CLASSIFICATION AND LOCATION OF FAULTS ON DOUBLE CIRCUIT SERIES COMPENSATED TRANSMISSION LINE USING WAVELET TRANSFORM

A Dissertation

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This Dissertation is dedicated to

My Respected Teacher

Dr. Amrita Sinha

CERTIFICATE

I hereby certify that the work which is being presented in Dissertation entitled, "**Classification and Location of Faults on Double Circuit Series Compensated Transmission Line using Wavelet Transform**", in partial fulfillment of the requirements for the award of degree of **Master of Engineering in Power Systems** at Thapar University, Patiala, is an authentic record of my own work carried out under the supervision of **Dr. Amrita Sinha, Assistant Processor (EIED)**. The matter embodies in this dissertation has not been submitted for the award of any other degree to any other university.

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ABSTRACT

On prevailing power system network, double circuit transmission lines are used to enhance the consistency and power transfer capability. To improve the power quality of the transmission lines, compensation circuits are integrated. In order to increase the reliability of the system and reinstate the power supply in time, it is of immense important to classify and locate the fault rapidly and to isolate the faulty section precisely. In this dissertation, wavelet transform has been used for classification and location of various types of faults with different inception angles on double-circuit series compensated transmission line with different compensation levels in both the lines. Db4 and Haar wavelets are used to calculate the fundamental frequency components of voltage and current signals. Data from one end of the line is utilized for this method. Db4 is considered effective for fault classification and Haar wavelet for fault location. Low frequency components of the signal i.e. approximation coefficients of wavelet has been considered to classify and locate the fault so as to remove the effect of transients and harmonics. Average values of Level 6 approximation coefficients of currents are calculated by using db4 wavelet to classify the various types of faults. Flow chart for fault classification has been proposed. The line impedance from the sending end to the occurrence of the fault position has been considered for fault location. Impedance of distributed parameter transmission line before and after compensation has been calculated using rms values of voltages and currents of A6 coefficients of Haar wavelet and has been compared with the actual impedance of the faulty section. Fault location error has been tabulated for various types of faults with different distances, inception angles and different compensation levels on line1 and line2.

LIST OF ABBREVIATIONS

SC	Series Capacitor
MOV	Metal Oxide Varistor
EHV	Extra High Voltage
CDPR	Current Differential Pilot Relay
AWA	Adaptive Wavelet Algorithm
GUI	Graphical User Interface
MATLAB	Matrix Laboratory
TEED	TEE Distribution Line
ANN	Artificial Neural Network
L-G	Line to Ground
L-L	Line to Line
L-L-G	Double Line to Ground
FT	Fourier transform
STFT	Short Time Fourier Transform
DWT	Discrete Wavelet Transform
db4	Daubechies four
SIL	Surge Impedance Loading
RMS	Root Mean Square

NOMENCLATURE

cA1	Level 1 approximation coefficients
cA6	Level 6 approximation coefficients
cD1	Level 1 detail coefficients
C	Shunt capacitance per unit length (Farad/km)
dWa, dWb, dWc	Wavelet coefficients of three phase currents
G	Shunt conductance per unit length (mho/km)
H_d	High pass filter
I_L	Line current (A)
l	Length of transmission line (km)
L	Inductance per unit length (Henry/km)
L_d	Low pass filter
P	Power
P_r	Surge impedance loading (VA)
R	Resistance per unit length (ohm/km)
VD	Voltage drop in line
V_S	Sending end voltage
V_R	Receiving end voltage
X_C	Capacitive reactance
X_L	Inductive reactance
Y	Shunt admittance per unit length (mho/km)
Z	Series impedance per unit length (ohm/km)
Z_0	Surge impedance (ohms)
Z_a	Actual impedance of distributed parameter line (ohm)
Z_b	Actual impedance of the line after compensation
$Z_{comp.}$	Compensation impedance
Ω	ohm
℧	mho
δ	Phase angle

ψ	Mother wavelet
ω	Angular frequency (rad/sec)
γ	Propagation constant
α	Attenuation constant
β	Phase constant

LIST OF FIGURES

LIST OF TABLES

TABLE OF CONTENTS

CHAPTER 1

CHAPTER 2

CHAPTER 3

CHAPTER 4

CHAPTER 5

CHAPTER 6

CHAPTER – 1 OVERVIEW

1.1 Introduction

In power distribution system, transmission lines are the most imperative part, as they play a key role in the transmission of power from generating station to load centres. Transmission lines function at distinctive voltage levels from 69kV to 765kV, and firmly interconnected for consistent operation. Various factors akin to de-regulated market environment, right of way, economics, environmental and clearance necessities have forced utilities to operate transmission lines near to operating limits. It is necessary to detect the faults; otherwise it will cause disturbances in the system which further led to extensive outages in the firmly interconnected system working within its limits. The design of transmission protection systems is in such a way so as to locate the fault location and segregate only the faulted part. It is a very challenging task to identify and isolate the faults in order to have a very reliable transmission line protection.

Enhanced transmittable power, better power system stability, decreased transmission losses, decreased voltage drop, supple power-flow control, and improved voltage control are the economical and technical reasons following which series capacitors installation becomes very useful [1,2,3]. The part of line's inductive impedance is compensated by use of series capacitors. Further an improved voltage profile can be obtained by using series capacitor. Line inductance is reduced by series capacitors, which induce voltage $(L\frac{di}{dt})$ along the line [4]. Induced voltage superposes to the voltage imposed by the source. Voltage is increased if the line current leads the voltage and there occurs a voltage drop when the line current lags behind the line voltage. In this perspective, series capacitors reduce voltage boost and voltage drop as the line inductance is lesser for series compensated line as compared to that for uncompensated line.

When two or more than two conductors make contact with one another or with ground in three phase system, there occurs a fault which can be either a symmetrical fault or unsymmetrical fault [5]. Stresses are produced in the power system equipments due to excessive currents which are produced by faults. Further these faults cause grave damage on power system components. It is not only the equipment which is ill effected by the faults but the power quality also gets poor. So, in order to prevent the power system equipments from damages and to enhance the power quality, it becomes imperative to identify the type of fault and its location on the transmission line so that it can be removed with suitable means.

1.2 Faults in Overhead Transmission Lines

To spread power from generating stations to remote load centres, transmission lines are used. Due to lightening, mis-operation, overload, short circuits, human errors, faulty equipments and aging, faults may occur on these lines. When fault occurs, the faulted phase voltage decreases and huge currents will flow which can burn out the components if not interrupted quickly.

1.2.1 Nature and Causes of Faults

Either insulation failure or failures of conducting path are the major causes for the occurrence of faults. In addition to this, faults are also caused due to over voltages which are occurring due to switching surges and lightening. Falling of conducting objects on overhead lines, encounter of flying birds, tree branches, direct lightening strokes, ice loading, creepers, storms etc. are the other reasons which can cause faults in overhead lines.

Moisture in the soil, heat of earth, ageing of cables may lead to the solid insulation failure in cables, transformers and generators [6].

Types of faults:

1. Symmetrical faults
2. Unsymmetrical faults

Table 1.1: Types of faults [6]

Types of faults	Symbol	% Occurrence	Severity
Line to Ground	L-G	75-80%	Very less severe
Line to Line	L-L	10-15%	Less severe
Double Line to Ground	L-L-G	5-10%	Severe
Three phase	3-ɸ	2-5%	Very severe

1.2.2 Effects of Faults

Following are the ill effects caused by a fault in a power system.

- Severe short circuit current may occur in the system due to fault which may prove fatal to the several equipments of the power system and lead to the overheating of the system. Heavy current is also the reason behind the setting up of very high mechanical stresses.
- Failure of industrial loads, due to drop in the voltage of healthy feeders.
- Heating of rotating machines may occur due to unbalancing of currents and supply voltages arising due to short circuit.
- Loss in system stability.
- Continuity of power supply is adversely affected.

1.3 Aim of Fault Location and its Significance

In order to enhance reliability of the system, reinstate the power supply in time and to lessen the instant of failure interruption, it is of immense important to find out the fault location rapidly and precisely to eradicate the fault. The process of locating the fault with the utmost possible accuracy is known as fault location [7]. When fault has to be located on more than one section of the line, identification of faulty section has to be done and distance of occurrence of fault on this section has to be calculated.

There are temporary and permanent faults on transmission and distribution lines. On overhead lines, temporary faults are the chief faults and are self cleared. So, the continuity of power supply is not enduringly affected, which is beneficial. When the permanent fault occurs, the circuit breakers enabled by protective relaying equipment de-energize the faulty section. And if the faulty line is taken out of service, then the load connected to this line is not supplied and if feasible, the other healthy lines can be enforced to supply the loads of the tripped line [8]. If series of cascading trips take place, larger part of the system goes out of service that leads to huge blackouts of power system, as happened lately in some countries. Modern power system operates nearer to their operating limits. Consequently to avoid blackouts, special care has to be taken for power system protective and control devices. In case of permanent faults, reinstallation of power supply can be done only after maintenance team finishes the repair of the damage caused by the fault. So, the position of the fault has to be ascertained, otherwise to find the damaged section inspection of the entire line has to be done. Thus, it is vital that the fault location is known or it can be determined with high precision. This allows saving time and money for the inspection and repair, also provide improved service by quicker restoration of power supply.

Temporary faults on overhead lines are self cleared so the continuity of supply is not eternally affected, though the location of these faults is also crucial [9]. In this case the location of fault can aid to identify the weak spots on the line. Accordingly, the schedules of maintenance can be set for avoiding further problems in the future.

1.4 Fault Location Techniques

- Technique based on fundamental-frequency voltages and currents, primarily on impedance measurement
- Technique based on high-frequency components of currents and voltages generated by faults
- Technique based on traveling-wave phenomenon
- Knowledge-based approaches.

Method based on the fundamental frequency currents and voltages at the line terminal in addition with the line parameters is the simplest way for determining the location of fault. It is generally considered that the impedance calculated for the faulted-line segment is a measure of the distance to fault. The Techniques belonging to this sort are simple and cheap for implementing. Performing such classification one has to take into account an availability of measurements: whether from one or both ends, and also whether complete measurements (voltage and current) or incomplete measurements (voltage or current) from a particular line end are utilized.

In traveling-wave methods, the current and voltage waves, traveling at the speed of light from the fault towards the line terminals are consider [7]. These methods are considered as very accurate, however, also as complex and costly for application, as requiring high sampling frequency.

1.5 Benefits of Fault Location Estimation

1.5.1 Time and Effort Saving

Since the networks in power system extends to the large area of several km having different geographical and environmental conditions. So, if the fault is occurring at some point in the line, it is very difficult to locate the fault efficiently with human skill and knowledge [8]. Hence, the process of locating fault becomes very time consuming. Moreover, we can sectionalize the fault but cannot locate the exact position of the fault with the mere human knowledge. Therefore, the benefits of using techniques devoted to fault location cannot be ignored.

1.5.2 Improving the System Availability

Faults in the transmission line leads to the loss in the availability of power to the consumers. Hence, precise fault location techniques are very useful to locate the fault so as to ensure the proper availability of power to the consumers.

1.5.3 Assisting Future Maintenance Plans

Even though the continuity of power supply is not affected by the temporary faults, but it is advantageous to locate and analyze these faults so as to have a proper future maintenance plans which further leads to avoidance of future problems [7]. Moreover, these preventive measures can avoid future blackouts and helps to boost system overall efficiency.

1.5.4 Economic Factor

The benefits of using techniques devoted to fault location as described above, all lead to effective cost reduction in the maintenance and supply of power.

1.6 Contribution of this Dissertation

In this work, extraction of fundamental-frequency voltages and currents, from original signal is a vital issue. So, wavelet analysis is used in this work for classification and location of different types of faults on series compensated double-circuit transmission line. Wavelet works for a short duration wave [10]. It is a mathematical scheme inured to divide a particular function into distinctive scale components. The particular signal is decomposed into ‘Scales’ using wavelet sample function known as ‘mother wavelet’ [11]. In this work, Daubechies four (db4) and Haar wavelet is used for analysis. Db4 is used for classification of different types of faults and Haar wavelet is used to locate the faults.

Simulation of faults is done for power system with ground faults and for without ground faults. This can be recognized by calculating ground current involving zero sequence components. The focus of this work is to develop a technique for classification and identify real-time fault location by using discrete wavelet transform. By using db4 and Haar as a mother wavelet decomposition of current and voltage fault signals is done. Then low frequency approximation and high frequency detail coefficients are extracted. Low frequency approximation coefficients are used to calculate the fundamental components of the signal. Average and rms values of the Level 6 approximation coefficients are calculated and used for classification and identification of location of faults respectively.

1.7 Organization of the Dissertation

Six chapters are included in this dissertation. Overview and all information included into these chapters are specified in the following:

Chapter-1 includes the introduction, faults in overhead transmission lines, aim of fault location and it also includes the contribution of this dissertation and organization of dissertation.

Chapter-2 explains the literature review pertaining to protection of double-circuit series compensated transmission line. The literature on detection, classification and Location of faults by multi-resolution wavelet analysis is discussed in this chapter.

Chapter-3 presents the concept of double circuit series compensated line. Distributed parameters of the line and effect of series compensation on transmission lines is studied.

Chapter-4 presents the introduction of wavelet transform. Discrete Wavelet Transform, wavelet multi-resolution analysis, and working of wavelet transform are presented.

Chapter-5 presents the MATLAB/SIMULINK based simulation and simulation results are discussed.

Chapter-6 presents the conclusions of the work presented in dissertation and future scope of this work.

2.1 Introduction

The Literature review on series compensation, use of wavelet analysis for classification and location of faults, scope of work and objective of the dissertation are presented in this chapter. The problem of classifying the faults in the transmission line and then locating them has been a very difficult task. It is a foremost worry of the power industry to locate faults and classify them. Basically, protective relays, special control devices, protection software and recording devices are used to detect the fault and separate the faulty section from the system. It is very important to know all the information about the fault so as to detect it and then correct it as soon as possible.

Presently, many researches are being carried to know about the techniques of fault location in distribution and transmission network which are based on artificial intelligence methods such as fuzzy - set theory, artificial neural networks, and expert systems.

2.2 Effect of Series Compensation on Transmission Lines

It is very important to know the effect of series compensation on transmission voltages [4]. If the effect of series compensation on voltages is not known it will cause various operational problems such as high voltages and low voltages. Series compensation can cause low and high voltages due to different line loading conditions and the method by which the voltage control is adjusted. The voltage on the one side of the capacitor should be adequately controlled otherwise the other end of the capacitor cause voltage problems. When the line is lightly loaded, over-voltages can cause problems and in this case, series compensation will decrease voltage. But in case of heavily loaded lines, low voltages occur across the line, so series compensation will increase the voltage. Voltage collapse results from low voltages. And high voltages either cause flashover or decrease the life cycle of insulation and short circuits. Occasionally, series compensation is used to control power flow.

On directional relaying, current and voltage inversions takes place in a series compensated line [1]. A fault direction can be identified by fault identification scheme for series compensated line by change in magnitude of positive-sequence fault voltages and by change in phase of positive-sequence fault currents. Simulations is done with EMTDC/PSCAD and a algorithm is developed for series compensated line which uses fault current and voltage phasors to obtain the decisions. The process is tested for series-compensated lines with the use of capacitor and without the use of capacitor, fault resistance, change in source capacity, power-flow direction, fault inception angle, and for different system conditions.

Unsynchronized measurements by taking current and voltage signals of two ends to obtain the fault location algorithm of distributed parameter double-circuit series-compensated line was performed [8]. In this algorithm two subroutines are used for locating faults. Different formulas are obtained with the help of generalized fault-loop model. The distance of fault is independent of the parameters of the compensating bank and depends only on the location of compensating bank. The use of two-end signals measured asynchronously has been taken into consideration. ATP-EMTP is used for simulate different types of faults on double-circuit series compensated line.

A method to determine that whether the detected fault is located on a protected double-circuit line or exterior the line is described [12]. It is suitable for protection of double-circuit uncompensated lines as well as for series-compensated lines. Only one-end measurements of phase currents are used. Simulation is done with ATP-EMTP software. A complete model of transmission line with the SCs & MOVs banks and measurement channels is developed. The proposed algorithm uses two subroutines: one for balanced lines and the other is used to detect unbalance in currents. Near 100% accurate fault classification is done for symmetrical parallel line and more than 85-95% in case when the line is unbalanced.

