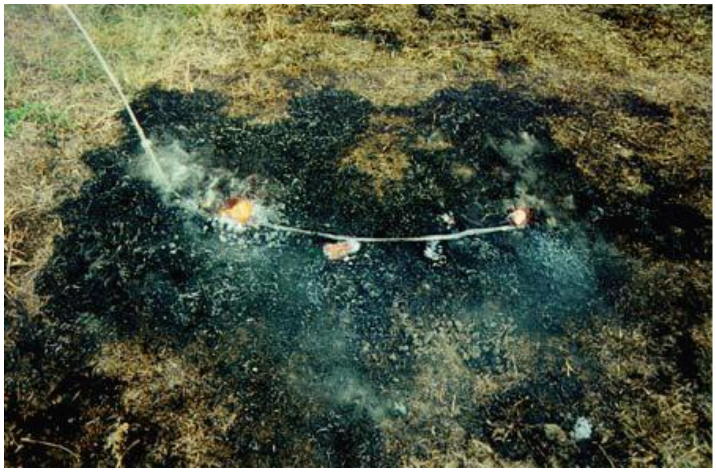


Fig 2.2: Conductor fallen on ground causing arching [14]

High impedance faults produce current levels in the range of 0 to 50 amperes. Typically, an HIF incorporates arcing and flashing at the point of contact. Only a few percent (5-20%) of all distribution faults are high impedance faults [13]. The detection of high impedance faults is one of the difficult problems which power industry is facing. Advances in digital technology have enabled practical solutions for the detection of these previously undetectable faults.

Table 2.1: Value of HIF currents for different insulating objects [16]

Insulating object	Current(A)
Wet grass	50
Wet sod	40
Dry grass	25
Dry sod	20
Wet sand	15

HIFs are accompanied by non stationary signals such as transient voltages and currents which are localized in both time and frequency domains. Therefore an approach which accounts for the non stationary nature of the signals is developed. The approach is based on discrete wavelet transformation. In this work the generated transient signal is decomposed into time and frequency domain and the wavelet analysis is done.

2.2 LITERATURE REVIEW

Location of faults in power transmission lines is one of the main concerns for all the electric utilities as the accurate and timely fault location helps to restore the power supply in the minimum time [17]. Fault location methods for transmission lines are broadly classified as impedance based method, travelling wave (TW) based method, and knowledge based method which uses artificial neural network and/or pattern recognition techniques. Impedance based method uses steady state fundamental components of voltage and currents. On the other hand, the travelling wave (TW) based method uses the voltage and current signals from both end(s) of the line [18]. Knowledge based method is one in which consists of new techniques like artificial neural network or pattern recognition.

For faults such as high impedance fault, in which there is not enough current to be detectable by protective equipments. HIFs are accompanied by non stationary signals such as transient voltages and currents which are localized in both time and frequency domains. To account for both time and frequency domain, since the early eighties, several techniques have been researched and proposed the detection of such faults, including the application of harmonics [19-21], Kalman filtering method [22] artificial neural networks [23,24], wavelet transform [25-29]. Today, only a few commercial protection devices, i.e., the GE F60 DFM, SEL 451, ABB's REF550, claim that they perform high impedance fault detection in overhead lines, with a good success [29].

A.Siadatan presents a technique [30] based on doffing function which utilizes chaotic function for determining the appropriate formula and setting parameters to carry out detection of fault.

In later 2011, A.N Milioudis [31] proposed a technique based on narrow band line communication. In this, the band frequency range is examined by monitoring the input impedance of the system. Besides [32] presented a novel time domain high impedance fault detection scheme based on low frequency patterns.

Distance protection is one of the most common methods used to protect transmission lines. A distance protection scheme [30,33] has been used based on analyzing the measured voltage and current signals at the relay location using WT with MRA. MRA can be used in estimating fundamental phasors of voltage and current needed to calculate the impedance to the fault point.

WT was introduced at the beginning of 1980s and has attracted much interest in the fields of speech and image processing since then. A new wavelet based method using multi resolution analysis [34] for the detection of HIF was introduced which analyses the effect of choice of mother wavelet on the detection performance. The technique involves the decomposition of transient signal in multi scale by utilizing the good localization performance of the wavelet in both time and frequency domain which calculates the size spectrum of each feeder line in timing floating window.

2.3 WAVELET TRANSFORMATION TECHNIQUE

As the electrical signature observed in quite unobvious in nature, Wavelet analysis is a good tool to solve this problem, it is different by signal decomposition, location and scale of wavelet function, so that in time domain and frequency domain have good localization properties of wavelet analysis of transient signals can be multi scale decomposition and then different amounts of spectrum analysis, extraction of different amounts of spectrum on characteristics as basis for identification. In order to minimize aliasing filter generated must be used strictly wavelet frequency while according to relay real-time requirements, the selection should be considered the mother wavelet with compact support

Fourier algorithm, frequency domain analysis or a simple time-domain analysis are insufficient to accurately describe the non-stationary signals such as transient voltage and current. Wavelet analysis is a good tool to solve this problem, it is different by the signal decomposition location and scale of the wavelet function, so that in the time domain and frequency domain have good localization properties of wavelet analysis of transient signals can be multi-scale decomposition, and then different amounts of spectrum analysis, extraction of different amounts of spectrum on characteristics as the basis for identification. In order to minimize aliasing filter generated must be used strictly wavelet frequency, while, according to relay real-time requirements, the selection should be considered the mother wavelet with compact support.

In the choice of wavelet basis functions, using the MATLAB wavelet toolbox of a series of wavelet experiment, test and found more suitable for the extraction of *db3* wavelet feature signal of these failures, this data processing are *db3* wavelet basis carried on. Simulation model of the sampling frequency f=20kHz. The collected signal processing, using the *db3* wavelet decomposition of five layers of the signal, respectively, be d1, d2, d3, d4, d5 and other detail coefficients.

Wavelet transform has successful applications in many fields such as acoustics, signal and image processing, speech discrimination, optics and, recently, power system analysis. Its application in power systems has been researched and developed for the past several years. Typical applications include power system protection [24], analysis of power system transients [35], power quality detection and classification [36] etc. Unlike traditional Fourier transform, a wavelet transform is capable of providing the time and frequency information simultaneously, and hence, gives multiple resolutions in frequency and time, which is a potential feature for analyzing transient signals containing both high and low frequency components together [20,32].

Wavelet transform (WT) has the ability to decompose signals into different frequency bands using multiresolution analysis (MRA). It can be utilized in detecting faults and to estimate the phasors of the voltage and current signals, which are essential for transmission line distance protection.

2.4 MRA (MULTI RESOLUTION ANALYSIS)

Fig 2.3 presents the multi-resolution analysis algorithm. The WT algorithm gives either currents or voltages signals as they change with respect to time at different scales, where large scales are associated with low-frequency components and small scales are associated with high frequency signatures.

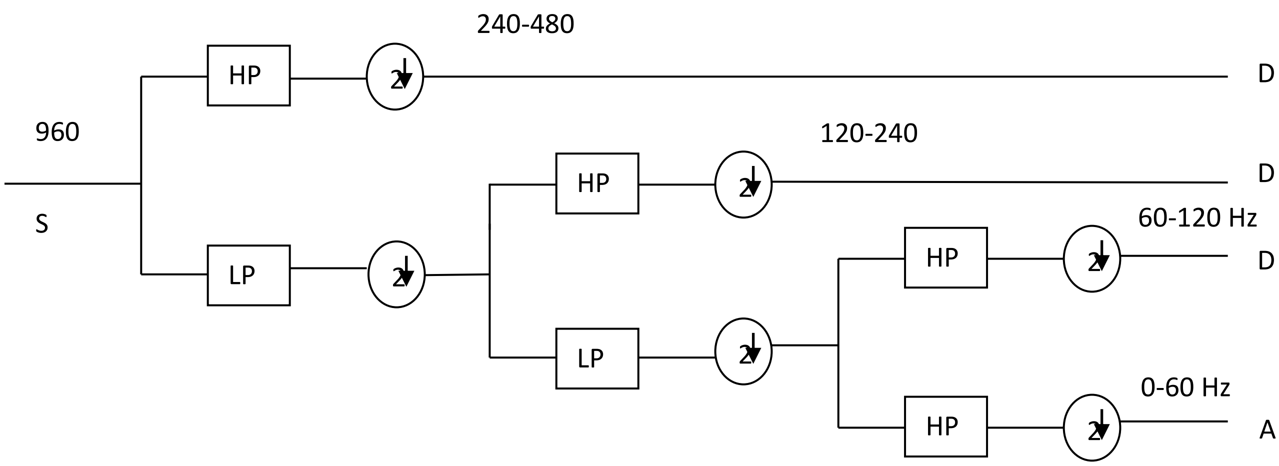


Fig 2.3: Multiresolution analysis algorithm

The WT can be implemented with a specially designed pair of FIR filters called a quadrature mirror filters (QMFs) pair. The QMF is also known as multistage filter because it decomposes a signal into high and low frequency components by going through various stages [28].

The output of the signal passing through the multistage filter is decimated by a factor of 2.The output of HP filter gives the detailed version of high frequency component known as "**details**". On the other hand, the output of LPF is processed through another multistage filter and this operation is repeated a no of times up to the desired frequency level which is called "**approximation**"

Fault detection can be obtained from the details of first decomposition level of current signal using db1 wavelet [34]. This level contains the high frequencies associated with the fault.

2.5 FAULT DETECTION ALGORITHM

Fig 2.5 represents the algorithm [25] which by utilizing distinct features of WT for phasor estimation. The algorithm depends on utilizing discrete WT with MRA due to its powerful analyzing and decomposing features. Since the sliding data window is short, containing one cycle of samples or sometimes less, the removal of the dc component using a pre-band pass filter with a small delay of 2 ms is essential for fast and accurate phasor estimation[28]. Although the pre-band pass filter introduces this small delay, it leads to faster phasor estimation for signals with long time constant.

The measured three-phase voltage and current signals are filtered using a pre-band pass filter with center frequency of 60 Hz to attenuate the dc component. These six signals are sampled at a sampling frequency of 960 Hz. The algorithm starts by collecting a one cycle sampled data window for each signal. Based on a sampling frequency of 960 Hz, one cycle contains 16 samples. A sliding data window is used, i.e., for each new sample to enter the window the oldest one is disregarded and the algorithm starts.

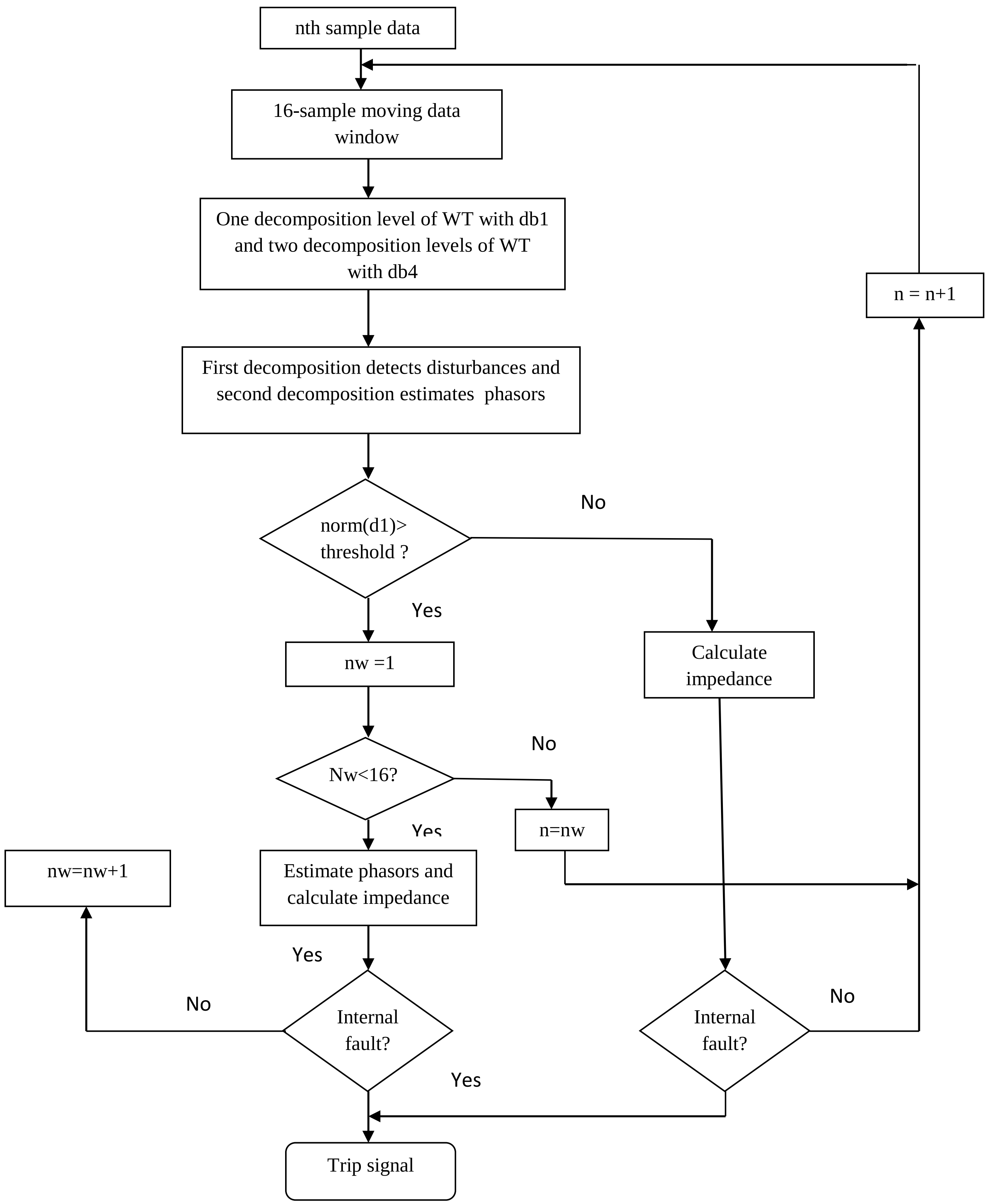


Fig 2.4: Fault detection algorithm[28]

