HIGH SPEED DIGITAL PROTECTION
OF EHV TRANSMISSION LINES
USING TRAVELING WAVES

A Thesis

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Saskatoon, Saskatchewan

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By

Harjinder Singh Sidhu

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ABSTRACT

Extra High Voltage (EHV) transmission lines are designed to transfer large amount of power from one location to another. The length exposed to the environment is a major reason for occurrence of faults on the lines. A fault on a high voltage transmission line affects the stability of the overall power system, which sometimes leads to permanent damage of the equipment. Relays are developed and installed to protect the lines. The transmission line protection relays, in the industry, are based on the fundamental frequency components of the voltages and currents. These relays need at least one fundamental frequency cycle for performing the protection operation.

Voltage and current traveling waves are generated when a fault occurs on the transmission line. The velocity of propagation of traveling waves is finite and the level of the waves decreases with increase in the distance traveled. Information about the fault can be obtained by analyzing the traveling waves. A few traveling wave techniques, which are based on analog signal processing, to protect transmission lines have been proposed in the past.

Two digital techniques, which use traveling waves for protecting EHV transmission lines, are proposed in this thesis. The traveling waves are extracted from the modal voltages and currents at the terminals of the transmission line. The techniques identify and locate the fault by using the information contained in the waves. A power system was modeled in the Electromagnetic Transient Direct Current Analysis (EMTDC) and several cases were created by varying different parameters related to the fault, fault type, fault location, fault resistance and fault inception angle. The techniques were implemented in hardware and their performance was tested on data, generated from the EMTDC simulations. Some cases are discussed in the thesis.

The performance of the digital techniques for protecting EHV transmission lines using traveling waves was confirmed to be satisfactory. The proposed techniques provide protection at speed and discriminate well between internal and external faults.

ACKNOWLEDGEMENTS

Dedicated

to

my grandfather

S. Sampuran Singh Sidhu

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LIST OF ACRONYMS

EHV	Extra High Voltage
EMTDC	Electromagnetic Transient Direct Current Analysis
PSCAD	Power Systems Computer Aided Design
GPS	Global Positioning System
DSP	Digital Signal Processor
A/D	Analog to Digital Converter
CPU	Central Processing Unit
ALU	Arithmetic and Logic Unit
ROM	Read-Only Memory
RAM	Random Access Memory
DRAM	Dynamic Random Access Memory
SRAM	Static Random Access Memory
SDRAM	Synchronous Dynamic Random Access Memory
SBSRAM	Synchronous Burst Static Random Access Memory
FPGA	Field Programmable Gate Array
SDB	Sundance Digital Bus
EMIF	External Memory Interface
DMA	Direct Memory Access
HPI	Host Port Interface

Chapter 1

Introduction

1.1 Background

An electric power system comprises of generation, transmission and distribution of electric energy. Growth in power systems has lead to very complex networks extended across large areas. A power system, most of the time, operates in a steady state but disturbances, temporary and permanent, occur occasionally by the presence of large number of components which are susceptible to failures caused due to natural calamities, human errors and aging. Faults cause large amounts of currents to flow in the components that would burn out if current flows are not promptly interrupted. The voltages of the faulted phases decrease on the occurrence of a fault. The waveforms of currents in three phases in steady state, during a fault and after a fault on phase-a are shown in Figure 1.1.

Faults, if not detected and eliminated quickly, may cause severe reduction in system voltage, loss of synchronism, loss of revenue and may damage the equipment permanently. Faults can be minimized by proper power system planning and using sophisticated equipment but the occurrence of faults cannot be eliminated fully. It is, therefore, necessary to protect power systems from faults.