A method based on digital distance relaying for first-zone protection of series compensated double-circuit transmission lines has been presented in [13]. To estimate the fault distance, data from one end of the line is considered. The proposed method is independent on source impedance and fault current. Double circuit series compensated 400kV; 300km transmission line is simulated by using MATLAB/SIMULINK software and simulation results shows that the proposed method can be used to estimate accurate fault distance.

An algorithm that is applicable both to single and double-circuit series-compensated lines for finding fault location on series-compensated lines is proposed [14]. At both the ends of line, current differential relays are considered in order to find more refined solution for fault location. The proposed fault location technique can be achieved by incorporating differential protective relays with the fault locators. In this manner differential relays communication infrastructure is utilized. So, extra communication links are not required. Furthermore, differential relay utility is increased to a great extent.

2.3 Use of Wavelet Analysis for Fault Classification and Location

In order to detach only faulted line, it is crucial to differentiate the faults zone precisely and indicate exact fault type with the aid of one end data only [15]. Transient current waves generated by faults contains distinct frequency bands and to capture two bands of frequencies from the transient current signal discrete wavelet transform db1 as a mother wavelet is used. Fault zone is determined by using the frequencies of these two bands. The mother wavelet Haar is used to select faulted phase. Faulted phase was classified by computing the average value of the coefficients of each current wave. A model signal is obtained using db6 as mother wavelet. The decision regarding fault to be external or internal was taken by determining the ratio of two energies for the modal signal.

A new scheme for the solution of the parallel transmission line protection problems which depends on the six phase line currents and three phase line voltages of the two parallel circuit lines at both ends is proposed [16]. Fault analysis is done by wavelet transform. And internal faults on double circuit line are recognized by comparing current phasors magnitudes of corresponding phases on each line. It is shown that at different loading conditions each type of fault can be properly recognized.

For the power to be efficiently distributed to different locations, it is necessary to accurately detect and classify the different faults [10]. Active tripping of circuit breaker ensures the accurate protection of transmission line and circuit breakers tripping action depends on the current and voltages waveforms during the fault. For analysis of waveforms of current during fault, Discrete Wavelet Transform (DWT) is used. The evaluation of discrete wavelet analysis for identification and classification of faults on a transmission line network is done. According to energy level percentage, classification of faults has been done.

The use of wavelet transform for protecting the series compensated line by Current Differential pilot Relay (CDPR) is discussed [3]. Simulation results are obtained using MATLAB and analysis is done using db4 as mother wavelet. Fault classification is done by detecting different types of faults using wavelet based approach.

Probability based technique of Bayesian linear discrimination can also be used to differentiate between the different types of faults [9]. An adaptive wavelet algorithm (AWA) is used to generate the wavelets using probability based method of Bayesian linear discrimination. It is shown that adaptive wavelets can be used in the transmission lines of high speed protection system as analysis filters.

Power need to be transmitted from the power station to the load centres located far away [17]. So, the possibility of fault in the transmission lines is considerable. Here, comes the use of signal processing in the digital distance protection. Fourier transform and wavelet transforms are used for locating faults. Simulation is done with MATLAB/SIMULINK. Simulation result shows that wavelet method is more robust tool to locate the faults in the transmission lines. Further it is showed that both wavelet transform and Fourier transform methods can be used to find the characteristics of disrupt signals irrespective of the noise levels present.

The discrete wavelet analysis has been used for the protection of high speed EHV transmission line [18]. An algorithm for fault detection and classification based on discrete wavelet analysis has been presented. By comparing different wavelet coefficients of all three phase signals, type of fault is identified. And simulation is done using ATP-EMTP and MATLAB Wavelet toolbox. Such an algorithm is presented that is not dependent not only on fault location but also on fault inception angle and fault impedance. The algorithm is suitable, strong and quick and this is very prolific for EHV transmission line protection.

For the fault classification and boundary protection of series-compensated transmission lines, a new technique is proposed [2]. Different frequency bands of the wave of transient fault current are detected in order to have the suitable boundary protection. In order to amass the two frequency bands of transient fault current signal, db4 as a mother wavelet is used. Whether the fault is internal or external, it is determined by calculating the spectral energies of two bands of frequencies. Faulted phases are classified by calculating the average value of the wavelet coefficients of every current wave. A simple modal signal is obtained using the fault current values of three phases for all types of faults. Analysis of modal signal is done by using db4 as a mother wavelet, then detail 1 and detail 6 coefficients are calculated of the modal signal. To distinguish whether the fault is internal or external, the ratio of spectral energy is obtained and average values of d6 coefficients of three phase currents and ground current are obtained which is further applied to classify the type of fault.

A new approach for protection of TEED transmission lines and use wavelet transforms for accurate detection, classification and to locate faults in TEED transmission lines is presented [19]. The three phase currents at each terminal are decomposed at single level by using Bior2.2 as mother wavelet to obtain D1 detail coefficients. Then these detail coefficients at the three ends of TEED transmission line are added to obtain the resultant detail coefficients which are further compared with threshold values to detect and classify distinct types of faults in TEED transmission lines.

The use of Fuzzy logic and neural network for protection of double circuit series compensated transmission line is described [20]. Fuzzy logic and Neural Network are used for accurate decision making and to estimate the actual power system condition respectively, which increases the selectivity of protection system that further improves the reliability of power system. Effect of mutual zero-sequence coupling, series compensation and fault resistance is studied. The effect of the mutual coupling of parallel circuit and of series capacitor impedance on the relays accuracy depends on actual condition of power system. Ultimately, it is shown that with change in power system condition, the relay sensitivity is reduced to almost zero with decision making system of Fuzzy logic.

An impedance based calculation method to locate fault on transmission line is of immense importance [21]. Results get changed by changing line parameters. This is showed by carrying out the analysis of the two widely used methods in real faults. Most commonly used fault location methods are compared and their relative disadvantages and advantages are described. In this manner it becomes simple for the users to go for the most accurate method. Ultimately, it is shown that the two end methods are stronger than the one end methods as sensitivity to errors in two end methods is less as compared to one end methods.

Discrete Wavelet Transform (DWT) is used to extract the concealed factors from the fault signals by decomposition at distinctive levels [22]. Daubechies db6 wavelet is used for decomposition at single level. For ground faults a threshold is calculated to classify and detect the faulted phase. The fault location is determined by getting the local fault information, remote fault information and the length of transmission line. The system is considered with negligible fault resistance.

The protection scheme of double circuit transmission line based on artificial neural network (ANN) has been proposed [23]. Three stages are involved in this scheme to detect and classify different types of faults. Data from one end of the double circuit transmission line has been utilized to calculate the wavelet coefficients. The primary protection is provided to entire transmission line by using one end data only. For forward and backward adjacent transmission line, back up protection is provided. This technique improves the first zone reach setting up to 99% of the length of line for protection of transmission line.

A scheme based on wavelet transform for fault classification is proposed [24]. Currents samples from the three lines are used to calculate dWI_{abc}. For different fault inception angles, different fault locations, and different fault distances and for different fault parameters simulation is done by EMTP software. It is shown that magnitude of wavelet transform is valuable to set threshold to discriminate between different types of faults hence to classify the faults.

An algorithm based on discrete wavelet transform is developed with C programming [25]. A 500-kv, 200km single line is simulated by using MATLAB. It is shown that as the fault resistance increases, the percentage error increases rapidly. And when, the reactance of the circuit is considered to calculate the distance to fault, then the percentage error in the measurement of distance increases with increase in fault resistance.

2.4 Scope of Work

According to literature review, numerous algorithms have been developed for the classification and location of faults. Wavelet transform is used for classification and location of faults. In almost every paper, high frequency components i.e. detail coefficients of wavelet transform are used to locate the faults by considering the average values over the whole cycle of the decomposed signal. Very less work is done on the fault location by using low frequency components i.e. approximation coefficients of the wavelet transform which gives the fundamental components of the signal. So in this dissertation, approximation coefficients of the wavelet transform are used to classify and to locate the faults by considering the average and rms values of the decomposed signal respectively.

2.5 Objective of the Present Work

The major objectives of the present work are summarized as follows:

- To develop the MATLAB/SIMULINK model of double circuit series compensated line.
- To calculate the fundamental frequency components of the signal by using db4 and Haar wavelet transform.
- To classify the different types of faults by taking the low frequency components of the decomposed signal.
- To find out the fault location on double circuit series compensated transmission line based on impedance measurements.
- To study the effect of series compensation on the location of fault.

CHAPTER – 3

DOUBLE CIRCUIT SERIES COMPENSATED TRANSMISSION LINE

3.1 Double Circuit Transmission Line

Low cost of construction, less floor space, reliability of power supply, huge economic benefits and permanence of power supply are the reasons behind using double circuit transmission lines on prevailing power system network. Basically, these lines are constructed to lessen the problems of obtaining new right-of-way. The circuits of these lines are either of different voltage levels or of same voltage levels. And, in same way, more than two three-phase circuits can be used i.e. multi-circuit lines. Because, the two circuits of double circuit lines, are closer to each other so they are mutually coupled. The magnetic coupling influences the current flowing in one of the circuit which further, affects the voltage profile of other circuit. So, it means that the profile of voltage of a given circuit is not utterly dependent on the current that flows in this circuit [26]. Also, the steady state stability is enhanced by using double circuit lines as compare to single circuit lines.

3.1.1 Comparison between Single Circuit and Double Circuit Lines

Single circuit and double circuit lines are compared as shown in Table 3.1.

Table 3.1: Comparison between single circuit and double circuit lines

Sr. No.	Single Circuit Lines	Double Circuit Lines
1.	It requires much lesser support for equal clearance of conductor to earth but it needs more right-of-way for same no. of circuits.	It requires taller structure but needs less way leave for equal number of circuits.
2.	The single circuit line requires two earth wires because these lines cannot be disposed at the top.	Double circuit line requires one earth wire only. These lines can be disposed at the top so more protection against lightening is required.
3.	Reliability concerning continuity of supply is less.	Reliability concerning continuity of supply is more.

4.	More spacing between conductors is required due to which inductive reactance is more.	Inductive reactance is less because lesser spacing between conductors is required.
5.	Along the line, the phase performance is unbalanced due to the passage of central conductor at the top of the support.	In this, phase performance along the line is more balanced because it provides better method to the triangular arrangement.
6.	It is more expensive.	It is most economical and cheaper.

3.1.2 Distributed Parameters of Line

Generally, lumped parameters are used for short and medium lines. But to enhance fault location accuracy, mainly in case of long lines, distributed parameters of the line are considered. The transmission line of unit length is considered as an electrical circuit which consists of series resistance R, series inductance L, shunt capacitance C, and leakage conductance G. R, L, C, and G are the parameters which are uniformally distributed along the whole length of the line. So, it is known as distributed parameter line. Each line consists of these four parameters and these parameters are recognized as primary constants of line.

Where,

R = Total series resistance/unit length (Ω/km)

L = Total series inductance/unit length (H/km)

C = Shunt capacitance/unit length (F/km)

G = Shunt conductance/unit length (℧ /km)

Then,

Total series impedance, $Z = (R + j\omega L)\ \mathrm{ohm/km}$ (3.1)

Total shunt admittance, $Y = (G + j\omega C)\ \mathrm{mho/km}$ (3.2)

The characteristics impedance (Z_0) and propagation constant (γ) parameters are extremely useful parameters used for analyzing transmission line. These parameters are known as secondary constants of the transmission line and these parameters are obtained in the form of primary constants. Even though, these parameters are known as constants but if frequency is changed then these will vary.

Where,

Surge impedance, $Z_0 = \sqrt{\frac{R+j\omega L}{G+j\omega C}} = \sqrt{\frac{Z}{Y}}$ (3.3)

Surge impedance will be the characteristics impedance of the lossless line.

Propagation constant, $\gamma = \sqrt{(R+j\omega L)(G+j\omega C)} = \sqrt{Z.Y}$ (3.4)

Since, γ is a complex quantity, it is given as: $\gamma = \alpha + j\beta$ (3.5)

α = attenuation constant

β = phase constant

And, the impedance of the distributed parameter line is calculated as given by equation (3.6).

$Z_a = 2^*Z_0 \sin h(\gamma * l)$ (3.6)

Where, Z_a is the actual impedance of the distributed parameter line and,

l = length of transmission line in km.

3.2 Series Compensation in Power System

Series compensation is an imperative and traditional way to enhance the performance of EHV lines. It consists of series capacitors installed in the line at appropriate locations. When *X/R* ratio of transmission line is high, then the inductive reactance of line can be reduced by installing series capacitors due to which voltage drop in the line is also decreased. Practically, transmission lines having length more than 300 km are series compensated [4]. In short circuit conditions, the high voltage may spoil the capacitor. So, series capacitor needs protection from these overvoltages. MOV is connected in parallel with series capacitor for its protection.

3.2.1 Advantages of Series Compensation

Series compensation with a series capacitor is convenient to lessen the series reactance of the line. The foremost advantages of series compensated lines are [27]:

a. Increase in Transmission Capacity

As we know that that power transfer over a transmission line is given by equation (3.7) [6, 27].

$$\mathrm{P} = \frac{\mathrm{V_s V_r \sin \delta}}{\mathrm{X}} \tag{3.7}$$

Where,

V_S = sending end voltage

V_r= receiving end voltage

X = Inductive reactance of transmission line

δ = Phase angle of V_s with respect to V_r

If a series capacitor 'C' having reactance X_c is inserted in the line, then the net series reactance becomes $X_L - X_c$ and the power transfer is given by equation (3.8).

$$\mathrm{P_c} = \frac{\mathrm{V_s V_r \sin \delta}}{\mathrm{X_L - X_c}} \tag{3.8}$$

So, here it is seen that for same values of V_S ,V_r, X and δ, P_c is greater than P i.e. series compensation enhance the capacity of transmission line.

b. Enhancement in System Stability

Series compensation with series capacitor also reduces the phase shift between the sending end and receiving end voltages. So, δ in series compensated line is less as compare to uncompensated line. And lower phase angle δ means improved stability [1].

c. Load Division between Parallel Circuits

Series compensation is a convenient method to balance the loading in double circuit lines by drop in series reactance of the line. When a system has to be strengthening by adding a new line for reduction in losses and maximum power transfer, series compensation is used.

d. Reduction in Voltage Drop

When a lagging power factor load is connected to transmission line, then the line voltage drop is given by equation (3.9).

$$VD = I(R\cos\emptyset + X_L \sin\emptyset) \tag{3.9}$$

And, now if a series capacitor 'C' having reactance X_C is connected in the line, then the net reactance will become (X_L – X_C) and voltage drop in line will reduces as given by equation (3.10).

$$VD = I(R\cos\emptyset + (X_L - X_C)\sin\emptyset) \tag{3.10}$$

Also the reactive power drawn by the line is reduced by reduction in voltage drop. So, series capacitor used in transmission lines decreases the voltage drop of the line having low power factor loads at receiving end and thus, improves the receiving end voltage profile of the transmission line. For variable load conditions, the voltage can be controlled by switching in suitable series capacitors in the line.

e. Increase in Surge Impedance Loading

The surge impedance loading (SIL) is defined as the power delivered by a lossless line to a load resistance equal to the surge (or characteristic) impedance *Zc*, and is given by equation (3.11).

$$P_r = \frac{V_r^2}{Z_0} \tag{3.11}$$

Where,

P_r: Total surge impedance loading in a three-phase line in VA
V_r: Line-to-Line nominal voltage in Volts
Z_0: Characteristics impedance of the line

So, the total power delivered by the line can be increased either by increasing the Vr or by reducing the surge impedance. Series capacitors used in the transmission line reduces the total line inductance and increases the capacitance of the line, therefore reduces the surge impendence. Shunt capacitors used in transmission lines also reduces the surge impedance but they increase the phase shift between the sending end voltage and receiving end voltage. So, stability becomes worsen in this case.