For each data window the WT decomposes the six measured signals. Using db1 and from the first decomposition level for the three-line currents, a fault can be detected by observing the norm of the detail coefficients D1. At this level the high frequency components can be extracted from the signal and any disturbance can be detected. If the norm of D1 for all line currents is less than a certain threshold (M), it means that the lines are healthy. Using db4 and from the approximations (A2) of the second decomposition level for the six signals, the phasors can be estimated.

As long as no disturbances are detected, the impedances seen by the relay are computed based on the WT phasor estimation and the 16 samples data window.

2.7 SYSTEM UNDER STUDY

To analyze the behavior of the HIF, the CFE DCO conducted field test [24] on a 13.8 kV feeder. Data records were obtained from this study. It was reproduced by the fall of a cover 13.8 kV feeder on dry grass, as is shown in Fig. 2.6.

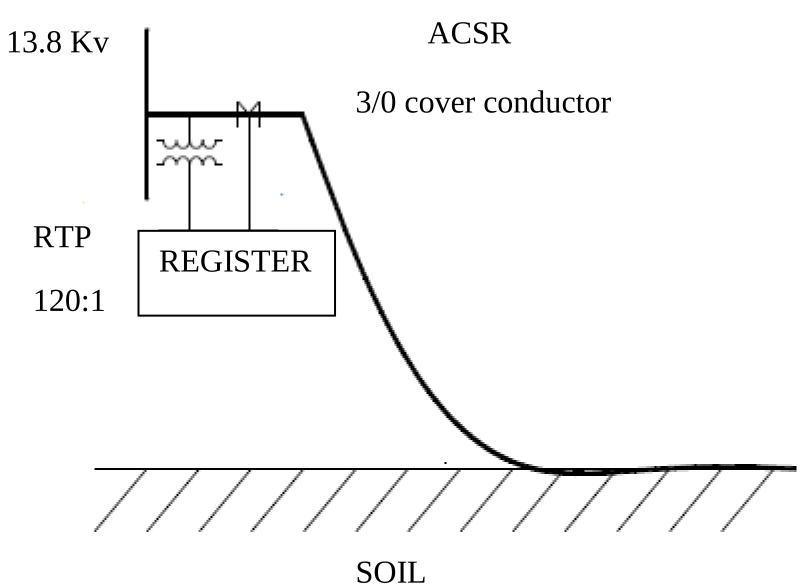


Fig 2.5: Case study system for tests conducted for HIF

Fig. 2.6 corresponds to the fall of a cover conductor, phenomenon which caused concern for dealing with high impedance faults mainly because the overcurrent protection did not operate. Fig. 2.7 shows oscillographic data of high impedance fault current on dry grass conditions.

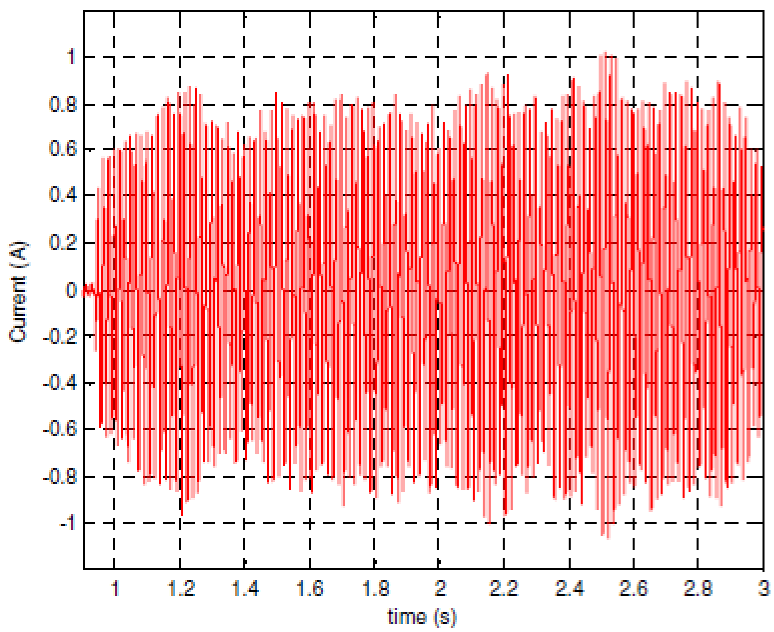


Fig 2.6: HiF current

Fig 2.6 shows that the fault current reaches up to 1 A peak and it is observed a highly random behavior, the current grows up in the first cycles, then it grows and maintains quasistable.

Fig. 2.7 presents the first cycles of high impedance fault current and voltage as a reference when field test was performed on it.

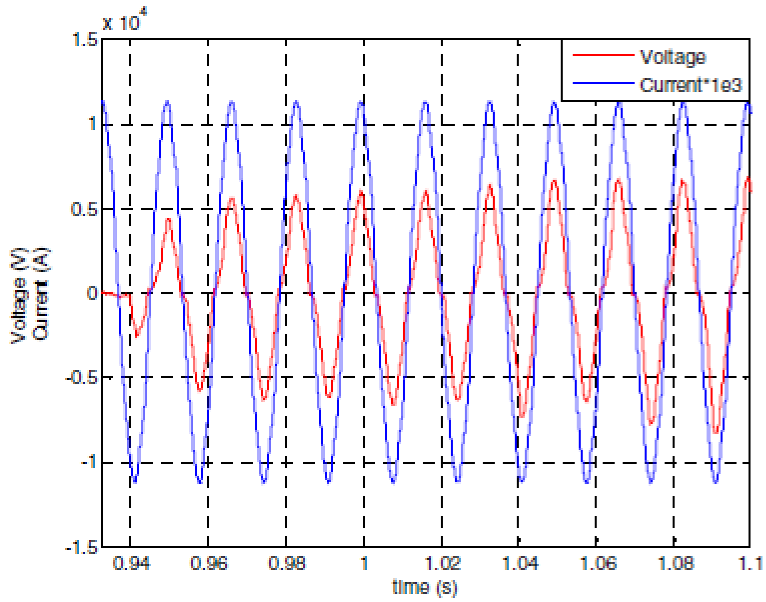


Fig 2.7: Voltage and current (field test)

In addition Fig. 2.7 shows the relation between current and voltage, the current grows up at the first cycles, also it is observed that the waveform of the current is asymmetric and an important feature for study is that the current is in phase with the voltage due a mainly resistive behavior.

The 13.8 kV system was simulated in ATP/EMTP, and the behavior of system was studied. WT was applied on the system resulting in its decomposition into details and approximations as shown in Fig 2.8. It can be observed that A4 is low frequency while D4, D3, D2, D1 are high frequency components.

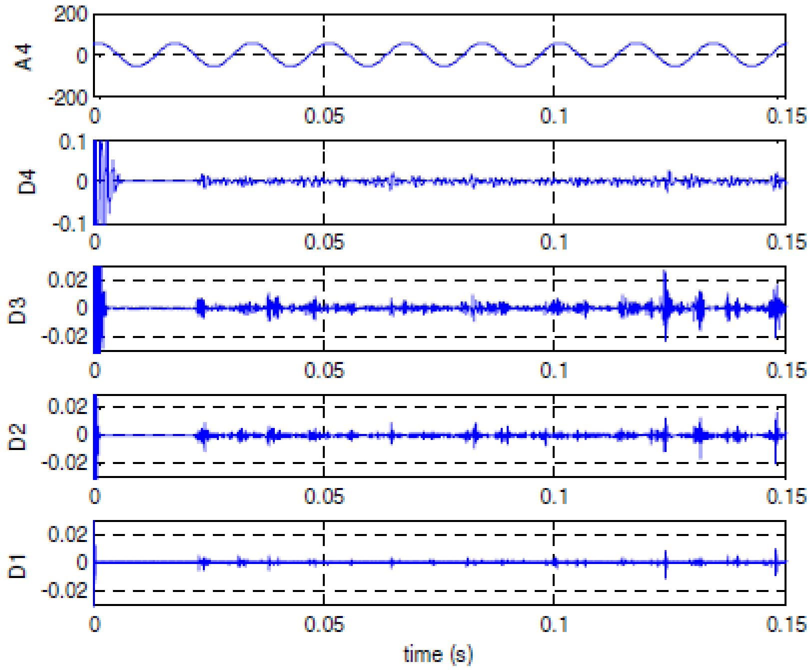


Fig 2.8: WT decomposition at feeder with downed conductor

Fig 2.9 shows decomposition D3 of healthy and faulty phases. The fault is in D3 (a) and D3(b),D3(c) are healthy phases.

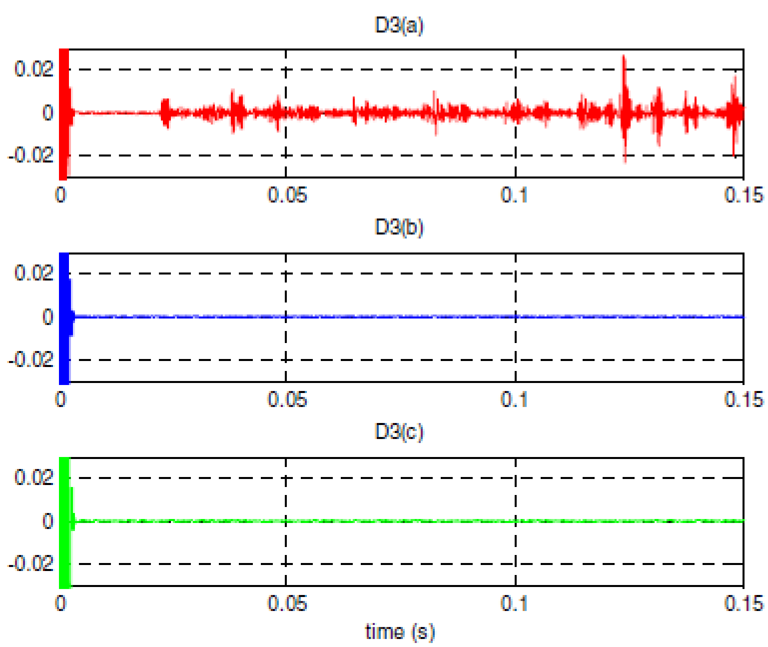


Fig 2.9: Current at substation

2.8 CONCLUSION

Discrete wavelet transform in high impedance fault make us capable of identifying the characteristics of the fault at different frequencies because they cannot be observed at a fundamental frequency.

In the analysis of field test there were important features of the high impedance fault such as low current and arcing, also were observed that the current of high impedance fault has random behavior, nonlinearity, asymmetry and current in phase with the voltage due to a mainly resistive behavior. DWT was used to study signals at different frequencies, the tool allowed us to observe the behavior of current in the frequency. The DWT analysis gives some signals from high impedance fault which can be used for a successful detection.