3.2.2 Suitable Location of Series Compensation

Series compensation can be done at one end of the line, both the ends of the line, along the line or at bus bars in the switching stations. These are some prevalent locations of series capacitors. In this thesis work, series capacitor is located at the 50% of the line length i.e. at the middle of the line [8]. Series capacitor located at the middle of the line gives improved voltage profile along the length of the line, minor short circuit currents at the instant of fault through the capacitor, and gives easy protection of the series capacitor.

The use of series compensation is economical for long lines having length more than 300km. The ratio X_C/X_L is known as degree of compensation [7]. The degree of compensation should be lies in the limit of 30% to 70% for economical use of series capacitor.

3.2.3 Series Capacitor Protection

The use of series capacitors in transmission lines presents numeral technical challenges during the protection of transmission lines [6]. At the instant of short circuit fault, the short circuit fault current flowing through the series capacitor produces overvoltage's at the terminals of the capacitor. Consequently, to limit the voltage across the terminals of the series capacitor, protection is to be provided. So, for the protection of the series capacitor a resistive device MOV which is non-linear connected in parallel with the series capacitor [28, 29]. MOV conducts currents at particular instantaneous voltages and MOV accumulates energy within itself. The MOV can absorb a limited amount of energy without breakdown so to prevent breakdown of MOV, it is bypassed at predetermined energy level [13]. If the energy engrossed by the MOV exceeds the pre-set value, then the bypass breaker switch operates. This bypasses both the series capacitor and MOV and when the energy becomes less than the pre-set value then it re-inserts them.

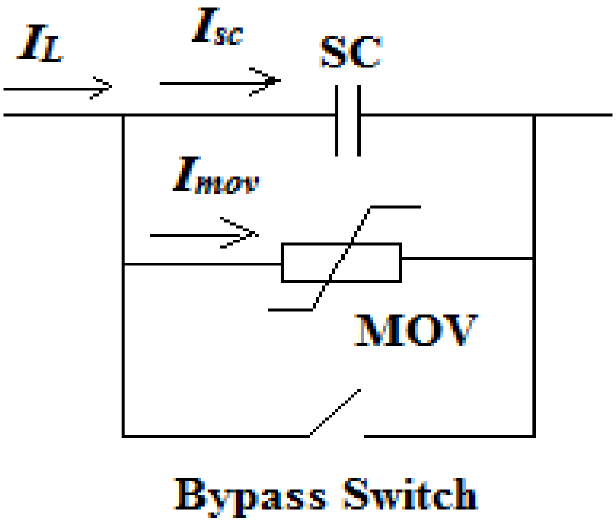


Figure 3.1: MOV equivalent model

3.2.4 Comparison of Series and Shunt Compensation

Series and shunt compensation have their own advantages and disadvantages. For example, series compensation has improved stability conditions whereas in shunt compensation, stability gets worse. Capacitor protection is necessary in series compensation as the overvoltage developed due to fault current may damage the capacitor which connected in series with the transmission line.

Some of the advantages and disadvantages of series and shunt compensation are given in Table 3.2 and Table 3.3 [1, 28, 29].

Table 3.2: Series capacitor compensation

	Advantages	Disadvantages
1.	Compensation naturally regulates with change in load currents.	Ferro-resonance may occur.
2.	Low risk of problems from load generated harmonics.	Fault level control.
3.	Reduced line currents.	Capacitor fault levels withstand.

Table 3.3: Shunt capacitor compensation

	Advantages	Disadvantages
1.	No inherent Ferro-resonance risk.	Automatic regulation only possible with expensive control gear.
2.	Capacitors do not carry line fault currents.	Switchgear and Control equipment generally required.
3.	Reduced line currents.	Voltage and VAR changes in discreet steps.
4.		Inability to respond to rapid load fluctuations.
5.		Risk of over current damage from load generated harmonics.

4.1 Introduction

Information which is not available directly from the original signal can be obtained by applying mathematical transformation. Most of the signals in their raw format are the time-domain signals. It means, whatever the signal is measuring will be a function of time or we can say that while plotting the signal, one axes will represent time which is an independent variable and the other axes will represent the other variable which is dependent on time. Usually, this dependent variable is amplitude. So, a signal in time-domain is plotted, representation of signal in time-amplitude form is obtained. Further for many applications related to signal processing, this representation is not useful. In several cases, the most important information is concealed in the frequency contents of the signal. The frequency spectrum of any signal is nothing but frequency components of the signal. The frequencies existing in the signal are shown by frequency spectrum of the signal. Basically, frequency is rate of change of a given variable and is measured in cycles per second. If this variable is changing rapidly, then we can say that the frequency of variable is very high and if the value of this variable is changing slowly, then we can say that the frequency of the variable is low. Further, if there is no change in the value of variable then the frequency is zero or no frequency. So, to measure the frequency of any variable or in other words to find frequency content of any signal we can use Fourier transform [8].

For analyzing the frequency contents of any signal, FT can be applied efficiently. Though, if the Fourier transform of the entire time axis is taken, then we cannot notify that at what instant a specific frequency rises. Short Time Fourier Transform (STFT) which uses a sliding window can also used to find information of both frequency and time. However, window length limits the resolution of frequency. So, the Wavelet transform is the ultimate solution of these problems. Small wavelets having limited duration are considered in wavelet transform.

A wavelet-based signal-processing technique is an effective tool for power system transient analysis and feature extraction [24]. Wavelet Transform (WT) is an efficient means of analyzing transient currents and voltages. Unlike DFT, WT not only analyzes the signal in frequency bands but also provides non-uniform division of frequency domain, i.e. WT uses short window at high frequencies and long window at low frequencies [5]. This helps to analyze the signal in both frequency and time domains effectively. And, WT is able of providing the frequency and time information concurrently, thus provides the time-frequency representation of the given signal. The time-domain signal passes through numerous low pass and high pass filters. And these filters, filters either the low or high frequency part of the signal [22]. This process is repeated, and each time a certain part of the signal equivalent to some frequencies is removed from the signal. A set of basis functions called Wavelets, are used to decompose the signal in various frequency bands, which are obtained from a mother wavelet by dilation and translation. Hence the amplitude and incidence of each frequency can be found precisely.

The WT can detect the low frequency and high frequency components precisely. One of the main properties of the WT, that it has the great ability to locate the signal's short-time high frequency features and determine the low frequency performance.

The convolution of the signal $f(t)$, which is under analysis, is taken with a wavelet ψ, to obtain wavelet transform [19].

$$C(Scale, position) = \int_{-\infty}^{\infty} f(t)\psi(Scale, position, t)dt \tag{4.1}$$

Where,

ψ belongs to a special wavelets family to compare with $f(t)$ is known as "mother wavelet".

There are various types of wavelets i.e. Haar, Symlets, Meyer, Daubechies, and Discrete Meyer. To analyze the portion of the signal which is not known using convolution, ψ is selected i.e. WT can detect if under a determined position and scale, the analyzed signal intimately correlated with ψ. Basically, wavelet transform is used to evaluate the non-stationary signals, those frequency response change in time.

4.2 Discrete Wavelet Transform

Signal is filtered and then sampling is done in DWT. This process reduces the data but the necessary information is kept as such [30]. Signal can be analyzed at different frequency bands in DWT process. Two data sequences cA1 and cD1 are obtained after the process as shown in Figure 4.1. Approximation (cA1) part of the signal consists of low frequency and high scale components of the signal while detail (cD1) consists of high frequency and low scale components of the signal [2].

Let V(t) is the original signal at 20 kHz and we want to obtain its discrete wavelet transform coefficients. So, this signal is then passed through a low pass and high pass filters. The output of these filters is sub-sampled by a factor of 2. And the output of these filters gives the first level DWT coefficients i.e. approximation and detail coefficients. They represent the signal at 10 kHz having 1004 simples. Approximation (cA1) contains the components of the signal which are at less than 10 kHz frequency (low frequency, high scale) while detail (cD1) contains greater than 10 kHz (high frequency, low scale) components of the signal. The approximation and detail coefficients of level 1 are further decomposed by passing them through low pass and high pass filters to give the level 2 coefficients of DWT which represents the signal at 5 kHz frequency having 502 samples. Approximation (cA2) coefficient of level 2 contains the components of the signal which are at below 5 kHz frequency and detail (cD2) coefficient of level 2 contains the components of the signal which are at greater than 5 kHz frequency. This process is recurring until the required level for a particular application is achieved. In a nutshell, in DWT process number of data is reduced at each step but it contains the entire useful information.

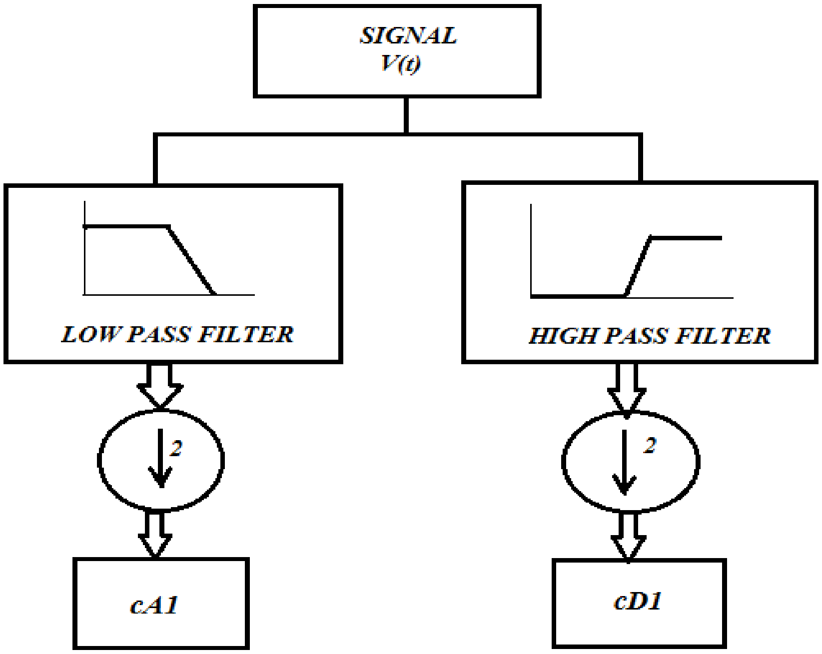


Figure 4.1: Discrete Wavelet Transform

4.3 Wavelet Multi-Resolution Analysis

Wavelets can present multiple resolutions in both time and frequency. The signal is decomposed at distinctive resolution levels by the use of wavelet and scaling functions in multiple resolution analysis [11]. The detail form of the decomposed signal will be generated by the wavelet function and the approximated form of the decomposed signal will be generated by the scaling function. It means that the wavelet function consists of the high pass filter and low pass filter is contained in the scaling function [17].

Let V(t) is the original signal obtained from a measuring device. V(t) is decomposed into detail and approximation. cA1 and cD1 are the decomposed signals of level 1 in the multi resolution technique. Where, cA1 is the approximation of the original signal and the cD1 is the detail version of the original signal. cA1 and cD1 are defined as given in equations (4.2) and (4.3) respectively [19].

$$cA1(t) = \sum_k V(t).L_d(k-2t) \tag{4.2}$$

$$cD1(t) = \sum_k V(t).H_d(k-2t) \tag{4.3}$$

Where,
L_d is the low-pass filter and,
H_d is the high-pass filter.

These filters are related to mother wavelet ψ. High frequency components of the signal are contained in cD1 whereas cA1 contains the low frequency components of the signal. When the original signal V(t) is passed through the low pass and high pass filters, it gets decomposed into cA1 and cD1 coefficients of the signal. Here the cA1 and cD1 are level1 coefficients. Further approximation cA1 is decomposed into cA2 and cD2 coefficients of the signal which are the level 2 coefficients. And this procedure is repeated again and again until the required level is obtained for a particular application as shown in Figure 4.2.

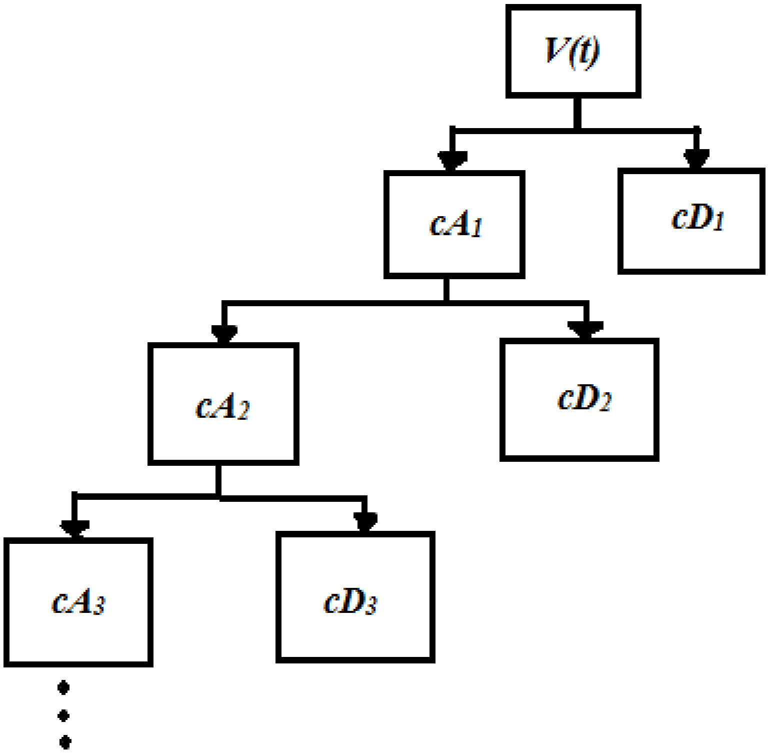


Figure 4.2: Wavelet decomposition tree

4.4 Working of Wavelet

Let the signal having sampling frequency 20 kHz is passed through the low pass and high pass filters where it is decomposed into two different frequency bands i.e. cA1 which contains less than 10kHz frequency portion of the signal and cD1 which contains greater than 10kHz frequency portion of the signal. Hence, cA1 contains the low frequency portion and cD1 contains high frequency portion of the signal. This decomposition is known as level1 decomposition. Further, cA1 is decomposed into two frequency bands i.e. low frequency portion (less than 5 kHz) and high frequency portion (more than 5 kHz). Similarly, cD1 is decomposed into two frequency bands i.e. low frequency portion (less than 5 kHz) and high frequency portion (more than 5 kHz). This decomposition is known as second level decomposition. In this way, next level decompositions are also obtained by dividing the parent frequency with a factor of 2 as shown in Figure 4.3. This process is continual until the required level of application is achieved.

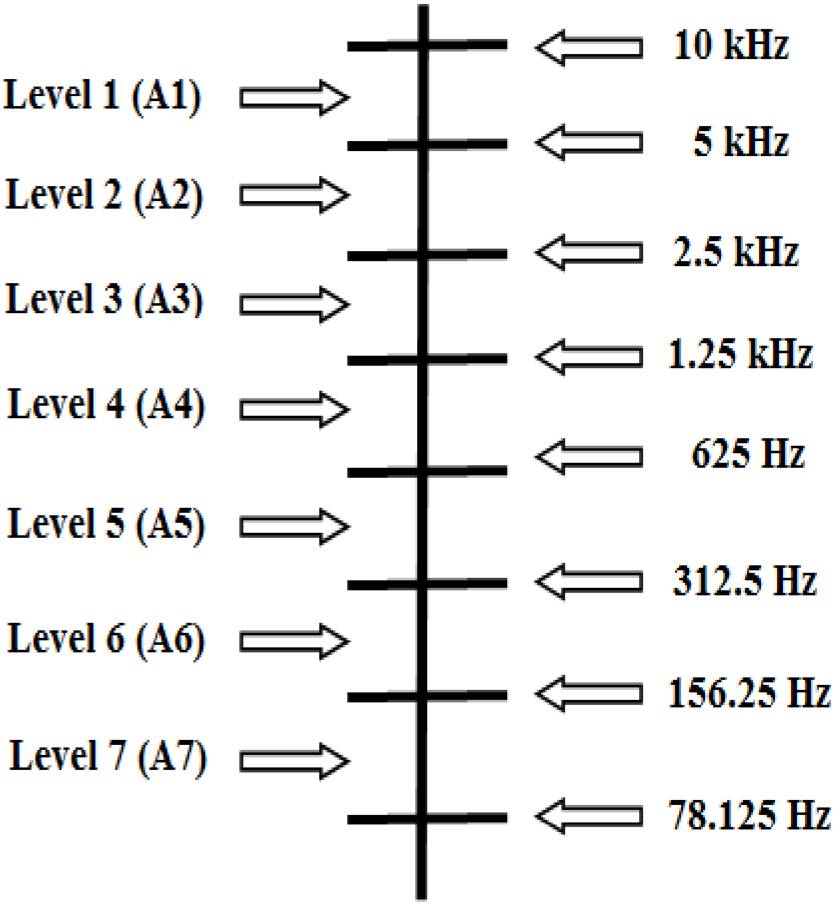


Figure 4.3: Wavelet decomposition of signals sampled at 20 kHz shows association of levels to components

CHAPTER – 5 TEST SYSTEM AND RESULTS

5.1 Model-Based Design Process

There are six steps to modeling any system.

- Defining the System
- Identifying System Components
- Modeling the System with Equation
- Building the Simulink Block Diagram
- Running the Simulation
- Validating the Simulation Results
- Running the Simulation

After building the Simulink block diagram, we can simulate the model and can analyze the results. Simulink allows us to interactively define the system inputs, simulate the model, and observe change in behavior [31]. It allows quickly evaluation of the model.

5.2 Simulated System

A double circuit 735 kV, 400 km (Figure 5.1) series compensated line is simulated using MATLAB/SIMULINK with different faults before and after compensation at different locations i.e. at an interval of 50 km and 25 km distance.

The simulated model shown in Figure 5.1 represents a double circuit, 50Hz, 735 kV power system transmitting power from a three phase source of 13.8 kV to an equivalent system through a 400 km transmission line. The transmission line is split into two 200 km lines. Both lines are series compensated by connecting a series capacitor midway the two lines. Series compensation is done to enhance the transmission capacity of the line by lessen the effect of series reactance of the line. Metal oxide varistors are used for the protection of series capacitors. Each line is shunt compensated by a shunt reactance of 330 Mvar.

The B1, B2……B8 blocks represents the bus bars which output the three line-to-ground currents and voltages. Then, these current and voltage signals are sent to Data Acquisition subsystem through go to blocks.

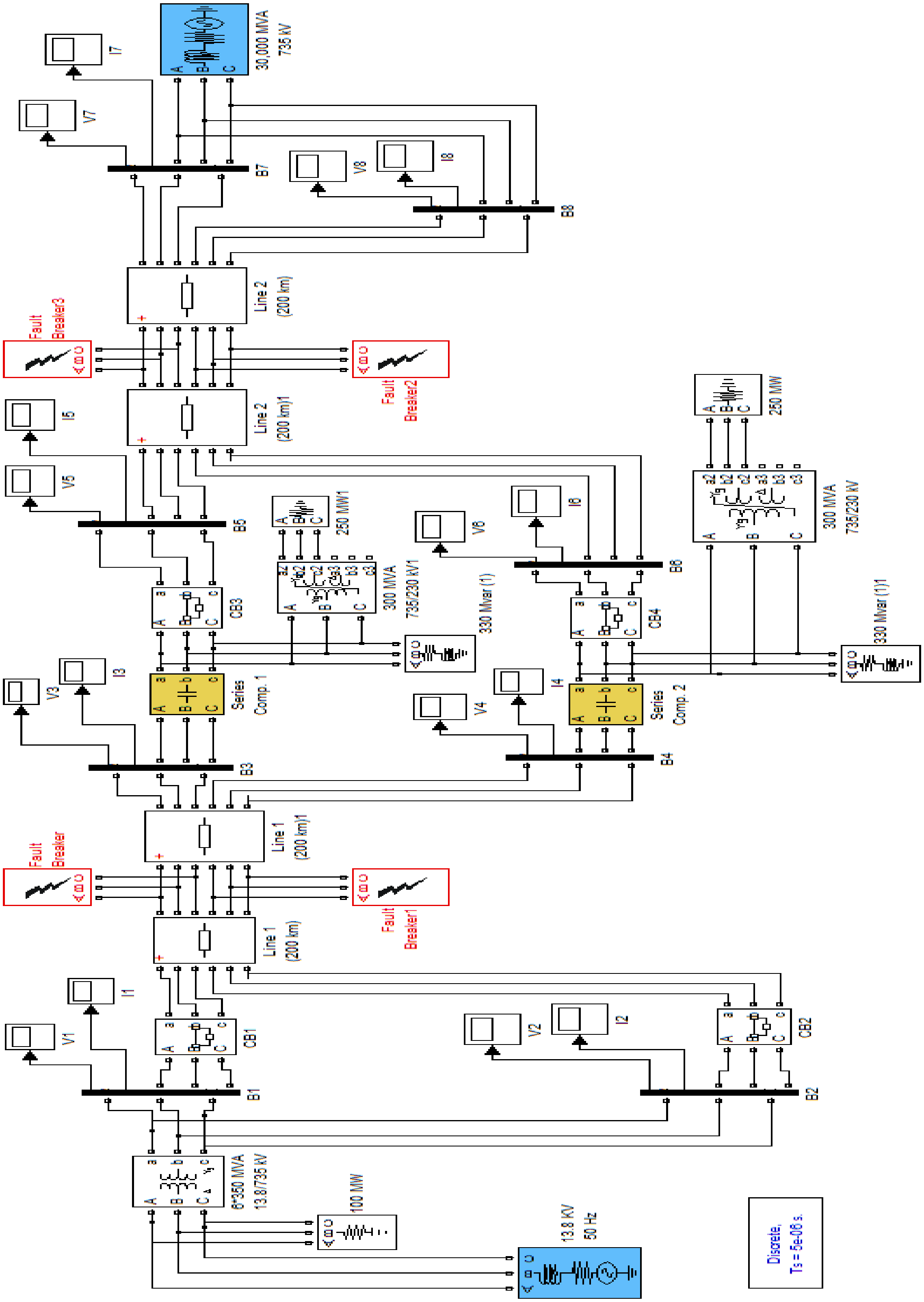


Figure 5.1: Simulated Circuit of double circuit series compensated network

5.3 Series Compensational Subsystem

In series compensation subsystem block, for each phase the module consists an identical subsystem. The transmission line is 30% compensated by a 90.429 µF capacitor. Similarly, 50% and 70% compensation is done. MOV is used for the protection of capacitor. MOV have 60 columns and the protection level of MOV is set at 248.83 kV with 30% compensation. The nominal voltage of capacitor is obtained at a 2 kA (rms) nominal current. A parallel gap is connected with MOV block which is fired if the energy absorbed by the MOV becomes greater than the critical value of 30MJ. A RL damping circuit is connected in series with the gap to limit the rate of rise of current flowing through capacitor.

5.3.1 Series Compensation Module

Total reactance of the line in positive-sequence:

$$X_1 = 0.9337e\text{-}3*(2*\pi*50)*400=117.33\ \Omega \tag{5.1}$$

For 30% compensation series capacitance required is:

$X_c = 0.3*117.33 = 35.19\ \Omega$

And $C_s = 90.429\ \mu F$

The protection level of MOV required for the protection of capacitor at 2.5 times the nominal voltage of capacitor is given by equation (5.2).

(The nominal voltage of capacitor is obtained at 2kA (rms) nominal line current)

$$U_{prot} = 2.5*2kA*35.19*\sqrt{2} = 248.83\ kV \tag{5.2}$$

The power system must be discretize so as to expedite the the simulation. In powergui block, the sample time as variable T_s is specified.

Table 5.1: The parameters of simulation are:

Stop time	0.3
Solver options type	Fixed step discrete
Fixed step size	$T_s = 5e^{-05}$ s

5.4 Simulation Results

5.4.1 Fault Simulation

Double circuit series compensated transmission line is simulated with different types of faults i.e. Line to ground faults, Line to Line faults and Double line to ground faults. Different inception angles of 0°, 20° and 40° are taken for simulation. Simulation is done at different compensation levels of 30%, 50% and 70%. Different levels of compensation are considered on both lines. Different faults are simulated before and after compensation at different locations i.e. at an interval of 50 Km distance. Haar and db4 wavelets are used to calculate the fundamental components of voltage and current. Db4 is used as a mother wavelet for classification of faults and Haar is used to locate the fault. Fault classification and fault location is done as follows:

5.4.2 Fault classification

Fault classification is done by using db4 as a mother wavelet. After detection of fault, fault classification is done. Voltage and current signals of the faulted line are decomposed by db4 wavelet into approximation and detail coefficients. By using level6 (A6) coefficients of approximation part, average values of the voltage and currents are calculated to classify the various types of faults. dW_a, dW_b, dW_c are the average values of three phase currents calculated from A6 coefficients. Ground current (dW_Z) involving zero sequence components is calculated as given by equation (5.3). If dW_Z is greater than unity, then ground is involved in the fault and if it less than one, then ground is not involved in the fault. Flow chart for fault classification is depicted in Figure 5.12. Different types of faults are classified as follows:

1. L-G Fault

The characteristics of this type of faults are that the faulted phase has a rapid change in Line current. The rate of change of faulted phase current is much higher as compared to other two phases. The phase in which fault occurs will have high value of current and a low value of voltage, e.g. for b-g fault, dW_{ac} is minimum i.e. $dW_{ac} < dW_{bc}$ and $dW_{ac} < dW_{ab}$. Ground current also has a very high value which is calculated from zero-sequence components of the line as given below:

$$dW_z = \left|\frac{dW_a + dW_b + dW_c}{3}\right| \tag{5.3}$$

And, dW_{ab}, dW_{bc}, dW_{ac} for L-G fault are calculated as follows:

$$dW_{ab} = |dW_a - dW_b| \tag{5.4}$$

$$dW_{bc} = |dW_b - dW_c| \tag{5.5}$$

$$dW_{ac} = |dW_a - dW_c| \tag{5.6}$$

Figure 5.2 shows the three phase currents at bus 1 when there is no fault on line. But when there occurs a single L-G fault on line, then the current of faulted phase increases rapidly and voltage of faulted phase decreases. Current and voltage waveforms at bus 1 during A-G fault on line 1 at 25 km distance before compensation (30% compensation) with inception angle 0° are depicted in Figure 5.3 and Figure 5.4. Figure 5.5 shows the three phase currents at bus 1, when there occurs a single L-G fault on phase B at a distance of 225 km (after compensation) with 30% compensation at inception angle 20°. It is shown that magnitude of fault current after compensation is less than the magnitude of fault current before compensation. Phase currents are decomposed by using db4 wavelet to extract the fundamental frequency current signals. Db4 approximation coefficients of Level 4, 5 and 6 at bus 1 for three phase currents for A-G fault on line 1 at 25 km with 30 % compensation at inception angle 0° are depicted in Figure 5.6.

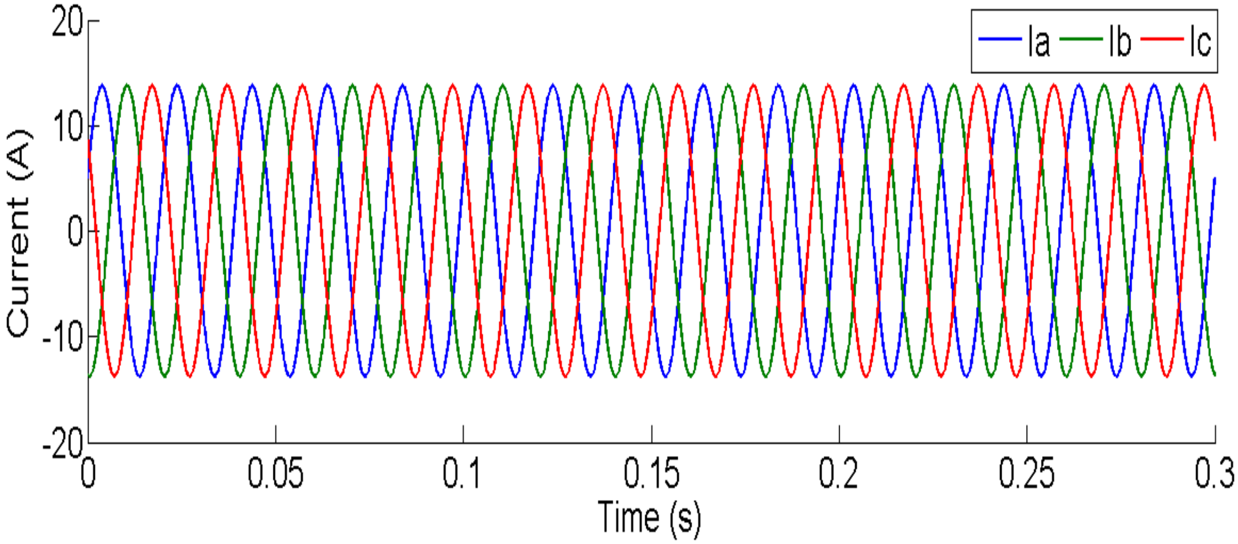


Figure 5.2: The phase currents at bus 1 when there is no fault on line

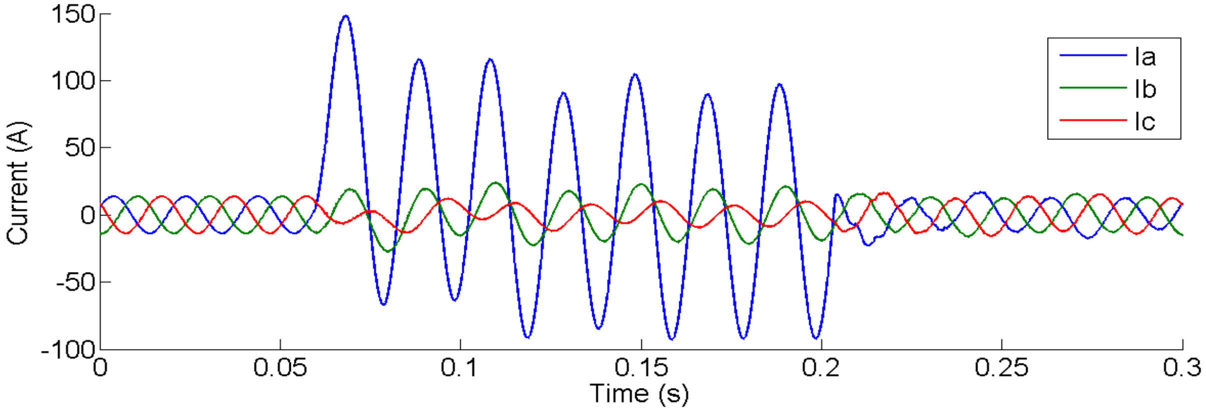


Figure 5.3: The phase currents at bus 1 during A-G fault on line 1 at 25 km distance with 30% compensation at inception angle 0°

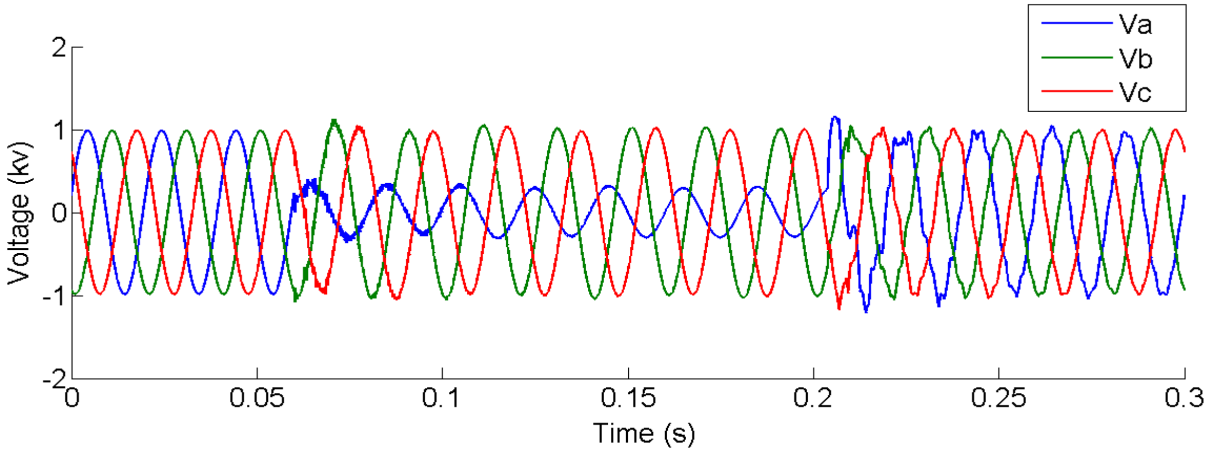


Figure 5.4: The phase voltages at bus 1 during A-G fault on line 1 at a distance of 25 km with 30% compensation at inception angle 0°