CHAPTER-3

MODELLING OF TRANSMISSION LINES

INTRODUCTION

As the interregional network has grown higher and higher, transmission voltages have been superimposed to provide additional transmission capacity. In this view, several geographic areas are connected to form a single network supplying power to millions of customers. Due to this, networks became more complex increasing the impacts of systems on each other [1]. This presented ever increasing difficulties in analysis. Hence a need arose to analyze the networks in detail. A proper study of transmission networks must be done in order to learn the impacts which are hampering the system capability. This chapter deals with the various transmission configurations and their detailed modeling.

In such power system networks, the occurrence of faults are more likely to happen, and fast and accurate determination of fault location on the transmission line is vital for stability, reliability and economic operations of power system.

In order to obtain highly accurate estimation of fault distance, it is important to consider the facts affecting the power system. The performance of fault location methods can only be tested by analyzing data during fault. But complexities arise [sk] in recording data during actual system faults. Some of these can be summarized as below:

i) Diversity in all types of fault data is impossible to achieve from real time system faults.
ii) Inconsistence data.
iii) Data may not be precise.
iv) Synchronization errors.
v) Equipment errors.

To overcome the above errors, an alternative was suggested which was actually a scaled down prototype of the faulted network [1]. But this method is costly and far more complex to design an accurate transmission network model. Besides, it is difficult to design a model which represents the entire transmission network.

Computer based power simulation methods are best to model transmission lines. Variety of transmission networks with specific requirements can be easily modeled in computer simulation packages and fault data can be recorded precisely during the entire simulation. In this research project, a transmission line has been modeled in MATLAB/SIMULINK software and the measured data is utilized in obtaining the fault location with the help of fault algorithm.

When considering a single line transmission network, transmission line can be represented as lumped pi cascaded network elements with mutually coupled resistances, inductances and capacitances [36].

3.2 TRANSMISSION NETWORKS

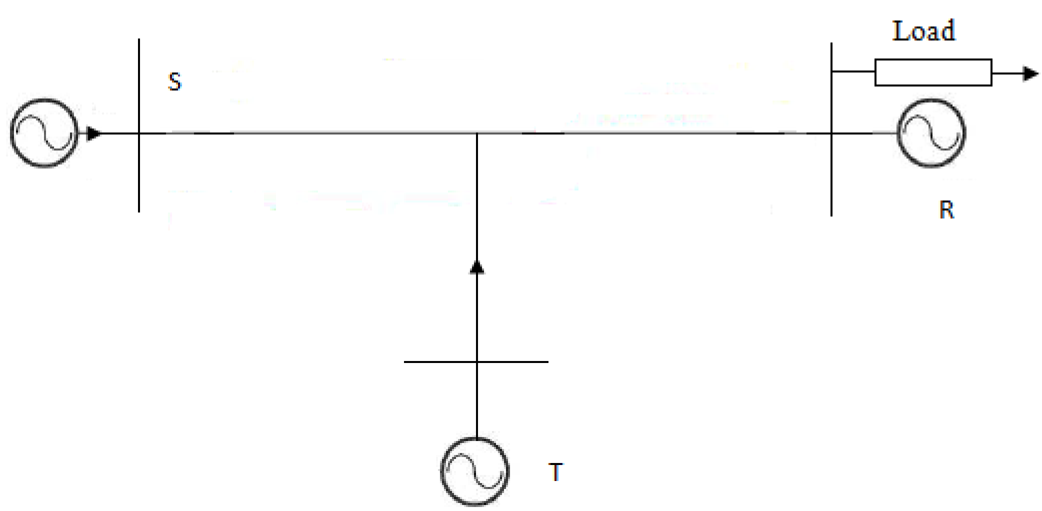
While studying fault analysis, the accuracy of fault location is found to be further dependent on the following network configurations:

i. Transmission network fed from one end.
ii. Transmission network fed from two ends.
iii. Transmission network with multi ends.

Estimation of fault location largely depends on the type of network. To ensure accurate fault location, these configurations need to be studied properly. In this regard, different transmission network configurations are shown in Fig 3.1.

i) Transmission network fed from one end

ii) Transmission network fed from two ends



iii) Transmission network fed from multiple ends.

Fig 3.1: Transmission network configurations

3.3 MODELLING OF TRANSMISSION LINES

A transmission line can be represented by series impedance and shunt admittance.

The shunt impedance matrix can be represented by equation (3.1) i.e.

$$[Z] = [R] + j\omega[L] \tag{3.1}$$

For a three phase line, R and L can be given by:

$$R = \begin{bmatrix} R_C & 0 & 0 \\ 0 & R_B & 0 \\ 0 & 0 & R_C \end{bmatrix} \quad \text{and} \quad L = \begin{bmatrix} L_A & L_{AB} & L_{AC} \\ L_{BA} & L_B & L_{BC} \\ L_{CA} & L_{CB} & L_C \end{bmatrix}$$

Where R is resistance of the conductor and L is the inductance.

The shunt admittance matrix can be given by:

[Y]= jω[C]

where C is the capacitance of the line

Shunt matrix X_C will be:

$$X_C = \frac{1}{J\omega[C]} \text{ , where } C = \begin{bmatrix} C_A & C_{AB} & C_{AC} \\ C_{BA} & C_B & C_{BC} \\ C_{CA} & C_{CB} & C_C \end{bmatrix}$$

Suffix A,B,C refer to three phases of the transmission with self impedances and AB, AC and BC indicates the mutual effect between phases.

3.4 CLASSIFICATION OF TRANSMISSION LINES

On the basis of length, transmission lines can be categorized as:

- Short transmission line
- Medium transmission line
- Long transmission line

3.4.1 SHORT TRANSMISSION LINE

For line lengths less than 80 Km, the voltage or current variations are not much and it can be said that, for line lengths below 80 Km, the parameters can be assumed to be lumped and not distributed. Such lines are known as short transmission lines.

In the case of short transmission lines, shunt capacitive currents can be neglected and it is assumed that the current injected from one end is identical to the other end. This approximation is valid in most studies where the line fault currents are high and hence the effects of shunt capacitance currents can be completely ignored [37].

The line series resistance and reactance can be lumped and represented for the total length of the line. In this case, voltages and currents at the sending and receiving ends can be related and expressed as:

$$V_X = V_S + I(x)*Z(x) \tag{3.2}$$

$$I_X = I_S \tag{3.3}$$

Where, x is a point on the transmission line at a distance from the sending end. V_X and I_X represents the voltage and current at x, and Z(x) can be written as R(x) + jωL(x) where R(x) and L(x) are the lumped resistance and reactance of the line up to the point x. In three phase transmission line, phase quantities can be related as above in a matrix form:

$$[Z_X] = \begin{bmatrix} R_{xA} & 0 & 0 \\ 0 & R_{xB} & 0 \\ 0 & 0 & R_{xC} \end{bmatrix} + j\omega \begin{bmatrix} X_A & X_{AB} & X_{AC} \\ X_{AB} & X_B & X_{BC} \\ X_{AC} & X_{BC} & X_C \end{bmatrix} \tag{3.4}$$

where A,B and C refer to phasors and diagonal terms of equation (3.4) represent the mutual inductive coupling between phases. If the shunt capacitive currents in the transmission line are considerable, the above equation must be written in a shunt capacitance matrix.

3.4.2 MEDIUM LENGTH TRANSMISSION LINE

Transmission line with lengths between 80 Km and 250 Km are considered as medium transmission lines. These can be modeled in two configurations, these are:

i. Nominal-T network

ii. Nominal-Π network

NOMINAL-T

If the transmission line is not very long, an approximate transmission line model can be developed considering the effects of shunt capacitive currents. In this case it is assumed that shunt capacitance can be lumped and connected at the centre of the line [36]. This representation is known as nominal-T network model as shown in Fig 3.2

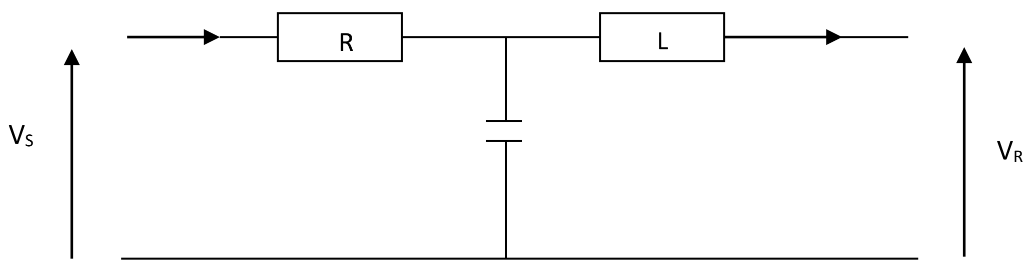


Fig 3.2: Nominal-T Transmission Line network

Using the above figure, the relationship between sending and receiving ends can be obtained as given by equation (3.5):

$$\begin{bmatrix} V_S \\ I_S \end{bmatrix} = \begin{bmatrix} 1 + \frac{YZ}{2} & Z(1 + \frac{YZ}{4}) \\ Y & 1 + \frac{YZ}{2} \end{bmatrix} \tag{3.5}$$

NOMINAL Π NETWORK MODEL

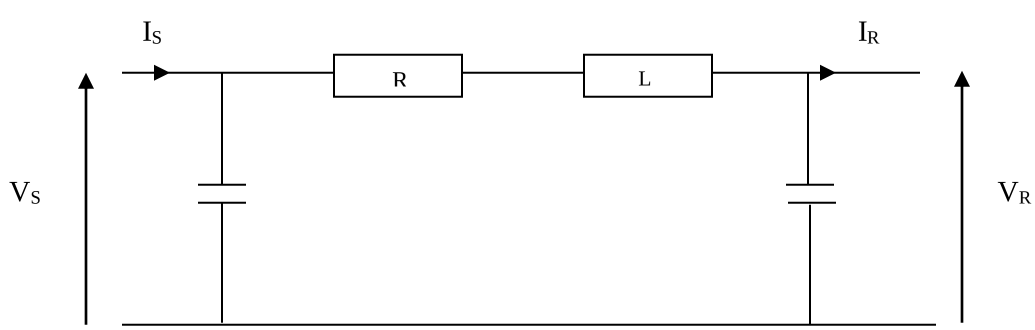


Fig 3.3: Nominal-Π Transmission Line Network

Using the above figure, the relationship between sending and receiving ends can be obtained as given by equation(3.6):

$$\begin{bmatrix} V_S \\ I_S \end{bmatrix} = \begin{bmatrix} 1 + \frac{YZ}{2} & Z \\ 1 + \frac{YZ}{4} & 1 + \frac{YZ}{2} \end{bmatrix} \tag{3.6}$$

V_S and V_R are the sending and receiving ends voltages respectively. I_S and I_R are the sending and receiving ends currents respectively. Z and Y are the total impedance and admittance of the transmission line [37].

The relationship shown in equation (above) can be identified as recursive and hence transmission lines can be represented as serially connected Π networks. However, this representation assumes that the line is ideal and resistance and reactance are uniformly distributed so that the equation (above) can be used to drive the relationship between sending and receiving ends of the line.

3.4.3 LONG TRANSMISSION LINE MODEL

In case, the lines are more than 250 Km in length the lines are known as long transmission lines. In the case of a long transmission line, series impedance and shunt admittance are uniformly distributed along the line, and can be represented as series connected Π networks and each block is considered to be very small[37].

In order to analyze the continuously varying series and shunt currents and voltages along the line, a small Π section of the line is considered at a distance x from the sending end as shown in Fig 3.3.

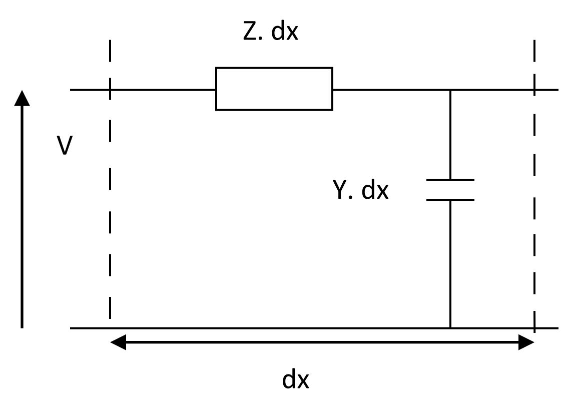


Fig 3.3: Long Transmission Line Model

The voltage and current at distance x are given by equation (3.7)

$$\begin{bmatrix} V(x) \\ I(x) \end{bmatrix} = \begin{bmatrix} \cos\gamma x & -Z_C\, sin\gamma x \\ \frac{1}{Z_C} sinh\gamma x & cos\gamma x \end{bmatrix} \tag{3.7}$$

If the line impedance Z and admittance y are known, surge impedance and propagation constant are given by equation (3.8)

$$Z_C = \sqrt{z/y} \quad \text{and} \quad \gamma = \sqrt{zy} \tag{3.8}$$

CHAPTER-4

FAULT ANALYSIS OF A SERIES COMPENSATED LINE

INTRODUCTION

The fault analysis of a power system is required in order to provide information for the selection of switchgear, setting of relays and stability of system operation [1]. A power system is not static but changes during operation (switching on or off of generators and transmission lines) and during planning (addition of generators and transmission lines).

A knowledge of currents resulting from various types of faults at a location is essential for the effective operation of a network. If fault occurs on the system, the power system engineers noting the presence of fault can operate the appropriate CB’s to remove the faulty line. This however takes considerable time and experience. Faults on power system resulting in high currents and possible loss of synchronism, must be removed as quickly as possible. It is the object of protection to accomplish this.

Short-circuit fault analysis is carried out to ensure the safety of workers as well as the general public. Power system equipment such as circuit-breakers can fail unfortunately if they are subjected to fault duties that exceed their rating. Other equipment such as bus bars, transformers and cables can fail thermally or mechanically if subjected to fault currents in excess of ratings. In addition, to ensure safety, short-circuit fault analysis is carried out and used in the calculation of rise of earth potential at substations and overhead line towers. Other areas where fault analysis is carried out are for the calculation of induced voltages on adjacent communication circuits, pipelines, fences and other metallic objects.

This chapter is confined to the analysis of various types of faults which may occur in a series compensated line. Although design of electrical plant is influenced by the knowledge of fault conditions, the major use of fault analysis is in the specification of protective equipments. Circuit breaker ratings are determined by the fault MVA at this particular location.

4.2 SERIES COMPENSATION

Nowadays power transmission networks are capable of delivering contracted power from any supplier to any consumer over a large geographic area under market control, and thus transmission lines are incorporated with series var compensated devices to increase the power transfer capability and improvement to system integrity [1]. While the new methods have been used to handle the rapidly increasing power demand and to drive the high voltage transmission lines up to the optimum limits, it is vital for the system to be free of disturbances, occurrence of faults are more likely and security of the supply became a critical issue.

In recent years, the highly increasing cost of building new transmission lines, compounded by the difficulty to obtain new transmission corridors, has led to a search for increasing the transmission capacity of existing lines [2]. Use of series capacitors for compensating part of the inductive reactance of long transmission lines increases the power transmission capacity [36]. It also increases transient stability margins, optimizes load-sharing between parallel transmission lines and reduces system losses [basic]. Transmission line compensation implies a modification in the electric characteristic of the transmission line with the objective of increase power transfer capability [38]. In the case of series compensation, the objective is to cancel part of the reactance of the line by means of series capacitors [37]. This result is an enhanced system stability, which is evidenced with an increased power transfer capability of the line and a reduction in the transmission angle at a given level of power transfer.

Series-compensated lines are very important links associated with power generation and energy consumption regions. All the advantages relevant for the series capacitor compensation [38] are the primary reasons for increased use of such the transmission links. However, installation of series capacitors (SCs), equipped with nonlinear Metal-Oxide Varistors (MOVs) for overvoltage protection, on transmission lines causes certain problems for protective relaying and fault location [40]. Accurate fault location requires to offset the series compensation effect and the problems associated with MOV has been developed [39].

Series capacitors are inserted into transmission lines, with a purpose to reduce the effective reactance of the line. This technique is often used with long transmission lines where the voltage drops at the end of line is very low. In this way it is possible to improve the line power transfer capability. It also helps to improve transient stability. However the combination series capacitor with line inductance can create sub synchronous oscillations resulting in damage to generators [40].

Since capacitors produce vars, shunt capacitors are primarily used to compensate poor power factor loads. In general, shunt capacitors are connected in parallel with motor loads to offset the reactive demand of the motors. In some instances, the presence of permanently connected capacitors could produce high receiving end voltage, particularly under light load conditions. Using thyristor switched capacitors, light load over voltage problem can be eliminated effectively.

Basic modeling of the standard transmission line discussed in the previous chapter can be used for developing a fault location algorithm. However, in the recent past new FACTS technology has been used in many transmission networks to control the power transfer in the line, with many other advantages such as higher power transferability, damping of oscillations and improvements to stability etc [38]. The next section describes the detail modeling of series line compensation which is a cornerstone of FACTS technology.

4.3 SERIES COMPENSATION UNIT

One of the main considerations in the design and application of series capacitors is their protection against overvoltage. In modern installations, the traditional gap type scheme which bypasses the series capacitor to avoid overvoltage is replaced with Metal Oxide Varistor (MOV). The main advantage of this protection scheme is that the capacitor is not entirely bypassed during a fault, so reinsertion is instantaneous and without transients [38]. The presence of the capacitor in the circuit immediately after a fault is very important, because it helps the transient stability of the system. Also in case of unbalanced faults, only the protection devices of the faulted phases operate leaving the capacitor of the other phases on line.

To determine the various design parameters for planning and implementing, MOV protected capacitors in a network; it is indispensable to be able to model such devices in a fault analysis program and predict the level of short circuit currents as well as the energy absorbed by the conducting MOV.

Fig 4.1 shows the typical configuration of the series compensation device, with its basic protection mechanism. During normal operations, the series capacitor (C) generates leading VARS to compensate for some of the VAR consumed by the network

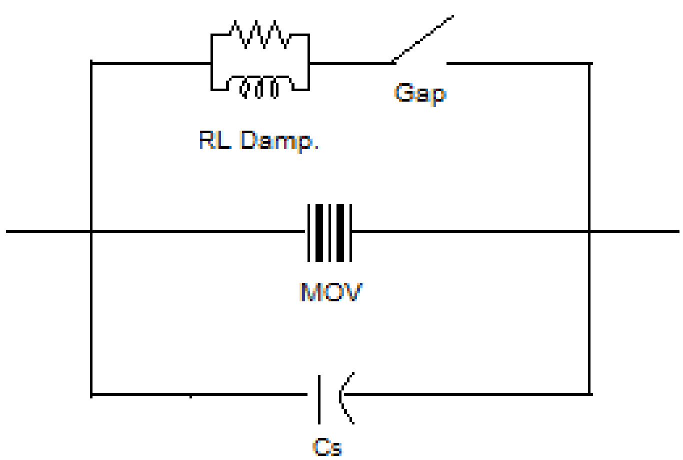


Fig 4.1: Basic series compensating unit with MOV protection

Series compensation device is located in the middle of transmission line and remote load is connected to the remote end of the transmission line network in order to obtain steady state load currents prior to the fault initiation.

4.3.1 CAPACITOR

Capacitor provides tremendous benefits to distribution system performance. Most noticeably, capacitor reduces losses, free up capacity and reduce voltage drop.

By cancelling the reactive power to motors and other loads with low power factor, capacitor decreases the line current. Reduced current frees up the capacity (the same network can serve more load). Reduced current also considerably lowers the I^2R losses.

4.3.2 METAL OXIDE VARISTOR(MOV)

The Metal Oxide Varistor (MOV) is the main protection device, which operates when an over voltage is detected across the capacitor. With a short circuit on the line, the capacitor is subjected to an extremely high voltage, which is controlled by the conduction of MOV. The voltage protection level of MOV is determined with reference to the capacitor voltage drop with rated current flowing through it.

Under normal operation, as long as the voltage across the capacitor is below a protective level, the varistor presents high resistance. When the varistor conducts, its resistance becomes very low and it diverts part of the fault current away from the capacitor. Since there is an upper limit for energy dissipation in the MOV, for its protection there is special circuitry with an energy monitor, which calculates the energy dissipated by the varistor and triggers the air gap to divert the current from the MOV. The bypass switch closes when the gap energy limit is reached.

4.3.3 SPARK GAP

during a severe fault current case, the MOV is subjected to overheating due to large energy dissipation exceeding its threshold limit. The energy limit of MOV depends on the intensity of current and duration of its conduction. To protect the MOV from such condition, spark gap is provided to bypass the current until fault level is reduced.

In this work, the behavior of fixed series compensated extra high voltage transmission lines during faults is simulated and its behavior is observed. Most of the over-voltage protection schemes for series capacitors are limited in terms of size and performance, and are easily affected by environmental conditions and the need for more compact and environmentally robust equipment is required. Use of series capacitors for compensating part of the inductive reactance of long transmission lines increases the power transmission capacity. Emphasis is given on the impact of modern capacitor protection techniques (MOV protection). The simulation study is performed using MATLAB/SIMULINK® and results are given for different types of fault.

4.4 SYSTEM UNDER STUDY

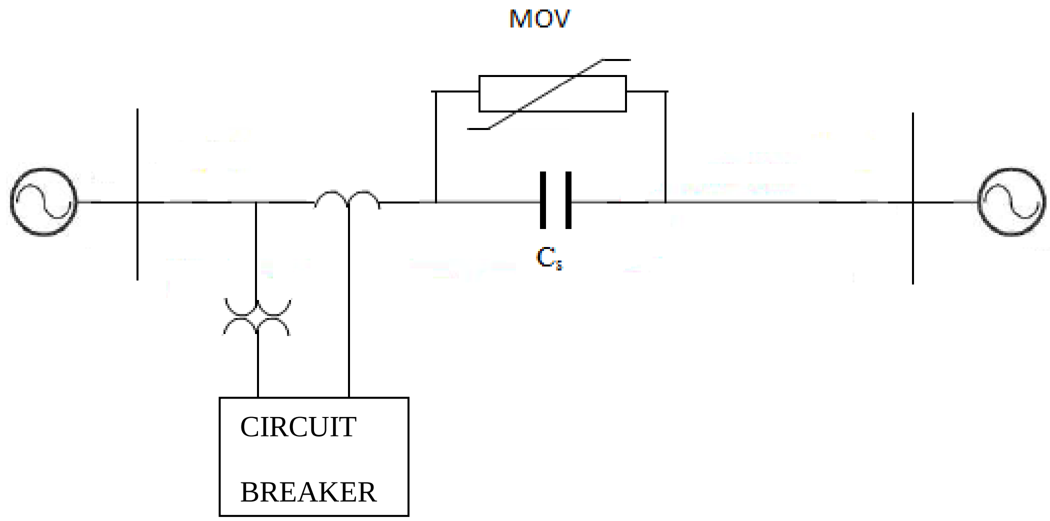


Fig 4.2: Single line diagram for system under simulation

The system of Fig. 4.2 is studied using MATLAB/SIMULINK. System comprises of a 400 kV line with series capacitor installed at its centre. The positive sequence impedance of the line is 94.5Ω. Compensation level is assumed to be 60%. Capacitive reactance required for the compensation is X_C=56.7Ω. MOV protection level required to protect the capacitors at 2.5 times the nominal capacitor voltage.