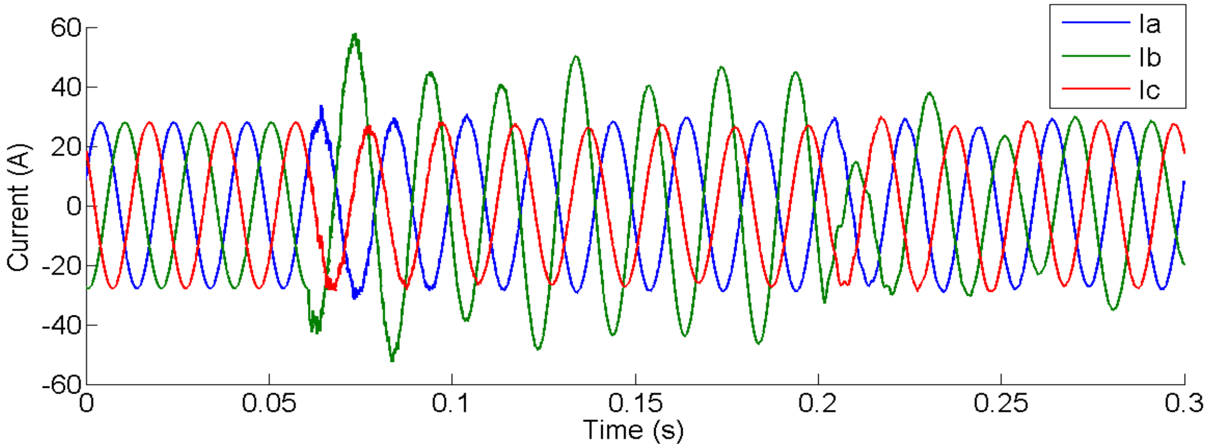
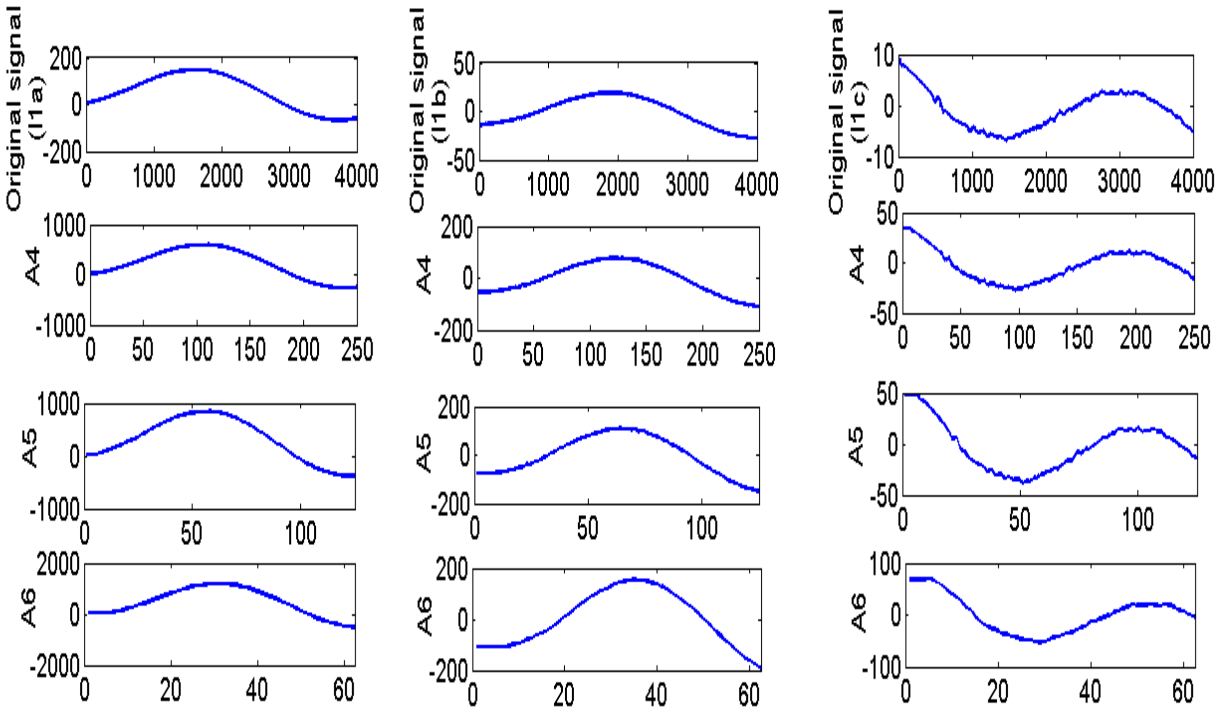


Figure 5.5: The phase currents at bus 1 during B-G fault on line 1 at a distance of 225 km with 30% compensation at inception angle 20°



(a) **(b)** **(c)**

Figure 5.6: db4 approximation coefficients of Level 4, 5 and 6 at bus 1 for three phase currents for A-G fault on line 1 at 25 km with 30 % compensation at inception angle 0° (a) Approximation coefficients of current of phase A (b) Approximation coefficients of current of Phase B (c) Approximation coefficients of current of phase C (X axis: no. of samples, Y axis: Magnitude of approximation coefficients)

2. L-L Faults

The main characteristic of this type of fault is that the two faulted phases has a rapid change in line currents. The currents of the faulted phases are of opposite polarity, e.g. for a-c fault $dW_{ac} < dW_{ab}$ and $dW_{ac} < dW_{bc}$. And ground current involving zero sequence components is negligible in this case which is calculated as given by equation (5.3) and dW_{ab}, dW_{bc}, dW_{ac} for L-L faults are calculated as follows:

$$dW_{ab} = |dW_a + dW_b| \tag{5.7}$$

$$dW_{bc} = |dW_b + dW_c| \tag{5.8}$$

$$dW_{ac} = |dW_a + dW_c| \tag{5.9}$$

Three phase currents at bus 1 during L-L fault on phase A and C (a-c fault) at a distance of 50 km (before compensation) at 20° inception angle with 70 % compensation are depicted in Figure 5.7. Db4 approximation coefficients of Level 4, 5 and 6 at bus 1 for three phase currents for B-C fault at 50 km with 70 % compensation in both the lines at inception angle 20° are depicted in Figure 5.8.

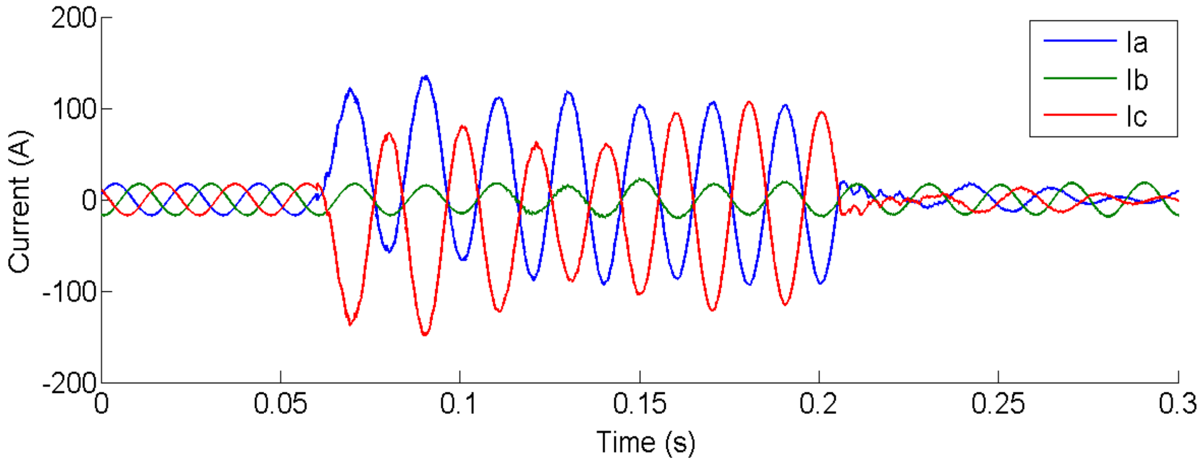
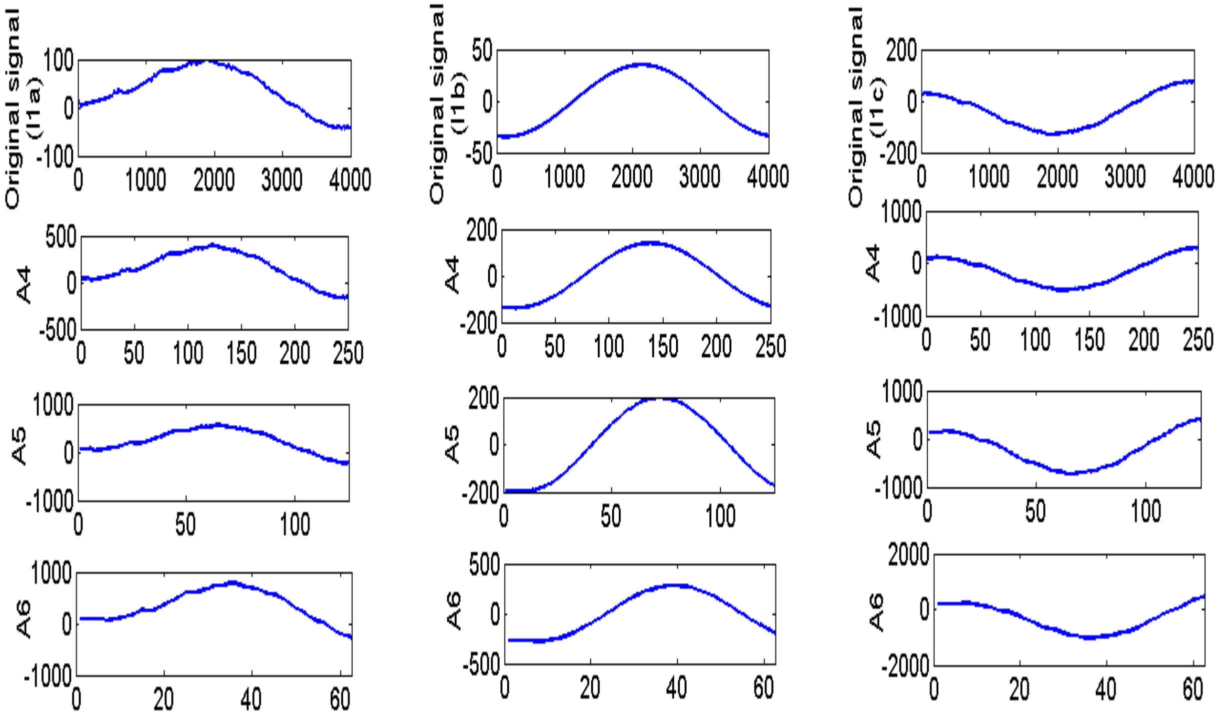


Figure 5.7: The phase currents at bus 1 during A-C fault on line 1 at a distance of 50 km with 70% compensation at inception angle 20°



(a) **(b)** **(c)**

Figure 5.8: db4 approximation coefficients of Level 4, 5 and 6 at bus 1 for three phase currents for A-C fault on line 1 at 50 km with 70 % compensation at inception angle 20° (a) Approximation coefficients of current of phase A (b) Approximation coefficients of current of Phase B (c) Approximation coefficients of current of phase C (X axis: no. of samples, Y axis: Magnitude of approximation coefficients)

3. L-L-G Faults

The characteristics of this type of faults are that the two faulted phases has a rapid change in Line current. For e.g. in case of a-b-g fault, dW_{ab} is maximum, $dW_{ab} > dW_{bc}$ and $dW_{ab} > dW_{ac}$. Ground current also has a high value in this case i.e. $dW_Z > 1$.

And dW_{ab}, dW_{bc}, dW_{ac} for L-G fault are calculated as follows:

$$dW_{ab} = |dW_a - dW_b| \tag{5.10}$$

$$dW_{bc} = |dW_b - dW_c| \tag{5.11}$$

$$dW_{ac} = |dW_a - dW_c| \tag{5.12}$$

Figure 5.9 shows the three phase currents at bus 1 during L-L-G fault (a-b-g fault) at a distance of 100 km (before compensation) with 30% compensation at inception angle 40°. The phase currents at bus 1 during L-L-G fault (b-c-g fault) at a distance of 300 km (after compensation) with 50% compensation at inception angle 20° are depicted in Figure 5.10. Db4 approximation coefficients of Level 4, 5 and 6 at bus 1 for three phase currents for B-C-G fault at 100 km with 50 % compensation at inception angle 20° are depicted in Figure 5.11.

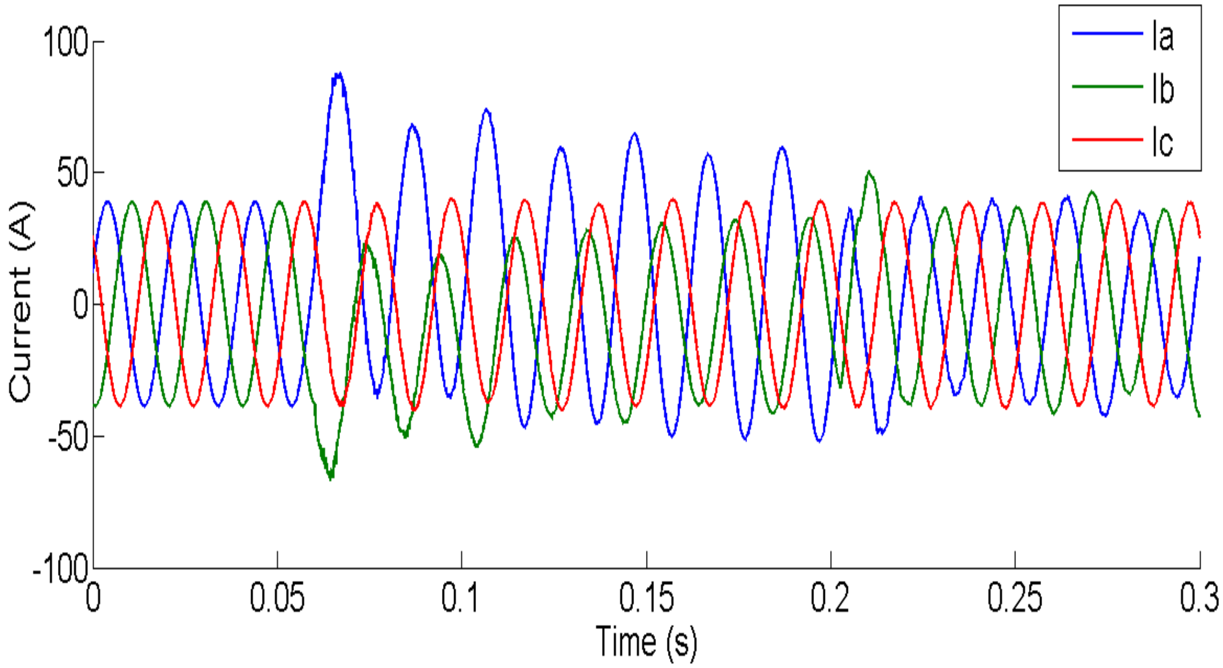


Figure 5.9: The phase currents at bus 1 during L-L-G fault (a-b-g fault) at a distance of 100 km with 30% compensation at inception angle 40°