4.5. MATLAB/SIMULINK MODEL

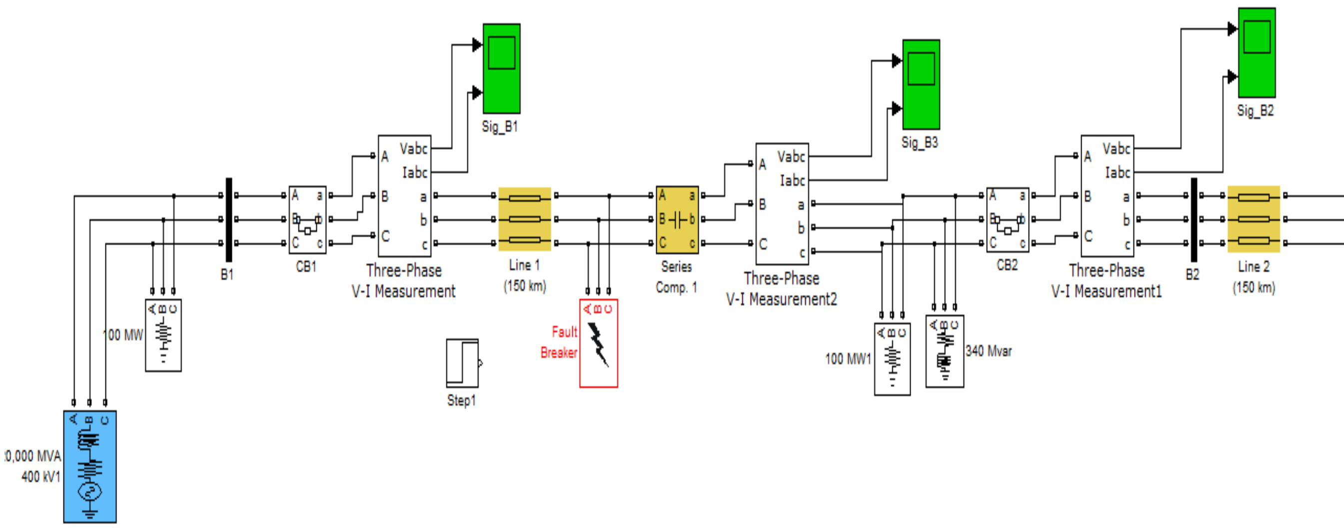


Fig 4.3: MATLAB/SIMULINK Model of system under study

A two end transmission line is modeled with the line configuration shown in Fig 4.3 in MATLAB/SIMULINK. A fault breaker is connected to simulate different types of fault

4.6 RESULTS

NORMAL CONDITIONS

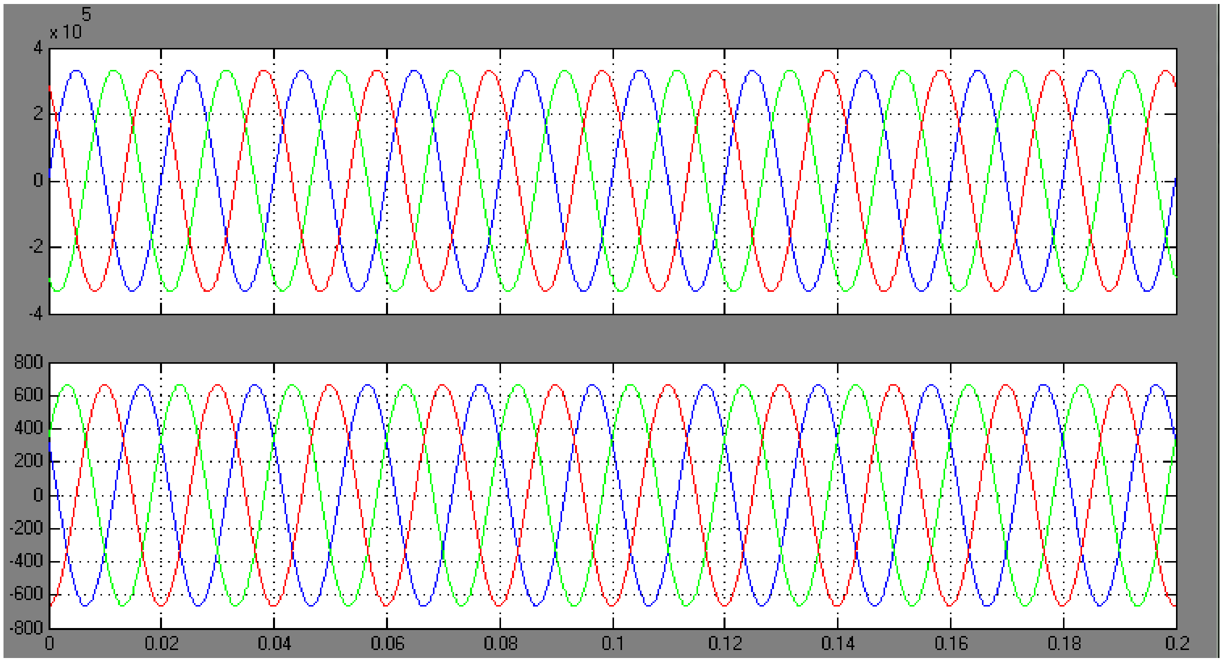


Fig 4.4: Voltage and current at sending end during healthy conditions.

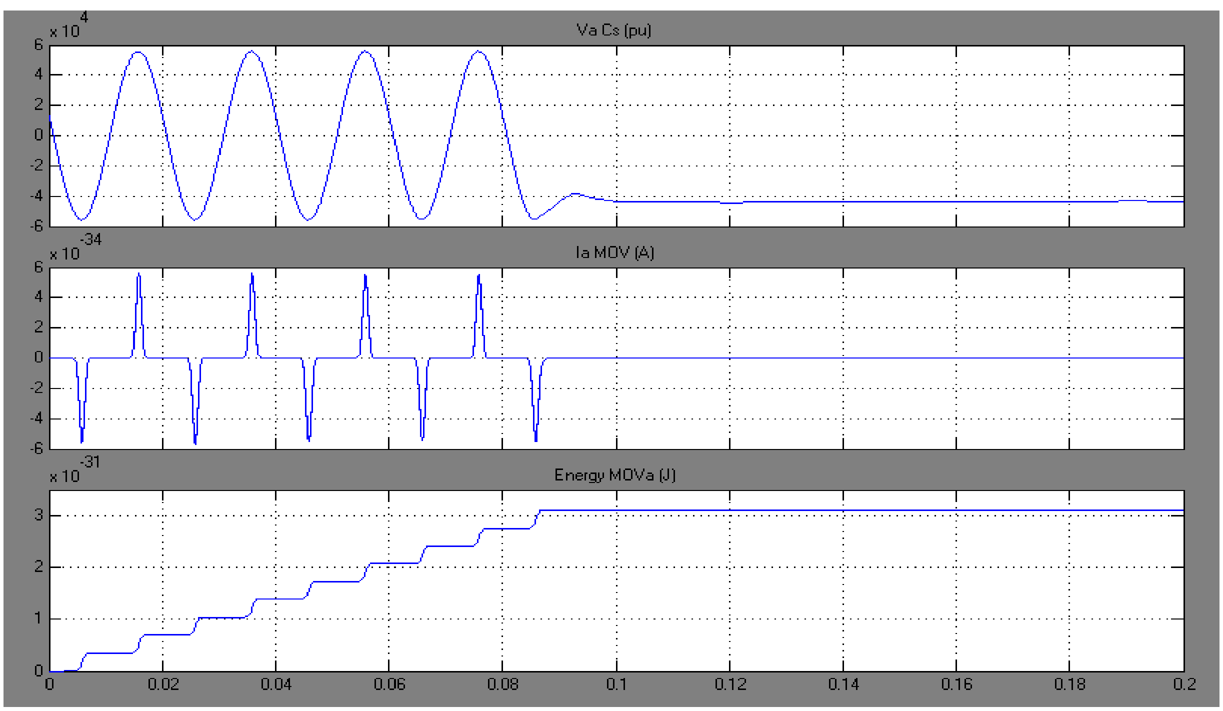


Fig 4.5: Capacitor voltage(V_{cs}), Current across MOV and energy dissipated across MOV during healthy conditions

L-G FAULT

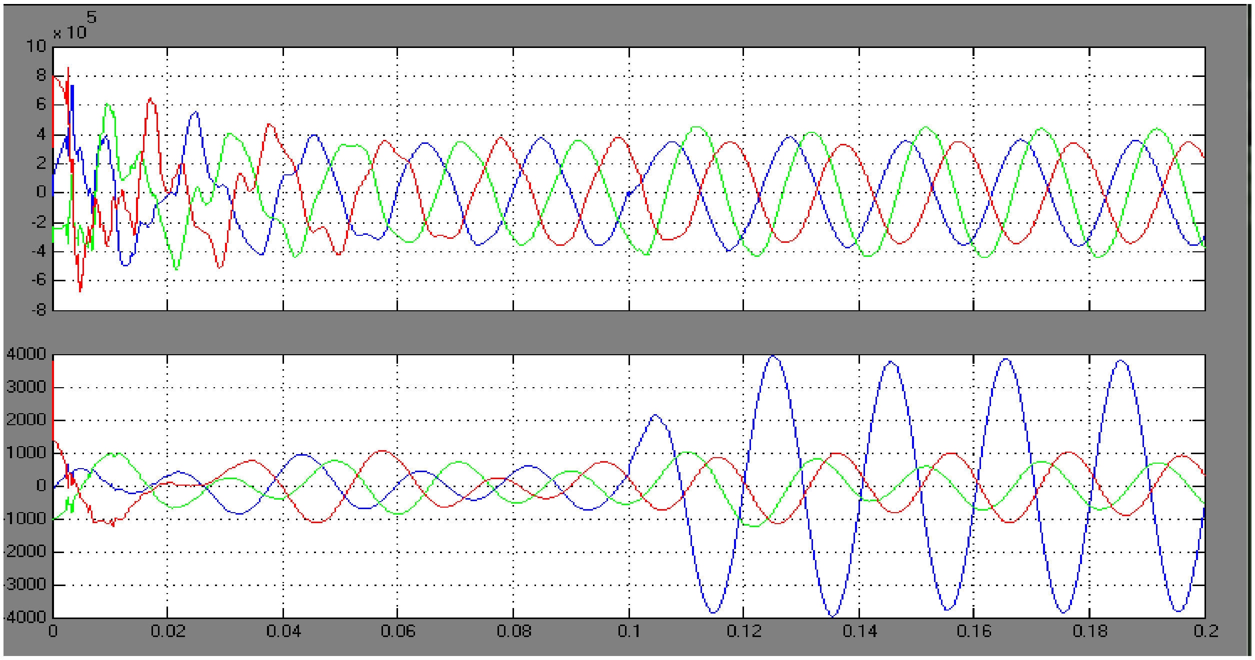


Fig 4.6 : Voltages and currents at faulty bus during L-G fault applied at 0.1 secs

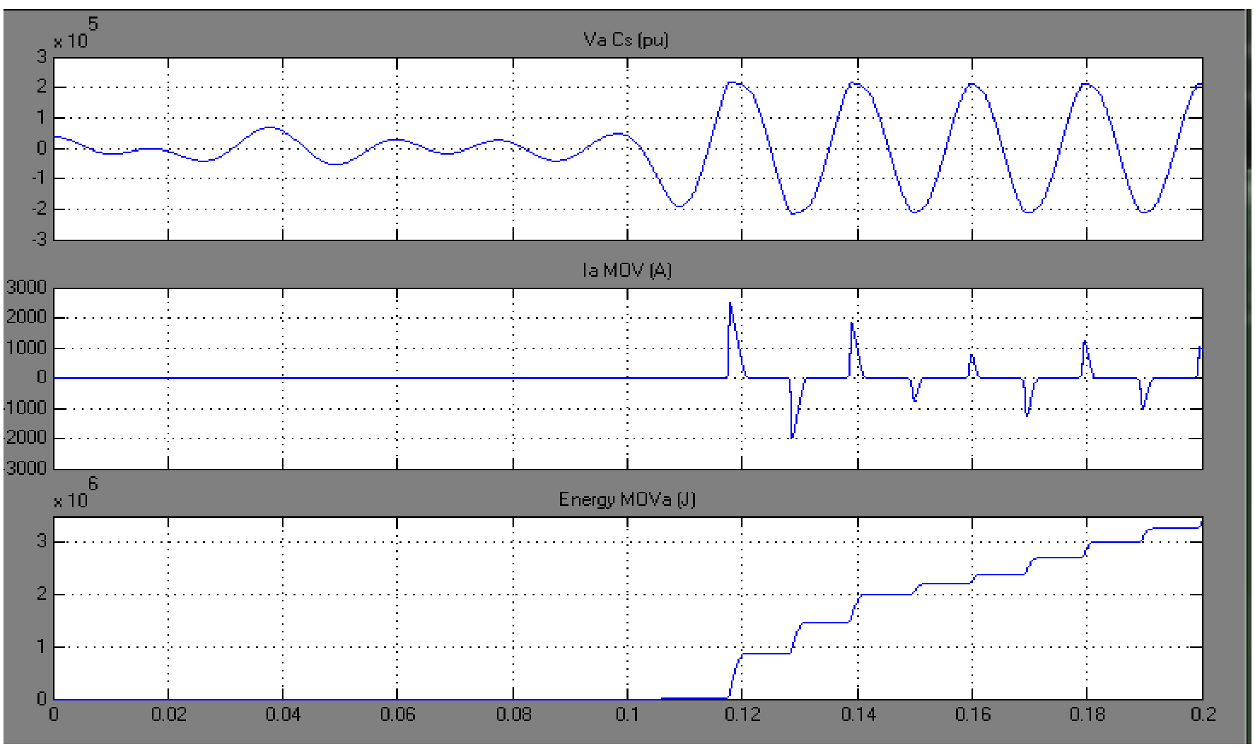


Fig 4.7: Capacitor voltage(V_{cs}), Current across MOV, and energy dissipated across MOV during L-G fault applied at 0.1 sec

L-L-G FAULT

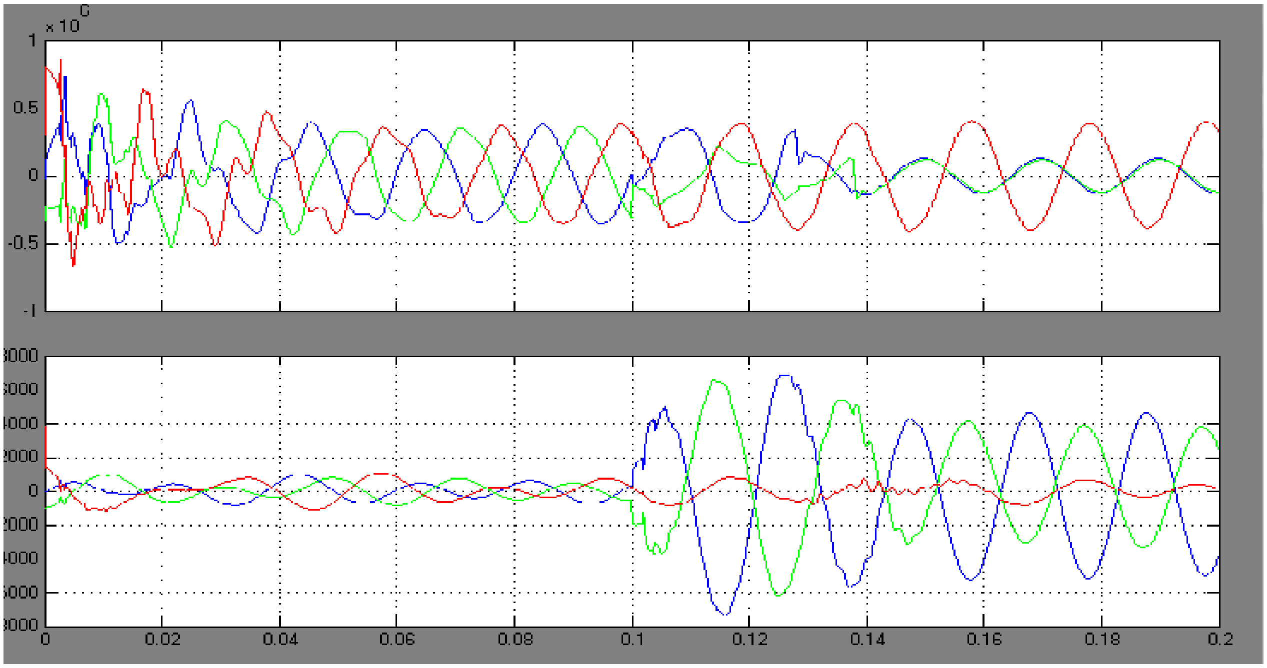


Fig 4.8: Voltages and currents at faulty bus during L-L-G fault applied at 0.1 secs.

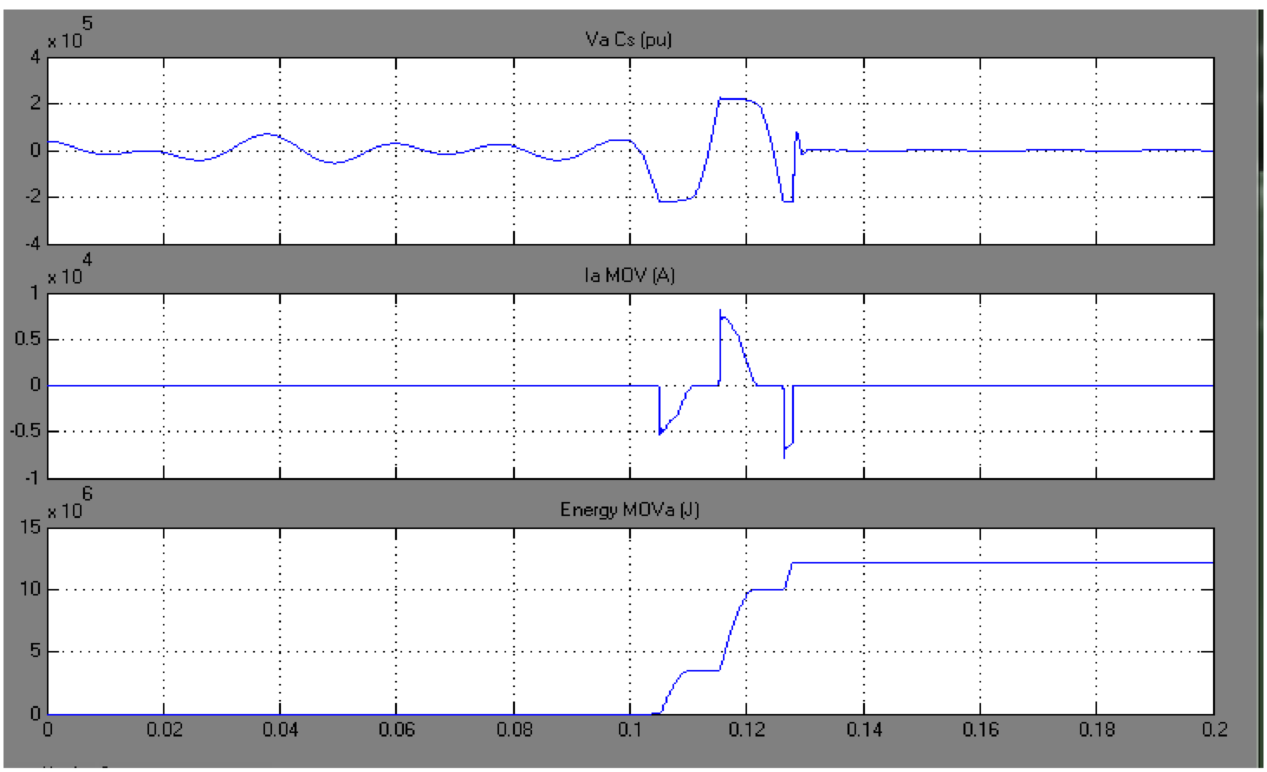


Fig 4.9: Capacitor voltage(V_{cs}), Current across MOV, and energy dissipated across MOV during L-L-G fault applied at 0.1 sec

L-L-L FAULT

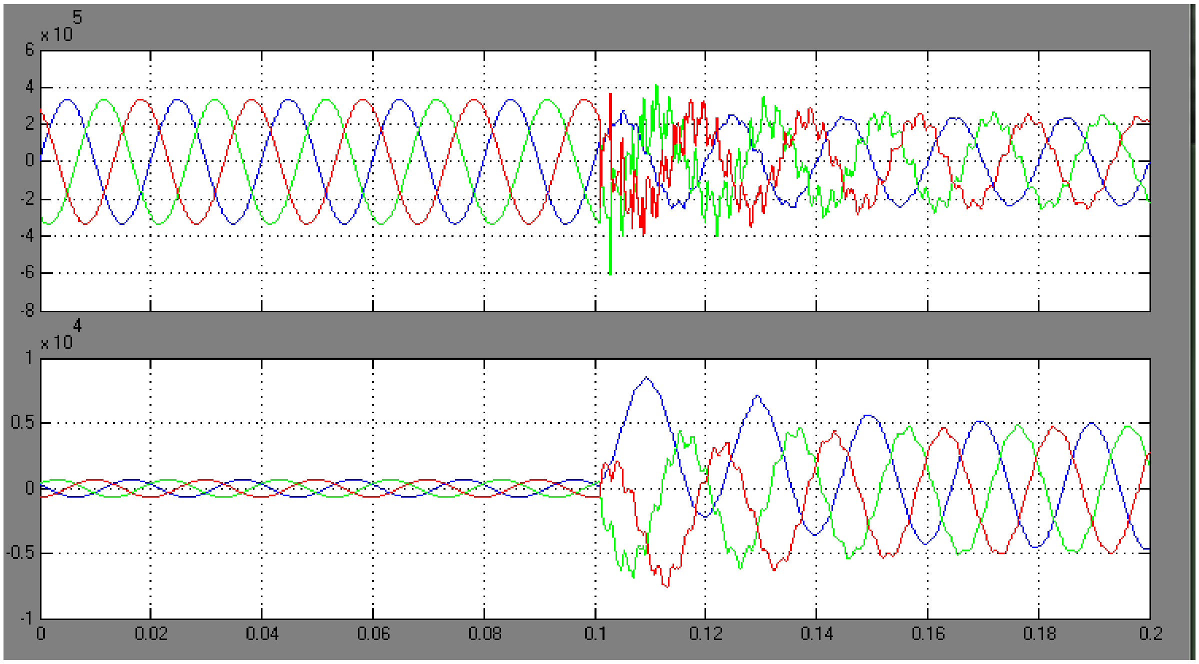


Fig 4.10: Voltages and currents at faulty bus during L-L-L fault applied at 0.1 secs

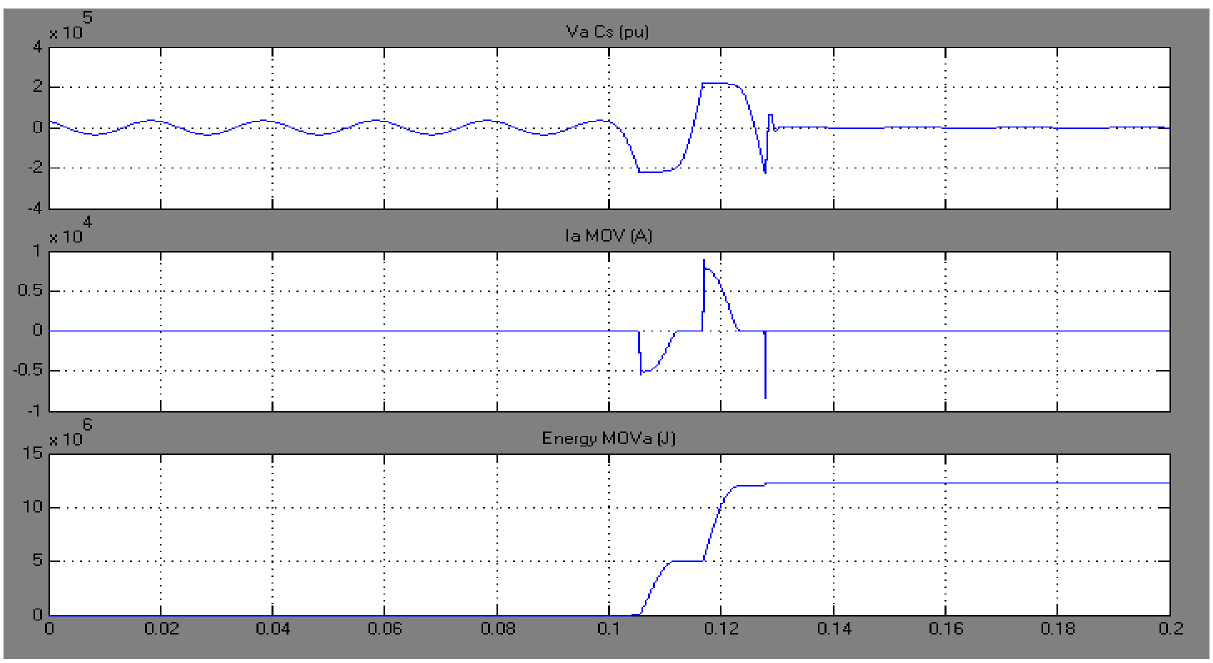


Fig 4.11: Capacitor voltage(V_{cs}), Current across MOV and energy dissipated across MOV during L-L-L fault applied at 0.1 sec