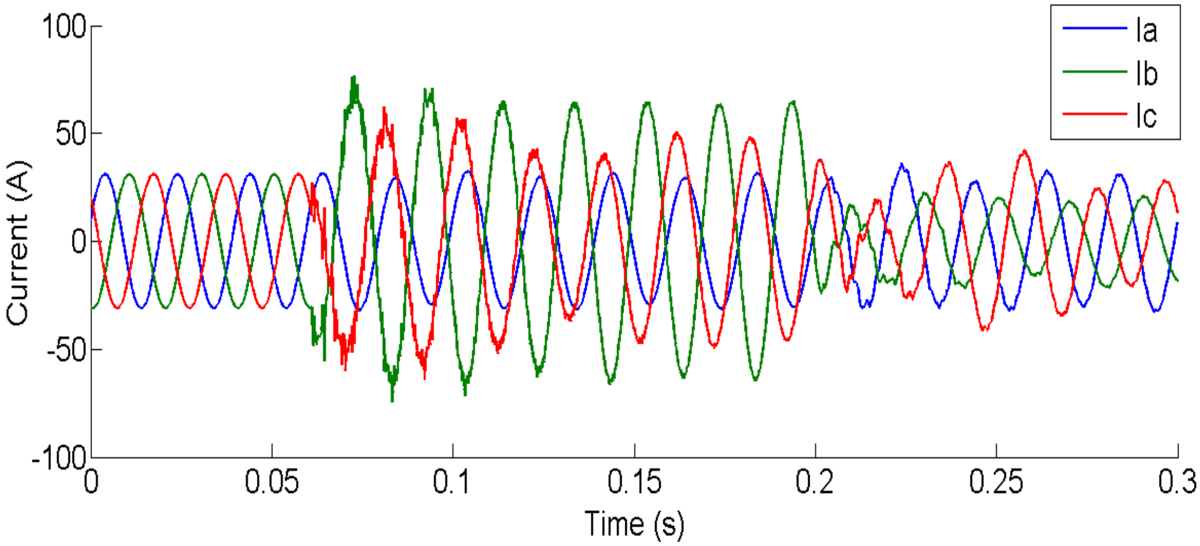
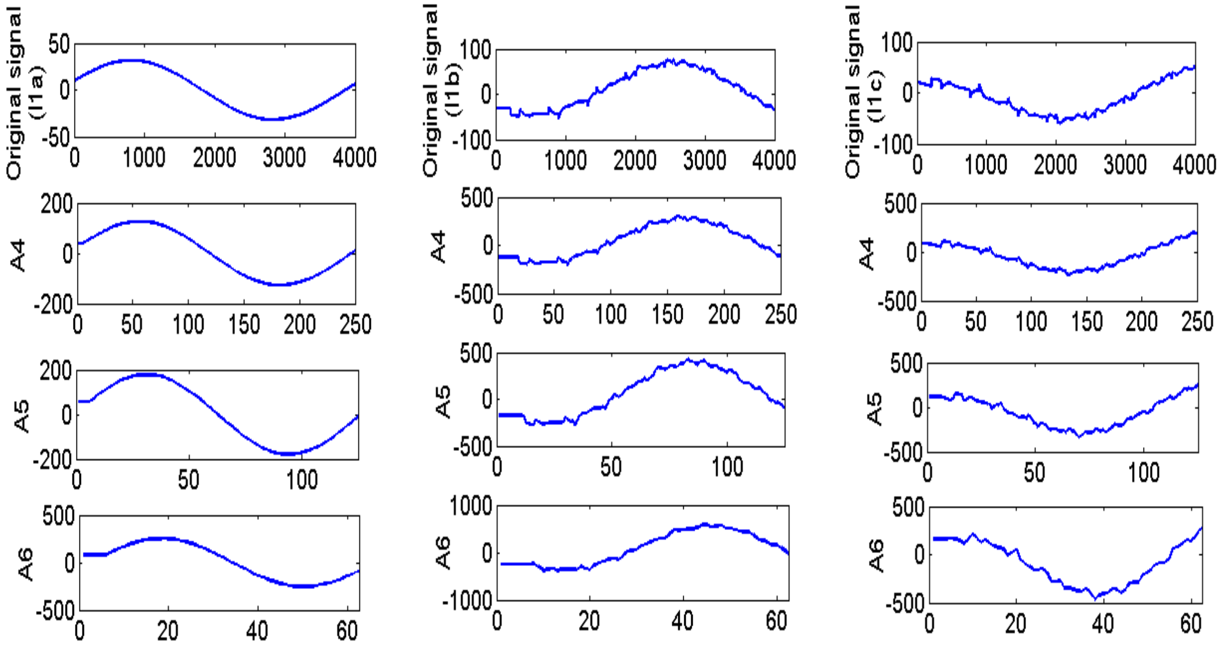


Figure 5.10: The phase currents at bus 1 during L-L-G fault (b-c-g fault) at a distance of 300 km with 50% compensation at inception angle 20°



(a) **(b)** **(c)**

Figure 5.11: db4 approximation coefficients of Level 4, 5 and 6 at bus 1 for three phase currents for B-C-G fault at 300 km with 50 % compensation at inception angle 20° (a) Approximation coefficients of current of phase A (b) Approximation coefficients of current of Phase B (c) Approximation coefficients of current of phase C (X axis: no. of samples, Y axis: Magnitude of approximation coefficients)

Table 5.2 shows the average values of Level 6 approximation coefficients of three phase currents and ground current for different types of faults. Similarly, Table 5.3 shows the average values of dW_{ab}, dW_{bc} and dW_{ac} to classify different types of faults. Flow chart for fault classification is depicted in Figure 5.12.

Table 5.2: The A6 coefficients of three phase currents and ground current for different types of faults on line 1 at 30 % compensation with inception angle 0°

Type of fault	dW_a	dW_b	dW_c	dW_Z
a-g	368.7292	-18.8783	-2.1383	115.9042
b-g	21.8741	-66.2565	24.5741	6.6028
c-g	-4.8126	-18.8525	-305.3519	109.6723
a-b	258.8917	-260.809	4.6042	0.8956
b-c	3.6437	150.5982	-152.9925	0.4165
a-c	417.7487	-9.3594	-408.8166	0.1424
a-b-g	388.7301	-130.6988	15.1088	91.0467
b-c-g	-2.7222	101.8836	-93.7295	1.8106
a-c-g	443.8128	-21.1646	-384.2929	12.7851

Table 5.3: dW_{ab}, dW_{bc}, dW_{ac} coefficients of three phase currents for different types of faults on line 1 at 30 % compensation with inception angle 0°

Type of fault	dWab	dWbc	dWac
a-g	387.6075	16.74	370.8675
b-g	88.1306	90.8306	2.7
c-g	14.0399	286.4995	300.5394
a-b	1.9173	256.2048	263.4959
b-c	154.2419	2.3948	149.3493
a-c	408.3893	418.1764	8.9317
a-b-g	519.4291	145.8078	373.6213
b-c-g	104.6058	195.6131	91.0073
a-c-g	464.9774	363.1284	828.1058

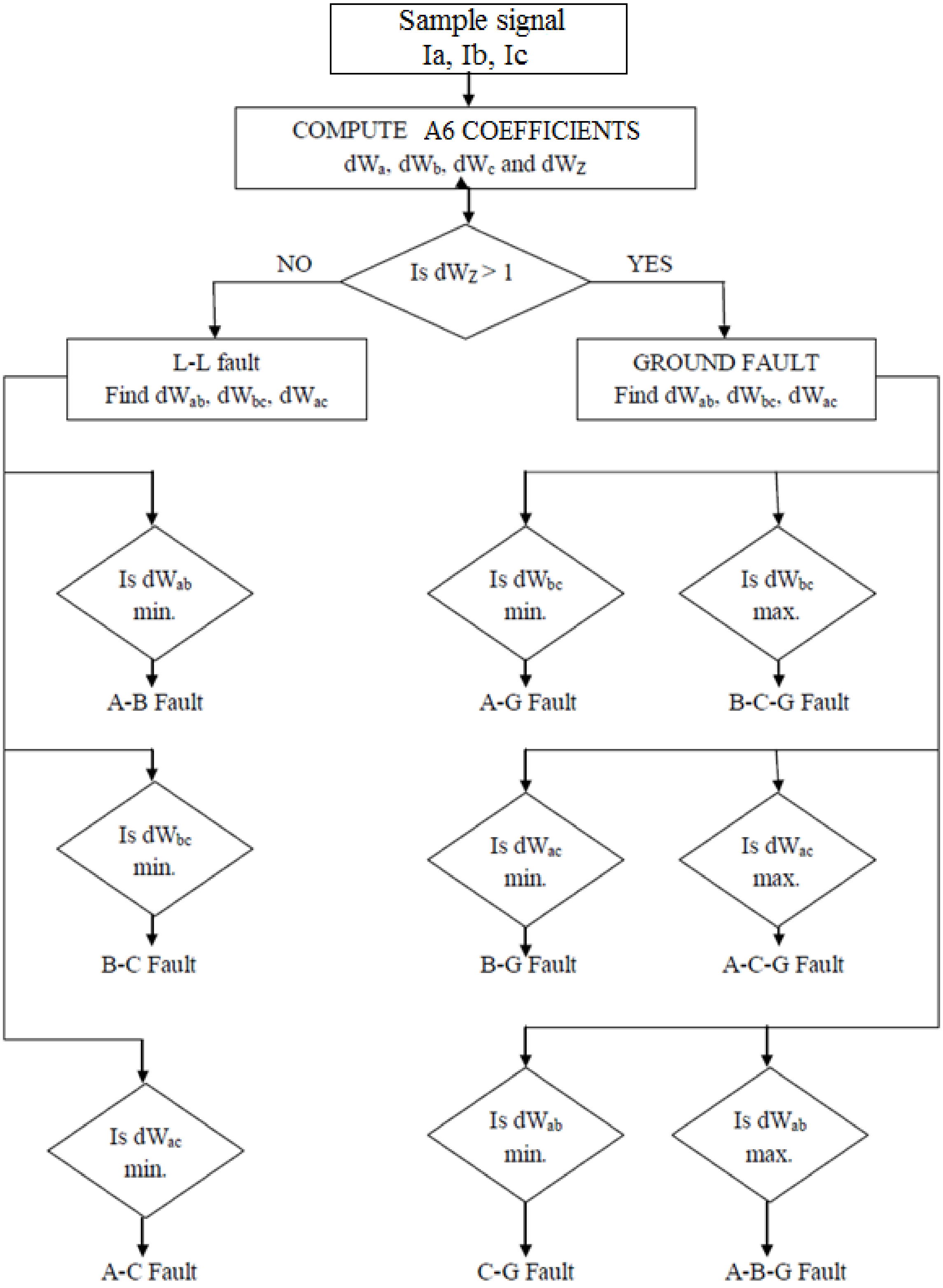


Figure 5.12: Flow chart for fault classification

5.3.3 Fault Location

After classification of different types of faults, fault is located. Haar wavelet is used as a mother wavelet to locate the fault. In this work, fundamental components of voltage and currents are used to locate the faults based on impedance measurements. The actual impedance of the distributed parameter line is calculated as given by equation (3.6). And actual impedance after series compensation is calculated by considering the effect of series compensation on line. It is calculated as given by equation (5.13).

$$Z_b = Z_a - Z_{comp} . \tag{5.13}$$

Where, Z_b is the actual impedance of the distributed parameter line after compensation. Z_a is the actual impedance of the distributed parameter line calculated as given by equation (3.6) and, $Z_{comp.}$ is the compensation impedance.

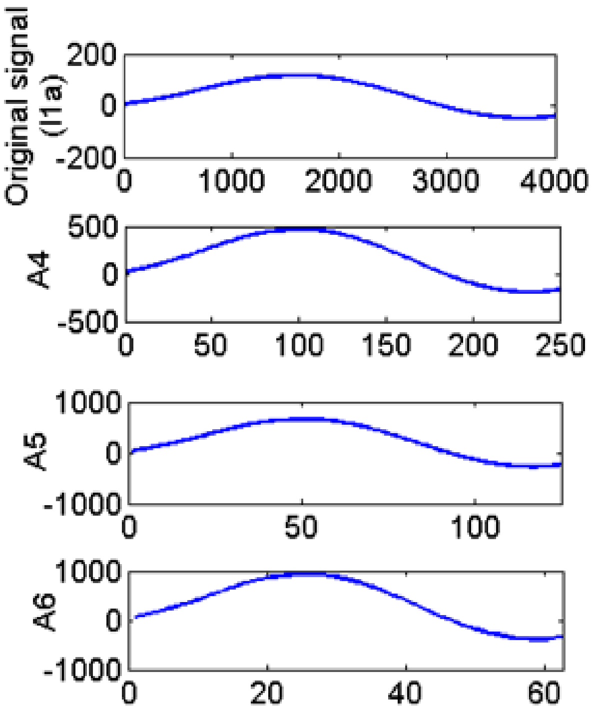
The voltage and current signals of the faulted line are decomposed by Haar wavelet into approximation and detail coefficients. By using Level 6 (A6) coefficients of approximation, rms values of voltages and currents are calculated to find the impedance of the faulted line. Percentage error is calculated as given by equation (5.14).

$$\%\ error = \frac{Z_{calculated} - Z_{actual}}{Z_{actual}} \tag{5.14}$$

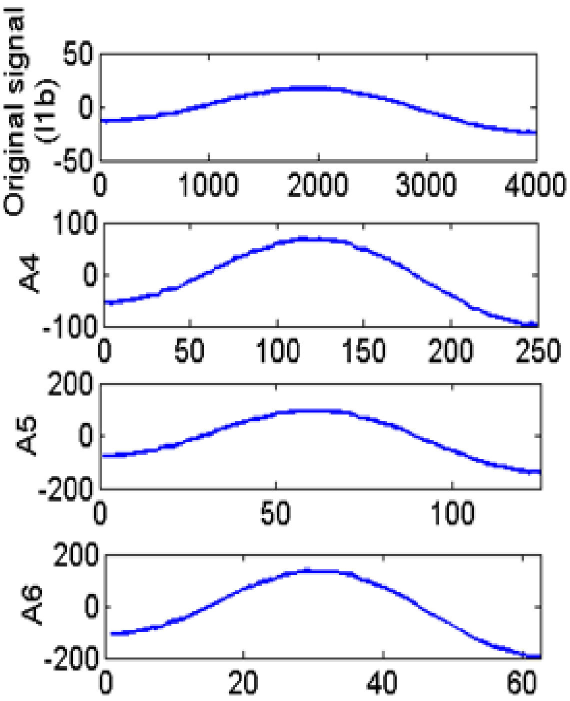
Where, Z_{actual} and $Z_{calculated}$ are the exact and calculated distance to fault in **Ω**.

While performing the fault location estimation, different factors are considered which affects the fault location accuracy i.e. different inception angles and different levels of compensation (30%, 50% and 70%) on both lines. Also, different compensation is considered on both the lines i.e. one line is 30% compensated and other is 0%, one line is 30% compensated and other is 50%. RMS values of the fault current have different values before and after compensation, so particular level of fault current i.e. 200A is considered for this given model to differentiate between the faults before and after compensation.

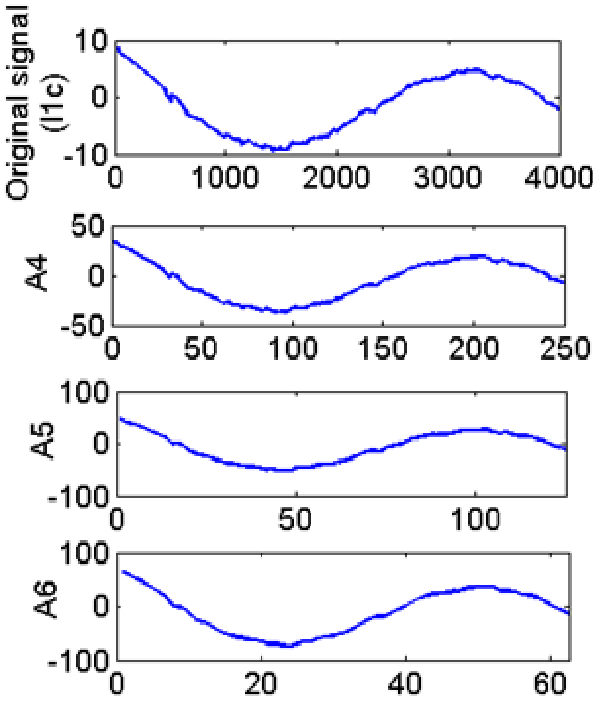
Fundamental frequency current and voltage signals are extracted by using Haar wavelet. Figure 5.13 shows the approximation coefficients of Haar wavelet of level 4, 5 and 6 at bus 1 for three phase currents and voltages for A-G fault at 50 km with 30% compensation at inception angle 0°.


Original signal (I1a)
200
0
-200
0
1000
2000
3000
4000
A4
500
0
-500
0
50
100
150
200
250
A5
1000
0
-1000
0
50
100
A6
1000
0
-1000
0
20
40
60

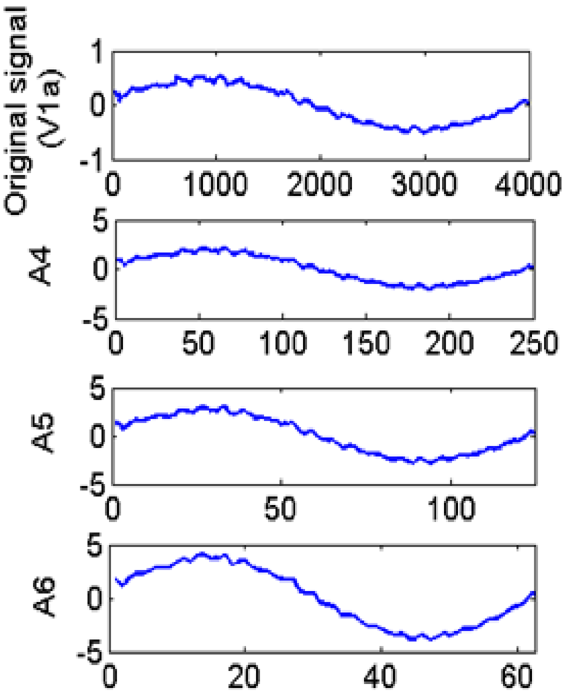
(a)


Original signal (I1b)
50
0
-50
0
1000
2000
3000
4000
A4
100
0
-100
0
50
100
150
200
250
A5
200
0
-200
0
50
100
A6
200
0
-200
0
20
40
60

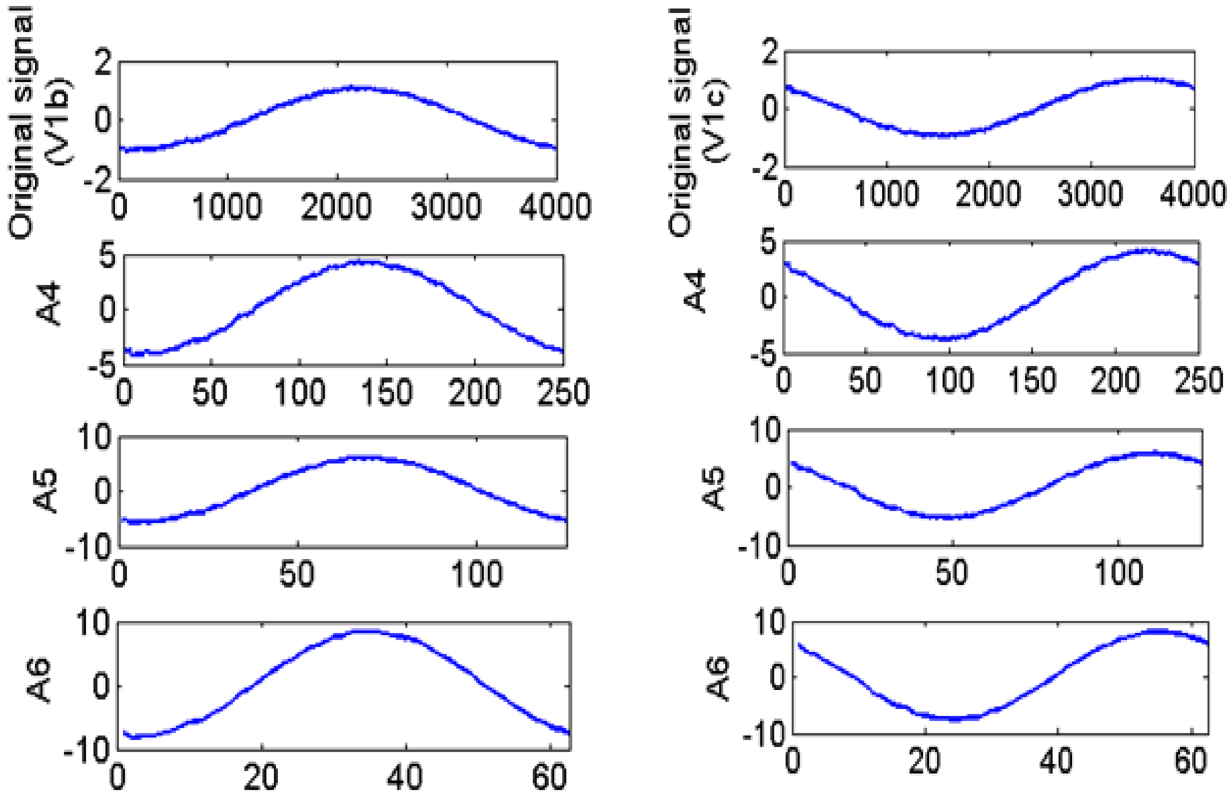
(b)


Original signal (I1c)
10
0
-10
0
1000
2000
3000
4000
A4
50
0
-50
0
50
100
150
200
250
A5
100
0
-100
0
50
100
A6
100
0
-100
0
20
40
60

(c)


Original signal (V1a)
1
0
-1
0
1000
2000
3000
4000
A4
5
0
-5
0
50
100
150
200
250
A5
5
0
-5
0
50
100
A6
5
0
-5
0
20
40
60

(d)



(e) **(f)**

Figure 5.13: Approximation coefficients of Haar wavelet of level 4, 5 and 6 at bus 1 for three phase currents and voltages for A-G fault on line 1 at 50 km with 30 % compensation at inception angle 0° (a) Approximation coefficients of current of phase A (b) Approximation coefficients of current of Phase B (c) Approximation coefficients of current of phase C (d) Approximation coefficients of voltage of Phase A (e) Approximation coefficients of voltage of Phase B (f) Approximation coefficients of voltage of Phase C
(X axis: no. of samples, Y axis: Magnitude of approximation coefficients)

RMS values of voltage and current signals are calculated from Level 6 approximation coefficients to find the impedance of the faulted section of the line. Percentage errors with different inception angles for fault location at 30% compensation in both the lines with A-G fault on line 1 are given in Table 5.4. And Bar graph of fault location at 30% compensation with different inception angles for single L-G fault on phase A (a-g fault) is depicted in Figure 5.14.

Table 5.4: Percentage error of fault location for A-G fault on line 1 with different inception angles at 30% compensation in both the lines

Distance (km)	% error at inception angle 0°	% error at inception angle 20°	% error at inception angle 40°
25	3.84%	-2.42%	-9.74%
75	-6.67%	-12.25%	-15.90%
125	-8.60%	-15.44%	-15.97%
175	-12.36%	-14.78%	-16.73%
225	2.27%	-6.14%	-8.89%
275	-5.66%	-11.92%	-13.24%
325	-9.49%	-13.64%	-17.11%
375	-14.19%	-17.41%	-20.61%

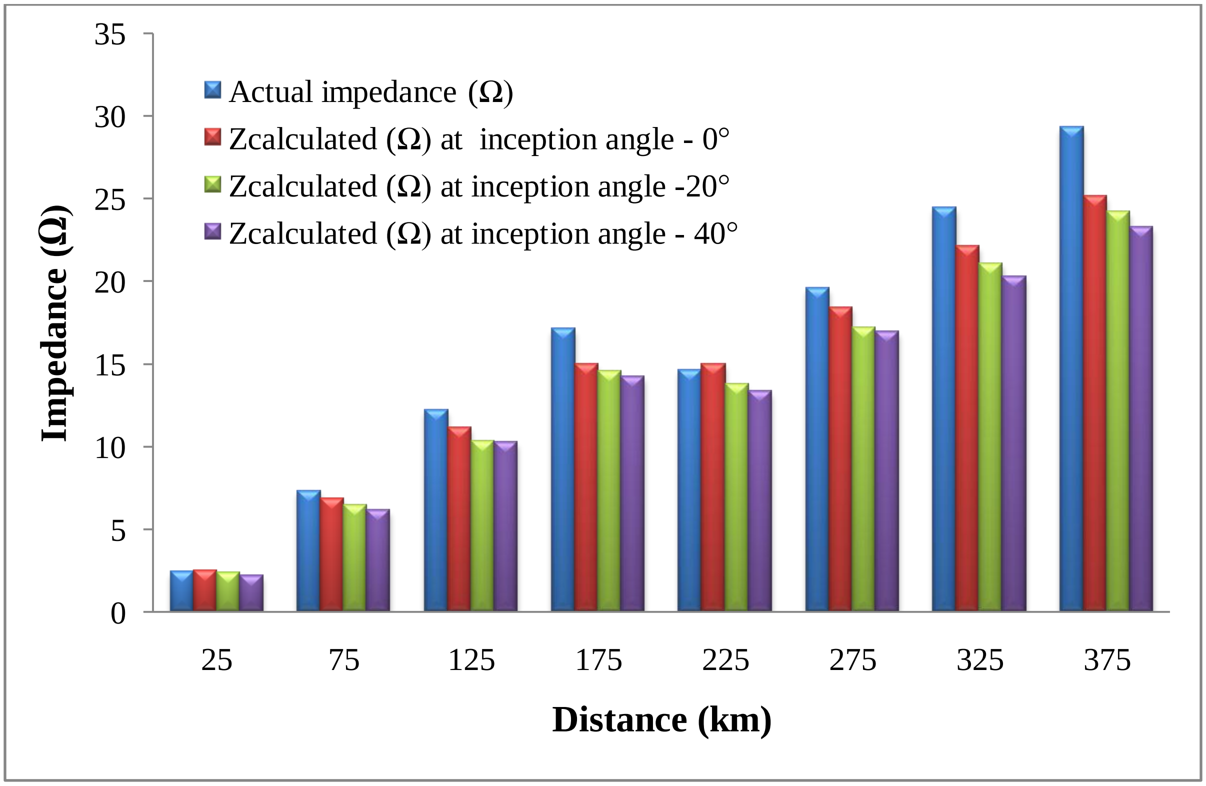


Figure 5.14: Bar graph of fault location for A-G fault on line 1 with different inception angles for 30% compensation in both the lines

Percentage error for fault location on line 1 with 50% compensations in both the lines at different inception angles with single L-G fault on phase B (b-g fault) are given in Table 5.5. And Bar graph of fault location on line 1 with 50% compensation at different inception angles for single L-G fault on phase B (b-g fault) is depicted in Figure 5.15.

Table 5.5: Percentage error of fault location for B-G fault on line 1 with 50% compensations in both the lines at different inception angles

Distance (km)	% error at inception angle - 0°	% error at inception angle - 20°	% error at inception angle - 40°
225	-3.43%	-5.23%	-7.88%
250	-6.12%	-6.78%	-10.11%
275	-8.59%	-13.08%	-15.87%
300	-9.58%	-13.73%	-16.93%
325	-9.82%	-19.53%	-19.80%
350	-10.76%	-20.57%	-22.43%

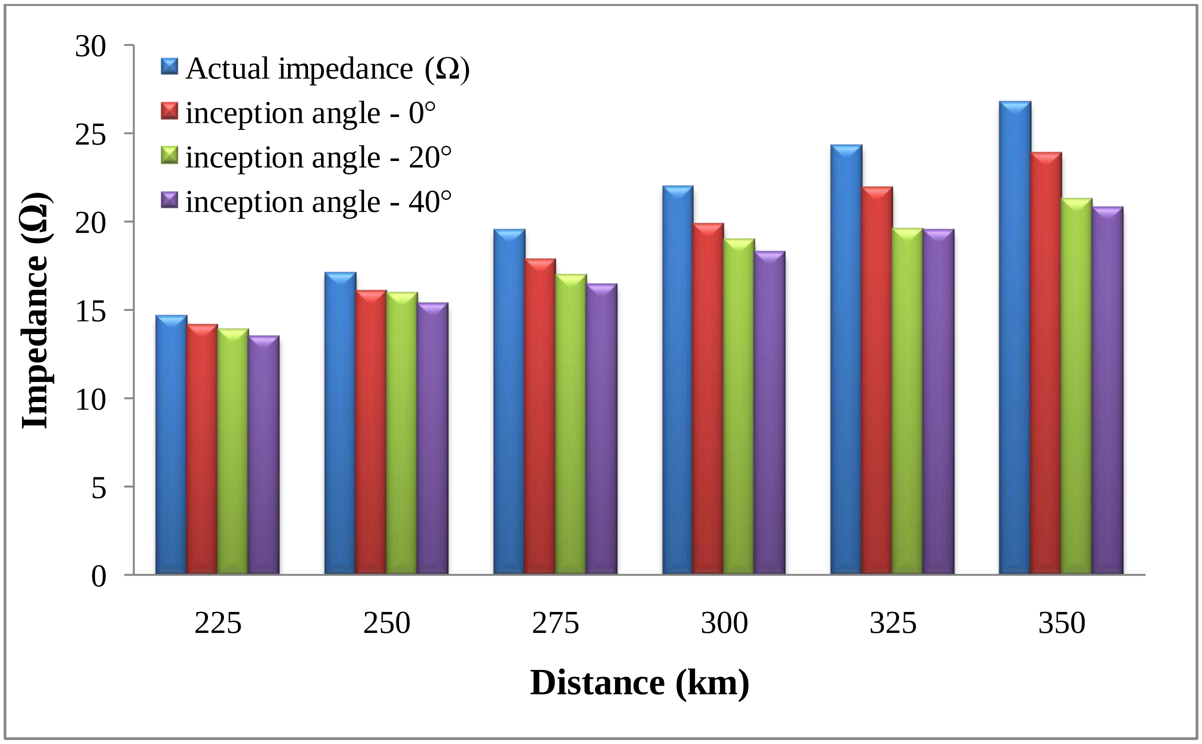


Figure 5.15: Bar graph of fault location for B-G fault on line 1 with 50% compensation in both the lines at different inception angles

Percentage error of fault location on line 1 with different compensations at inception angle 0° with single L-G fault on phase C (c-g fault) are given in Table 5.6. And Bar graph of fault location with different compensations at inception angle 0° for single L-G fault on phase C (c-g fault) is depicted in Figure 5.16.

Table 5.6: Percentage error of fault location for C-G fault on line 1 with different compensations at inception angle 0°

Distance (km)	% error at 30% compensation	% error at 50% compensation	% error at 70% compensation
25	8.59%	19.73%	20.84%
50	8.29%	16.48%	15.66%
75	7.67%	11.81%	9.83%
100	5.06%	7.56%	7.35%
125	7.11%	8.46%	8.94%
150	3.72%	4.14%	3.97%
175	-1.39%	-1.80%	-2.94%

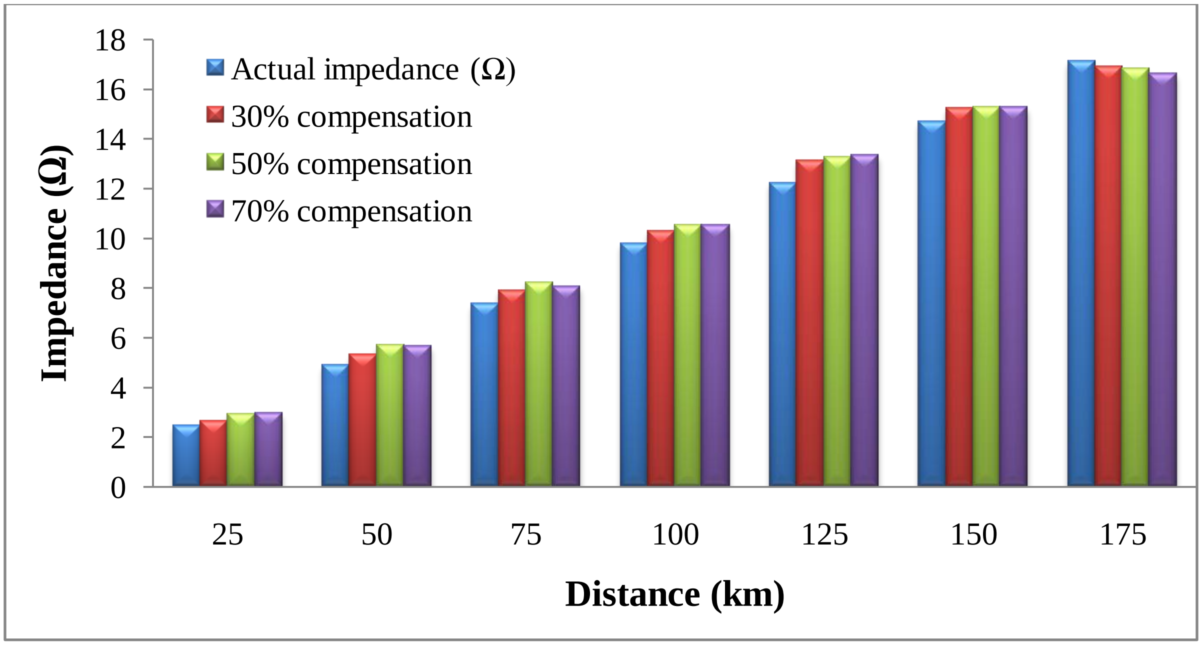


Figure 5.16: Bar graph of fault location for C-G fault on line 1 with different compensation levels at inception angle 0°

Percentage error for fault location on line 1 with different compensations in both the lines i.e. one line is 30% compensated and other line is 0% compensated at different inception angles with single L-G fault on phase C (c-g fault) are given in Table 5.7. And Bar graph of fault location on line 1 when one line is 30% compensated and other line is 0% compensated at different inception angles for single L-G fault on phase C (c-g fault) is depicted in Figure 5.17.