L-L-L-G FAULT

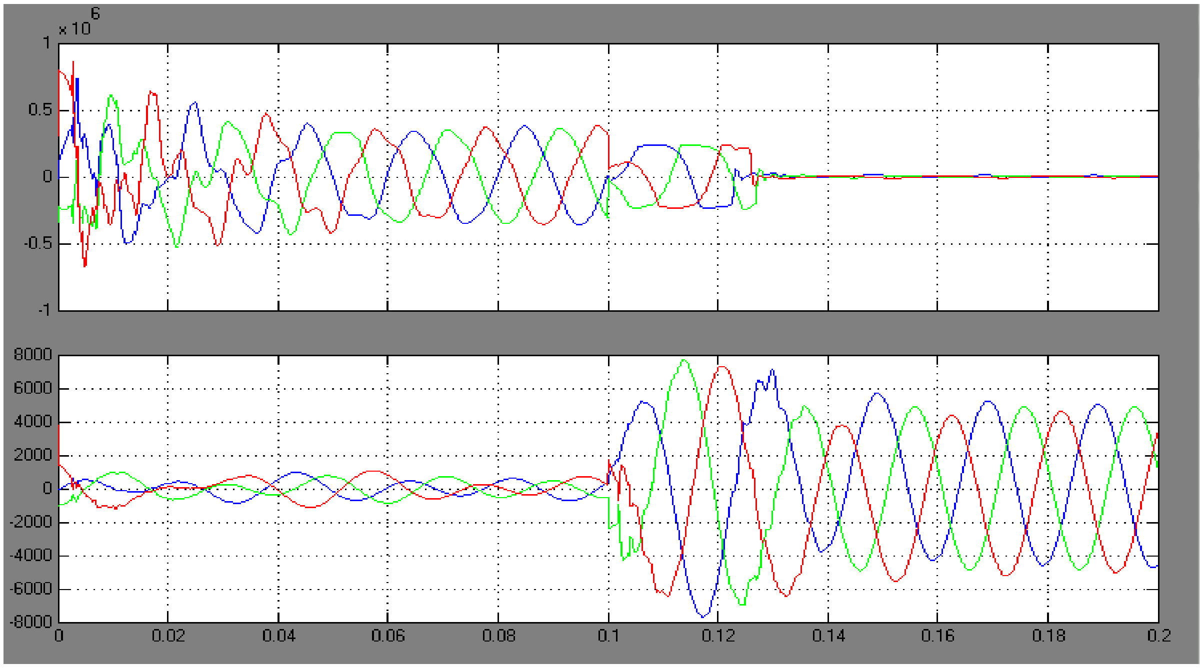


Fig 4.12: Voltages and currents at faulty bus during L-L-L-G fault applied at 0.1 sec.

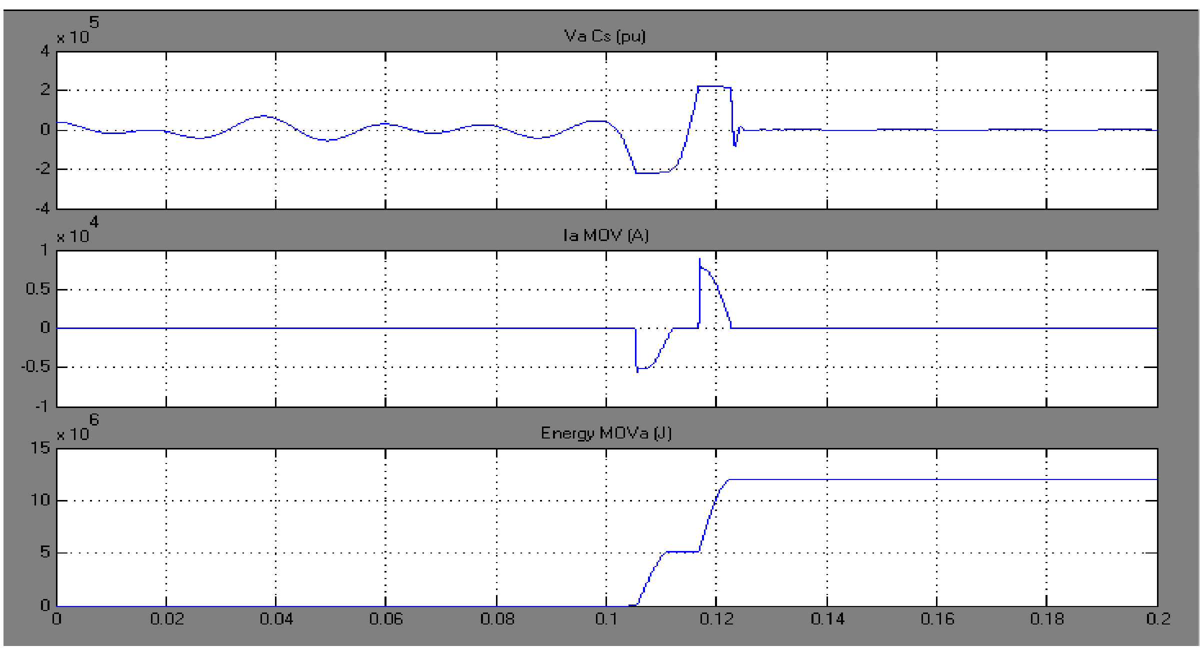


Fig 4.13: Capacitor voltage(V_{cs}), Current across MOV, and energy dissipated across MOV during L-L-L-G fault applied at 0.1 sec.

The energy dissipated in the faulty phases is in MJ in case of unfaulted phases in mj(millijoules).

Fig 4.4 shows the voltage and current signatures during healthy conditions. In fig 4.5 it is shown that under normal conditions or with low fault currents, neither the air gap nor the MOV conducts any current. Therefore, the series capacitor voltage drop is caused by capacitor reactance.

Fig 4.6 shows the voltages and currents during L-G fault. In fig 4.7, when L-G fault is applied at 0.1 sec Due to higher fault current, the voltage drop across capacitor becomes rectangular due to voltage protection level. The energy build up during L-G fault is 3 MJ. As threshold energy is 12 MJ spark gap is not fired.

Fig 4.8 shows the voltage and current signatures during L-L-G fault. As shown in fig 4.9 the fault current is higher. The energy dissipation across MOV reaches 12 MJ and stays constant. At 0.125 sec spark gap is fired and MOV stops conducting.

Fig 4.10 shows the voltage and currents during L-L-L fault applied at 0.1 sec. In Fig 4.11 it can be seen that, as intensity of fault current is increasing the capacitor voltage waveform becomes more rectangular. The energy reaches 12 MJ and stays constant.

Fig 4.12 shows the voltage and currents during L-L-L-G fault applied at 0.1 sec. As Vcs reaches 240 kV, MOV starts conducting at 0.1 sec. Energy across MOV increases spontaneously and reaches 12 MJ. After that, it stays constant at 12MJ.

4.7 CONCLUSION

The behavior of a series compensated line is studied. It is clearly seen from the results that MOV protects capacitor during overvoltage conditions by bypassing all the current through it. And when energy dissipation in MOV reaches a specified limit, the spark gap is fired thereby protecting the MOV.

CHAPTER-5
FAULT LOCATION ALGORITHM

INTRODUCTION

Power transmission lines play a significant role in delivering power safely and continuously. Modern power systems cover a large geographic area and are exposed to external events and circumstances such as lightening, falling trees, dirt, animals, ice, etc. These events sometimes would cause faults rendering the lines out of service [1]. Upon occurrence of the fault it is of vital importance for the utility company to send out the maintenance crew to repair the faulted component and to restore the supply as soon as possible. The company's ability to do so relies on fast and accurate fault location.

There are many types of short-circuit faults that can occur on transmission lines: single line-to-ground faults (L-G), line-to-line faults (L-L), line- to-line-to-ground faults (L-L-G), and three-phase faults (L-L-L, L-L-L-G). Single line-to-ground faults are the most common type of fault usually caused by lightning stroke. Three-phase faults are the least occurring faults. Most transmission lines posses a single circuit line structure. On the other hand, in modern power systems transmission lines with compensation have been increasingly adopted, mainly because they can improve the reliability and power transfer capability. Due to the non linear behavior of the compensation devices, it is still challenging to design an accurate fault location algorithm [39], despite the wider application of FACTS devices.

The Series Compensator (SC) is a device that is sometimes installed for long transmission lines to improve power transfer capability, enhance power system stability, damp power system oscillations, etc. The SC device can be either a capacitor bank or a thyristor-based powerflow controller, which is usually protected by a Metal Oxide Varistor (MOV) and a spark gap. however installation of SCs equipped with metal oxide varistor (MOV) for overvoltage protection cause certain problems itself [39].For such series-compensated lines the harmonics and non-linearities introduced by the series capacitor and its MOV make transmission line protection and fault location more difficult.

5.2 LITERATURE REVIEW

Single end impedance based fault location algorithm is very simple because it does not require any communication channel and they utilize only one-terminal voltage and current data. Diverse fault location algorithms designed for double-circuit lines have been developed in the past few decades and will be henceforth reviewed. The authors of [41-43] proposed methods which are applicable to multi ended transmission lines also. All these methods use the measured data either from one end of the transmission line or from all ends. The method which uses the data from all ends requires synchronized fault locator with time stamping and online communication of data to one common location [44, 45]. On the other hand, the one-end method which does not require synchronous measurement and online communication of data is easier to apply to multi-terminal lines.

The one-end fault location method applicable to all types of faults using TWs requires identification of the faulted half of the line in the case of two-ended line [7], and the faulted line section as well as the faulted half of the line section in the case of multi-ended lines. A method of identifying the faulted half of the line in the case of two-terminal line using the polarities of wavelet transform coefficients (WTCs) is reported in [46]. Another method of identifying the faulted line section and the faulted half of the line section for three-terminal line using the peak value of WTC is presented in [47]. These methods are found to be unreliable for multi-terminal lines. A method which combines the impedance based method with the TW based method to identify the fault in two-terminal line is reported in [48]. Here, the impedance based method is used first to find the fault location approximately and the accuracy is then improved by TW based method. As the fault location is determined approximately in this case using the impedance based method there is no need to identify the faulted half of the line. A method using the cross correlation between the forward and backward TWs to identify the fault location is proposed in [49]. It may be noted that the methods reported in [47, 48] are applicable to two terminal lines only.

Fault analysis methods are an important means used by protection engineers to calculate power system currents and voltages during disturbances. It provides information for protection system setting, coordination and efficiency analysis studies. Today, three approaches are used in the industry for such analysis: classical symmetrical components, phase variable approach and complete time-domain simulations [49]. Classical fault analysis of unbalanced power systems is based on symmetrical components approach [50]. However, in untransposed feeders with single-phase or double- phase laterals, the symmetrical component methods does not provide accurate characteristics. Hence, techniques incorporating symmetrical components may not give precise results for power distribution systems, which are normally characterized by those asymmetries.

With industrial computer facilities improvement, the fault analysis phase variable approach has been proposed to substitute the symmetrical components methods on distribution systems [51]. In the phase variable approach, system voltages and currents are related through impedance and admittance matrices based on phase frame representation, considering the typical distribution systems asymmetries. However, fault analysis is still fault resistance dependant. Due to fault resistance stochastic nature, typical fault analysis studies consider the fault paths as an ideal short-circuit. To overcome this limitation, recent studies suggest the usage of fault estimation algorithms [52]. These algorithms provide a fault resistance estimate using symmetrical components techniques, restricting the application on balanced systems with equally transposed lines.

5.3 PREREQUISITES FOR FAULT LOCATION ALGORITHM

5.3.1 SUPPLY SYSTEM

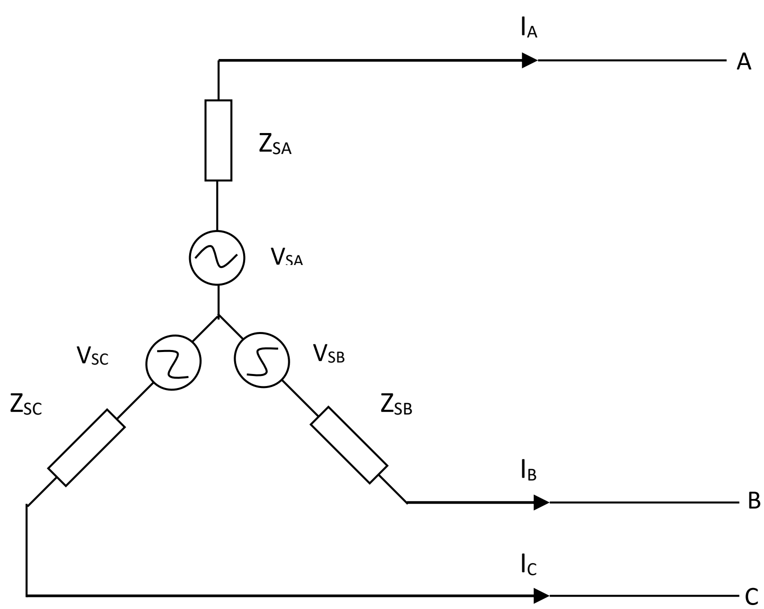


Fig 5.1 Three phase supply system

Fig 5.1 represents a Y connected generator with three phase supply system. V_{sa}, V_{sb}, V_{sc} are the three phases respectively. Z_{sa}, Z_{sb}, Z_{sc} are the generator impedances.

$$E_s = \begin{bmatrix} E_{sa} \\ E_{sb} \\ E_{sc} \end{bmatrix} \tag{5.1}$$

$$V_{sa} = E_{sa} - I_a * Z_{sa} \tag{5. 2}$$

$$V_{sb} = E_{sb} - I_b * Z_{sb} \tag{5.3}$$

$$V_{sc} = E_{sc} - I_c * Z_{sc} \tag{5.4}$$

The impedance matrix would be:

$$Z_S = \begin{bmatrix} Z_{Ss} & Z_{Sm} & Z_{Sm} \\ Z_{Sm} & Z_{Ss} & Z_{Sm} \\ Z_{Sm} & Z_{Sm} & Z_{Ss} \end{bmatrix} \tag{5.5}$$

Where Z_{Ss} and Z_{Sm} are self and mutual impedances respectively.