Table 5.7: Percentage error of fault location of line 1 for c-g fault with different inception angles and when compensation of line 1 is 30% and of line 2 is 0%

Distance (km)	% error at inception angle 0°	% error at inception angle 20°	% error at inception angle 40°
25	5.29%	9.94%	-4.74%
75	-5.85%	1.89%	-15.87%
125	-6.15%	-4.23%	-16.22%
175	-6.54%	-9.98%	-19.36%
225	2.13%	7.58%	-1.52%
275	1.63%	-3.91%	-10.31%
325	1.50%	-10.72%	-17.45%
375	1.38%	-14.74%	-21.07%

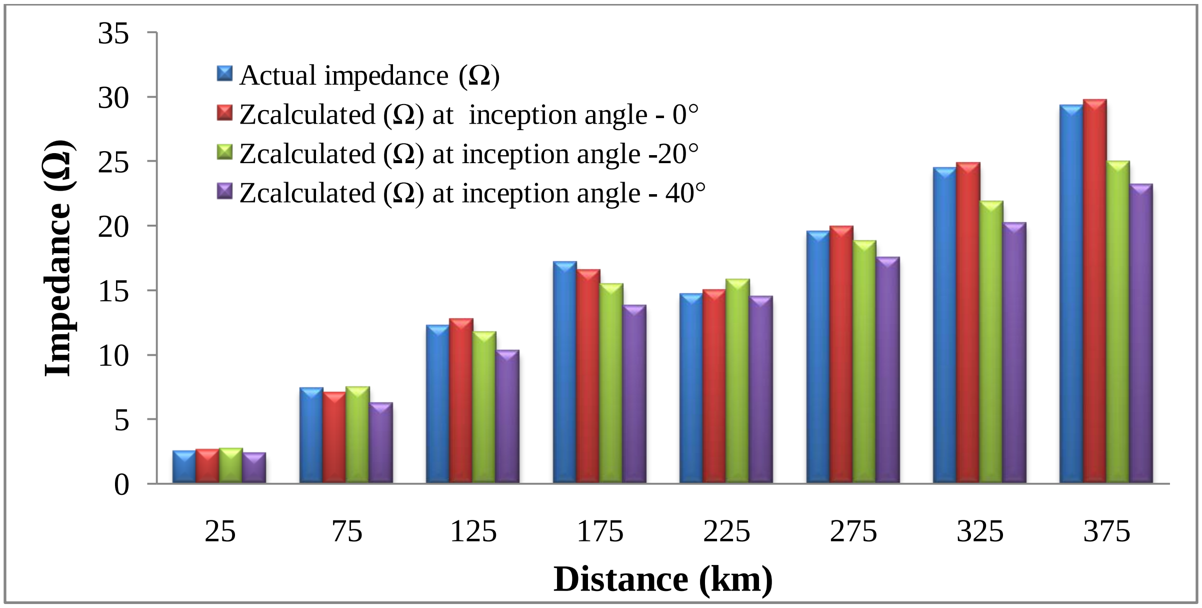


Figure 5.17: Bar graph of fault location of line 1 for c-g fault with different inception angles and when compensation of line 1 is 30% and line 2 is 0%

Percentage error for fault location on line 1 with different compensations in both the lines i.e. one line is 30% compensated and other line is 50% compensated at different inception angles with single L-G fault on phase B (b-g fault) are given in Table 5.8. And Bar graph of fault location on line 1 when one line is 30% compensated and other line is 50% compensated at different inception angles for single L-G fault on phase B (b-g fault) is depicted in Figure 5.18.

Table 5.8: Percentage error of fault location of line 1 for b-g fault with different inception angles and when compensation of line 1 is 30% and of line 2 is 50%

Distance (km)	**% error at inception angle 0°**	**% error at inception angle 20°**	**% error at inception angle 40°**
25	22.77%	24.32%	11.98%
75	13.20%	9.31%	-7.88%
125	9.24%	1.30%	-14.17%
175	-6.54%	-5.50%	-16.48%
225	6.60%	4.53%	-1.42%
275	5.28%	-3.91%	-10.48%
325	4.80%	-6.31%	-14.59%
375	2.20%	-6.82%	-21.04%

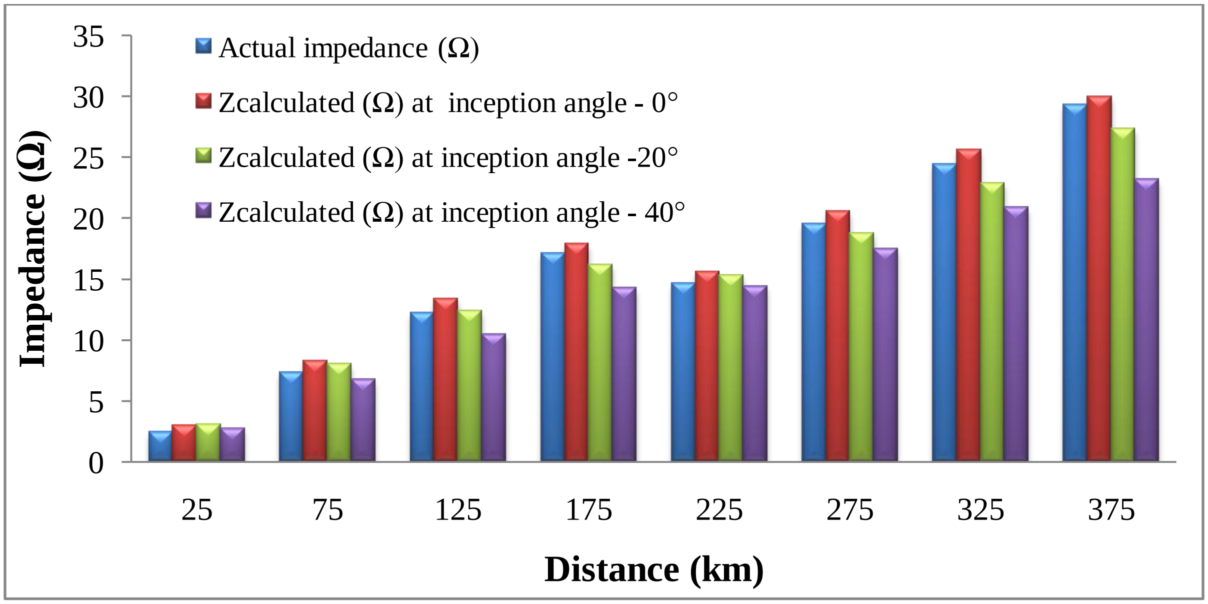


Figure 5.18: Bar graph of fault location of line 1 for b-g fault with different inception angles and when compensation of line 1 is 30% and of line 2 is 50%

Percentage error for fault location on line 1 when both the lines are 30% compensated, when one line is 30% compensated and other line is 0% compensated, when one line is 30% compensated and other line is 50% compensated and when one line is 30% compensated and other line is 70% compensated at inception angle 0° with single L-G fault on phase A (a-g fault) are given in Table 5.9. And Bar graph of fault location when both lines have same compensation and different compensation levels at inception angle 0° for single L-G fault on phase A (a-g fault) is depicted in Figure 5.19.

Table 5.9: Percentage error for fault location of line 1 when both the lines having same and different levels of compensation with inception angle 0° for A-G fault

Distance (km)	% error when both lines are 30% compensated	% error when one line is 30% compensated and other is 0% compensated	% error when one line is 30% compensated and other is 50% compensated	% error when one line is 30% compensated and other is 70% compensated
25	3.84%	-2.45%	5.78%	7.44%
75	-6.67%	-7.36%	-5.50%	-3.70%
125	-8.60%	-7.60%	-7.77%	-4.25%
175	-12.36%	-16.02%	-10.80%	-8.93%
225	2.27%	1.16%	6.09%	9.07%
275	-5.66%	-8.00%	-2.10%	2.52%
325	-9.49%	-12.24%	-4.96%	-0.02%
375	-14.19%	-19.06%	-12.33%	-7.02%

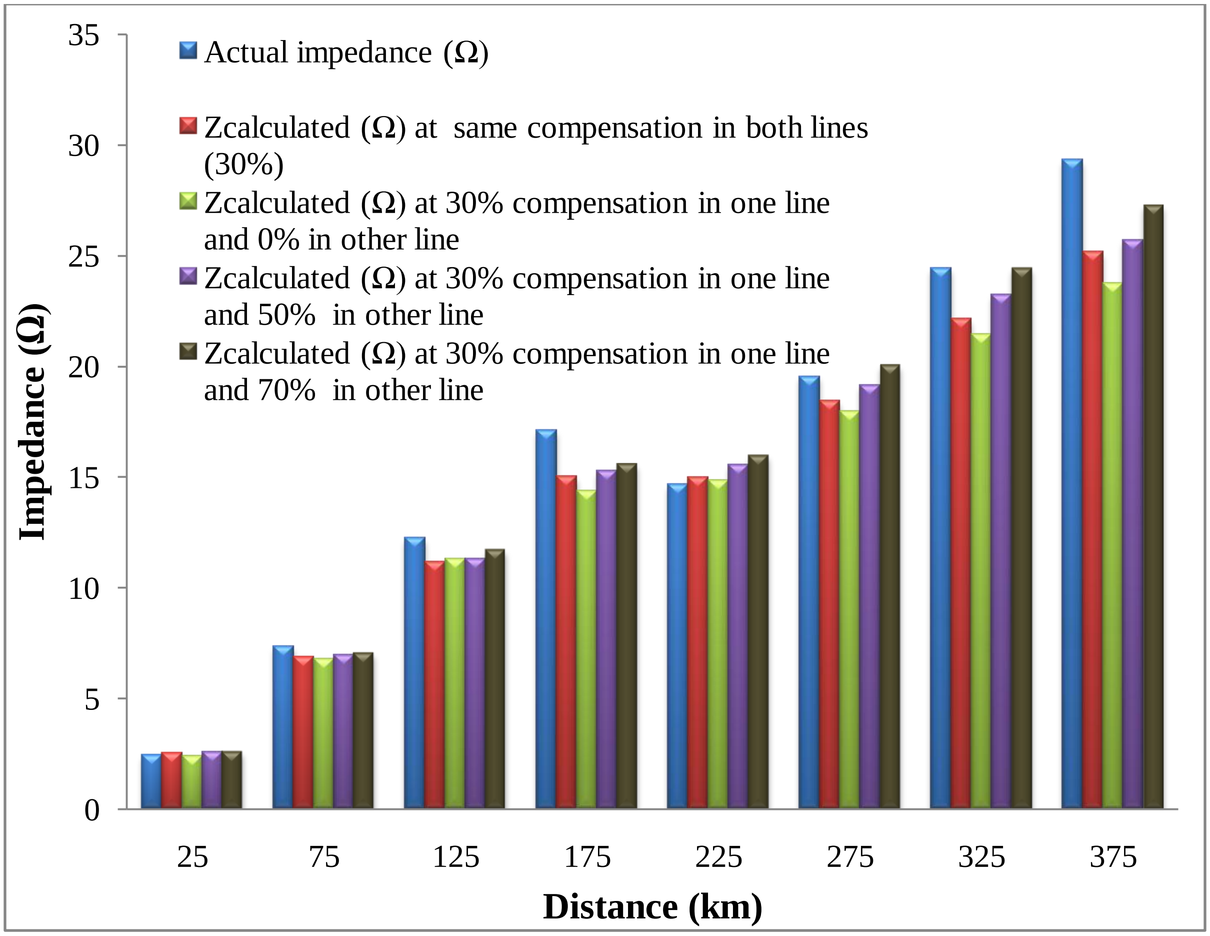


Figure 5.19: Bar graph of fault location of line 1 when both the lines having same compensation and different compensation levels with inception angle 0° for A-G fault on line 1

CHAPTER – 6 CONCLUSIONS AND FUTURE SCOPE OF WORK

6.1 Conclusions

In this work, double circuit series compensated transmission line is simulated with different types of faults in MATLAB/SIMULINK. The use of Wavelet transform in protection of double circuit series compensated line has been presented. From the results obtained, following conclusions have been drawn:

- Average values of Level 6 approximation coefficients of current signals are calculated and it is concluded that db4 is more effective than Haar wavelet for fault classification. For classification of different types of faults, only difference between three lines currents has to be calculated i.e. calculation of $dW_{ab,}$ $dW_{bc,}$ dW_{ac} and comparing them together. It is shown that magnitude of wavelet transform is convenient to set a threshold to differentiate between ground faults and line to line faults, hence valuable information is obtained from wavelet transform. An algorithm for fault classification has been proposed.
- By calculating the rms values of Level 6 approximation coefficients of voltages and currents, impedance of the faulted section of the line has been measured, to locate the fault. Actual impedance of the double circuit line has been calculated as given by equation (3.6) and actual impedance after series compensation has been calculated by considering the effect of series compensation on line as given by equation (5.13). Error is calculated for fault location as given by equation (5.14). It is concluded that error is decreased with increase in distance for fault location. Fault location is done by Haar wavelet.

6.2 Scope for Future Work

In this work, three types of faults are classified i.e. L-G fault, L-L-G faults, L-L faults on double circuit series compensated line. Further, the location of line to ground fault has been found on double circuit series compensated line in this work. Data from one end of the line is utilized in this method. Based on this dissertation, the following area of work is suggested for further exploration:

- ✓ This work can be extended for classification of three phase faults on double circuit series compensated line.
- ✓ In future, it is proposed to find the location of Line to Line faults on double circuit series compensated line.
- ✓ Data from both ends of the line can be used to classify and locate the faults on double circuit series compensated line.
- ✓ It is proposed to find the location of series faults i.e. open conductor faults on double circuit series compensated line.

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APPENDIX

Double Circuit line parameters [**18**]:

Positive sequence resistance (R1), Ω/km	0.01273 Ω/km
Zero sequence resistance (R0), Ω/km	0.3029 Ω/km
Zero sequence mutual resistance (R0m), Ω/km	0.37367 Ω/km
Positive sequence inductance (L1), H/km	0.9337e-3 H/km
Zero sequence inductance (L0), H/km	4.1264e-3 H/km
Zero sequence mutual inductance (L0m), H/km	3.1927e-3 H/km
Positive sequence capacitance (C1), F/km	12.74e-9 F/km
Zero sequence capacitance (C0), F/km	7.751e-9 F/km
Zero sequence mutual capacitance (C0m), F/km	-2.0444e-009 F/km
Length (km)	400 km

Source parameters:

Phase – to – Phase rms voltage (V_P): 13.8kV

X/R ratio: 10

Frequency (Hz): 50Hz

Internal connection: Yg

Generator type: Swing

MOV ratings:

Number of columns: 60

Rated voltage: 150 kV

Current level: 1.5 kA