5.3.2 MEASUREMENT OF FAULT DATA

Most of the algorithms developed so far uses synchronization of signals to obtain the fault data. But this algorithm does not involve synchronization , rather signals from one end are utilized. The fault data is hereby taken from the fault analysis performed in chapter 4.

5.3.3 SERIES COMPENSATING UNIT

Current across MOV

The metal oxide varistor is the main device which conducts when an overvoltage is observed across capacitor. So, the fault current mainly depends on MOV current. The V-I characteristics of MOV are given by the equation (5.6) [45] :

$$i = x * \left(\frac{V}{V_{ref}}\right)^y$$

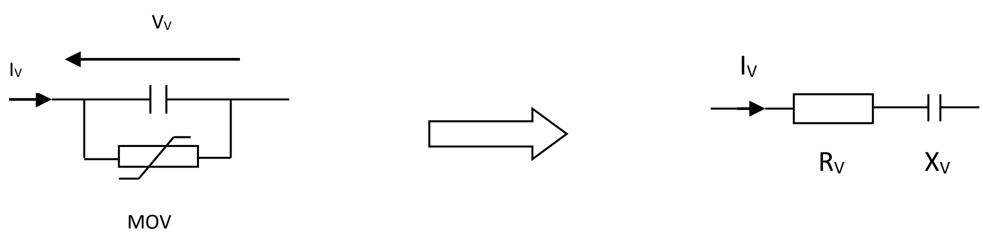
(5.6)

y is exponent of MOV characteristics and x is a constant.

Capacitor voltage drop

Under normal conditions, neither MOV nor spark gap conducts. In this case, capacitor voltage drop is due to capacitor reactance. During faulty conditions, the voltage across capacitor goes beyond its threshold level, the majority of current is passed through MOV and the drop is evaluated from the steady state values obtained during fault analysis. Theoretically, the phasor voltage drops can be calculated if equivalent impedance is known.

Series capacitor-MOV can be represented as:



a) Series compensation unit b)equivalent branch

Fig 5.2: Capacitor-MOV equivalent circuit

Voltage across series compensation can be expressed as :

$$V_{SC} = \begin{bmatrix} Z_V I_A & 0 & 0 \\ 0 & Z_V I_B & 0 \\ 0 & 0 & Z_V I_C \end{bmatrix} \quad (5.7)$$

I_A, I_B, I_C are the three phase currents measured from the sending end.

5.4 FAULT LOCATION ALGORITHM

5.4.1 SYSTEM MODEL

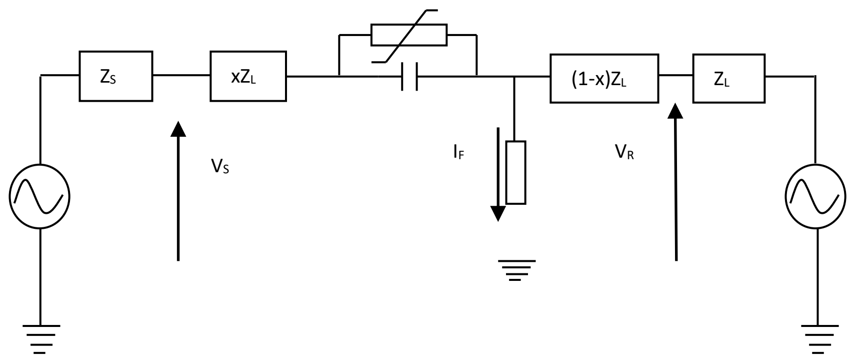


Fig 5.3: Two end transmission line

As from eqn (5.5)

$$Z_L = \begin{bmatrix} Z_{Ls} & Z_{Lm} & Z_{Lm} \\ Z_{Lm} & Z_{Ls} & Z_{Lm} \\ Z_{Lm} & Z_{Lm} & Z_{Ls} \end{bmatrix}$$

5.4.2 NETWORK EQUATIONS

i) Fault behind the SCU

$$[V_S] - x[Z_L][I_S] = [V_R] - (1-x)[Z_L][I_R] - [V_D] \tag{5.8}$$

V_R and VS are the voltages at receiving and sending end respectively. VD is the voltage drop across series capacitor.

Equation (5.8) can be expanded as:

$$\begin{bmatrix} V_{Sa} \\ V_{Sb} \\ V_{Sc} \end{bmatrix} - x \begin{bmatrix} Z_{Ls} & Z_{Lm} & Z_{Lm} \\ Z_{Lm} & Z_{Ls} & Z_{Lm} \\ Z_{Lm} & Z_{Lm} & Z_{Ls} \end{bmatrix} \begin{bmatrix} I_{Sa} \\ I_{Sb} \\ I_{Sc} \end{bmatrix} = \begin{bmatrix} V_{Ra} \\ V_{Rb} \\ V_{Rc} \end{bmatrix} - (1 - x) \begin{bmatrix} Z_{Ls} & Z_{Lm} & Z_{Lm} \\ Z_{Lm} & Z_{Ls} & Z_{Lm} \\ Z_{Lm} & Z_{Lm} & Z_{Ls} \end{bmatrix} \begin{bmatrix} I_{Ra} \\ I_{Rb} \\ I_{Rc} \end{bmatrix} - [\, V_D] \qquad (5.9)$$

$$[V_D] = \begin{bmatrix} X_C I_A & 0 & 0 \\ 0 & X_C I_B & 0 \\ 0 & 0 & X_C I_C \end{bmatrix} \qquad (5.10)$$

ii) Fault in front of SCU

$$[V_S] - x[Z_L][I_S] - [V_D] = [V_R] - (1 - x)[Z_L][I_R] \qquad (5.11)$$

Equation (5.11) can be expanded as:

$$\begin{bmatrix} V_{Sa} \\ V_{Sb} \\ V_{Sc} \end{bmatrix} - x \begin{bmatrix} Z_{Ls} & Z_{Lm} & Z_{Lm} \\ Z_{Lm} & Z_{Ls} & Z_{Lm} \\ Z_{Lm} & Z_{Lm} & Z_{Ls} \end{bmatrix} \begin{bmatrix} I_{Sa} \\ I_{Sb} \\ I_{Sc} \end{bmatrix} - \begin{bmatrix} X_C I_A & 0 & 0 \\ 0 & X_C I_B & 0 \\ 0 & 0 & X_C I_C \end{bmatrix} =$$

$$\begin{bmatrix} V_{Ra} \\ V_{Rb} \\ V_{Rc} \end{bmatrix} - (1 - x) \begin{bmatrix} Z_{Ls} & Z_{Lm} & Z_{Lm} \\ Z_{Lm} & Z_{Ls} & Z_{Lm} \\ Z_{Lm} & Z_{Lm} & Z_{Ls} \end{bmatrix} \begin{bmatrix} I_{Ra} \\ I_{Rb} \\ I_{Rc} \end{bmatrix} \qquad (5.12)$$

The fault distance x can be calculated using equations (5.9) and (5.12).

5.5 IMPLEMENTATION OF ALGORITHM

The above algorithm is coded in MATLAB software and results are obtained for different types of fault with different fault resistances at various locations.

CHAPTER-6

RESULTS

To illustrate the performance of the algorithm different faults are simulated using the transmission line model shown in chapter 4. The fault data is applied in the algorithm and results for the same are shown below:

L-G FAULT

Table 6.1: Fault distance measurement in L-G fault (just before SCU)

Fault type	Fault resistance	Fault distance(p.u)
L-G Fault	5Ω	0.4877
	10Ω	0.4926

Table 6.2: Fault distance measurement in L-G fault (just after SCU)

Fault type	Fault resistance	Fault distance(p.u)
L-G Fault	5Ω	0.5003
	10Ω	0.5198

L-L-G FAULT

Table 6.3: Fault distance measurement in L-L-G fault (just before SCU)

Fault type	Fault resistance	Fault distance(p.u)
L-L-G Fault	5Ω	0.4787
	10Ω	0.4799

Table 6.4: Fault distance measurement in L-L-G fault (just after SCU)

Fault type	Fault resistance	Fault distance(p.u)
L-L-G Fault	5Ω	0.5081
	10Ω	0.5111

L-L-L-G FAULT

Table 6.5: Fault distance measurement in L-L-L-G fault (just before SCU)

Fault type	Fault resistance	Fault distance(p.u)
L-L-L-G Fault	5Ω	0.4888
	10Ω	0.4900

Table 6.6: Fault distance measurement in L-L-L-G fault (just after SCU)

Fault type	Fault resistance	Fault distance(p.u)
L-L-L-G Fault	5Ω	0.4567
	10Ω	0.4665

L-L FAULT

Table 6.7: Fault distance measurement in L-L fault (just before SCU)

Fault type	Fault resistance	Fault distance(p.u)
L-L Fault	5Ω	0.4943
	10Ω	0.4958

Table 6.8: Fault distance measurement in L-L fault (just after SCU)

Fault type	Fault resistance	Fault distance(p.u)
L-L Fault	5Ω	0.5009
	10Ω	0.5100

The results can be validated from the fact that if a fault is simulated just before SCU, the fault distance must be within (0.48-0.5) p.u range. Otherwise if fault is applied after SCU it must be within (0.5-0.52) p.u range.

To estimate the accuracy of the algorithm, where the fault has actually occurred must be known. This cannot be quantized without synchronization of signals.

CHAPTER-7

CONCLUSIONS AND FUTURE SCOPE OF WORK

CONCLUSION

Fault location is estimated by implementing the said algorithm and the fault distance is found to be within acceptable limits. Fault locator was placed just before the series capacitor placed at 0.5 p.u and just after the series capacitor. Fault is applied at different locations with different fault resistance and results are validated for it.

The implemented algorithm is based on the relative placement of fault with respect to the series capacitor.

To estimate the accuracy of the algorithm, where the fault has actually occurred must be known. This cannot be quantized without synchronization of signals.

FUTURE SCOPE OF WORK

- The algorithm presented in the paper considered only the series parameters of the line. The shunt capacitive currents associated with long transmission lines are assumed to be negligible. Considering the shunt capacitance, it is possible to develop the same
- Thyristor controlled FACTS devices may be considered for line compensation
- Fault location for multi-ended and parallel lines may be possible.

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APPENDIX

The sample power system studied is a 400 kV, 1000 MVA, 50 Hz single-circuit transmission line compensated at the degree of 60%. The total length of the line is 300 km, with the series compensation device installed at 150 km (0.5 p.u.) from local end.

Supply System

Line to line voltage = 400kV

Phase voltage = 230.94 kV

Total line positive reactance = 94.5Ω

Compensation level = 60%

Capacitive reactance = 0.6*94.5 = 56.5 Ω

Value of series capacitor = $\frac{1}{2*\pi*50*56.7}$ = 56.14 μF

Table 1: Voltage source data

Parameters	Sending end	Receiving end
Positive sequence impedance	1.31+j15.0	1.31+j15.0
Zero sequence impedance	2.33+j26.8	2.33+j26.8
Degree of compensation	60	

Table 2: Transmission line data

Parameter	Positive sequence(Ω)	Zero sequence(Ω)
Positive sequence impedance	8.25+j94.5	82.5+j308
R	0.0275Ω/km	0.275Ω/km
L	0.836Mh/km	2.7233mH/km
C	0.038μF/km	0.038μF/km
Length	300 km	

Table 3: MOV data

Parameter	**Value**
Reference current(kA)	1.0 kA
Reference voltage(Kv)	240.6 Kv
Exponent	23
Threshold energy(spark gap)	12MJ

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