1.2 Power System Protection

Modern power systems involve large amount of investment. Proper operation and protection of power systems is necessary to minimize the consequences of faults. Devices, called protective relays, are installed at various places in the power system to detect faults and isolate the faulted part from the remaining system. Depending on the application, relays receive voltages and/or currents as inputs from a power system via voltage and current transformers.
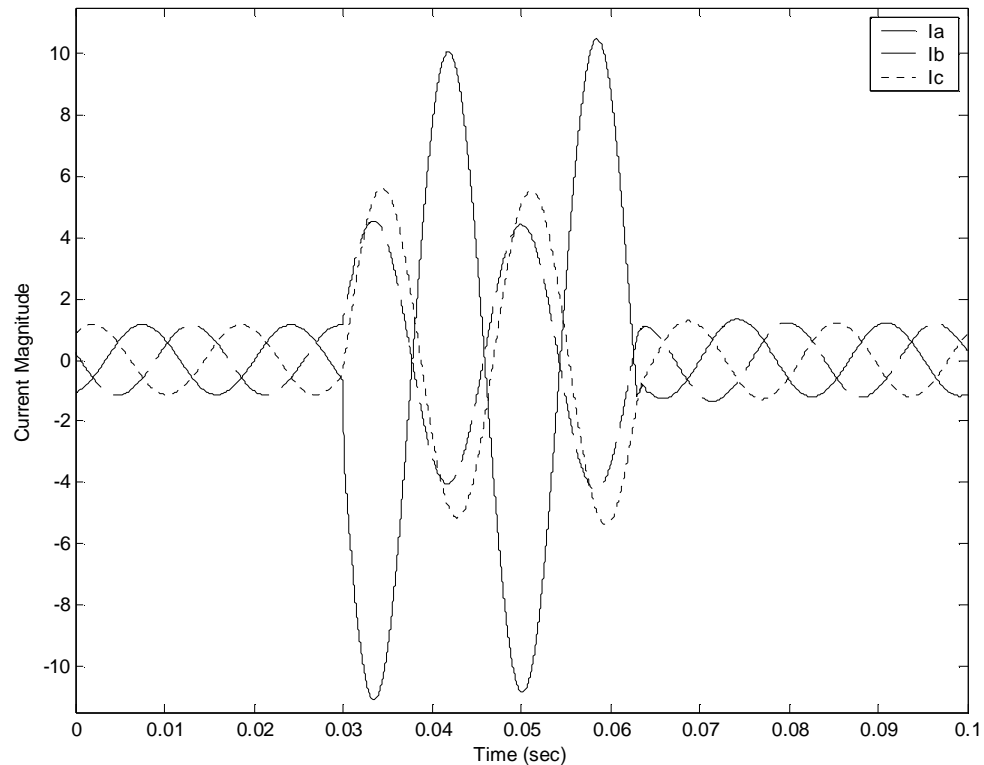
Figure 1.1: Three phase current waveforms in steady state, during a fault and after a fault on phase-a

Relays continuously monitor the power system and operate when the inputs deviate from their normal levels. Each relay, used for power system protection, performs a pre-defined function and responds to change in pre-specified parameters. The changes to which the relays respond are

- increased current in one or more phases,
- direction of the current flow,
- under voltage,
- reduction in apparent impedance,
- under frequency,
- specified direction of power flow, and
- increase in the temperature of equipment.

According to their functionality, relays are classified as

- current relays (directional and non-directional),
- voltage relays,

- distance relays,
- power relays,
- differential relays, and
- frequency relays.

Relays are installed in various configurations to protect the major components of a power system without leaving any part of the system unprotected. This is achieved by dividing the power system into segments called protective zones. A protection zone normally includes a generator, a transformer, a bus, a transmission line, a distribution line or a motor. Protection zones are overlapped so that every part of system is protected. Figure 1.2 shows an example of the protection zones [1] of a sample system.

In the event of a fault in a zone, relays associated with that zone open the circuit breakers to isolate that zone from the rest of the system. To cover the risk of failure of relays, backup protection is provided in the adjacent zones. Backup relays isolate the faulted zone and an adjoining zone, in which backup relay is located, in case primary relays fail to isolate the faulted zone.

1.3 Protection Relays

In the previous century, protective relays have gone through major transitions with the change in technology. Electromechanical relays, the oldest in the family of protective relays, served the power system quite reliably. With the development in electronics, solid-state relays were developed. Small size, light weight and quiet operation are the advantages of solid-state relays over the electromechanical relays. Microprocessors technology made the relays even more compact, multifunctional and flexible.

1.3.1 Electromechanical Relays

Electromechanical relays consist of parts that move due to force produced by currents flowing in the electromagnets. Usually, an electromagnetic relay protects one phase and is dedicated to single protection function. Presence of mechanical parts makes the device big and heavy. Environmental condition is an important aspect to decide monitoring and maintenance needs of the relay. Dusty environment increases wear and
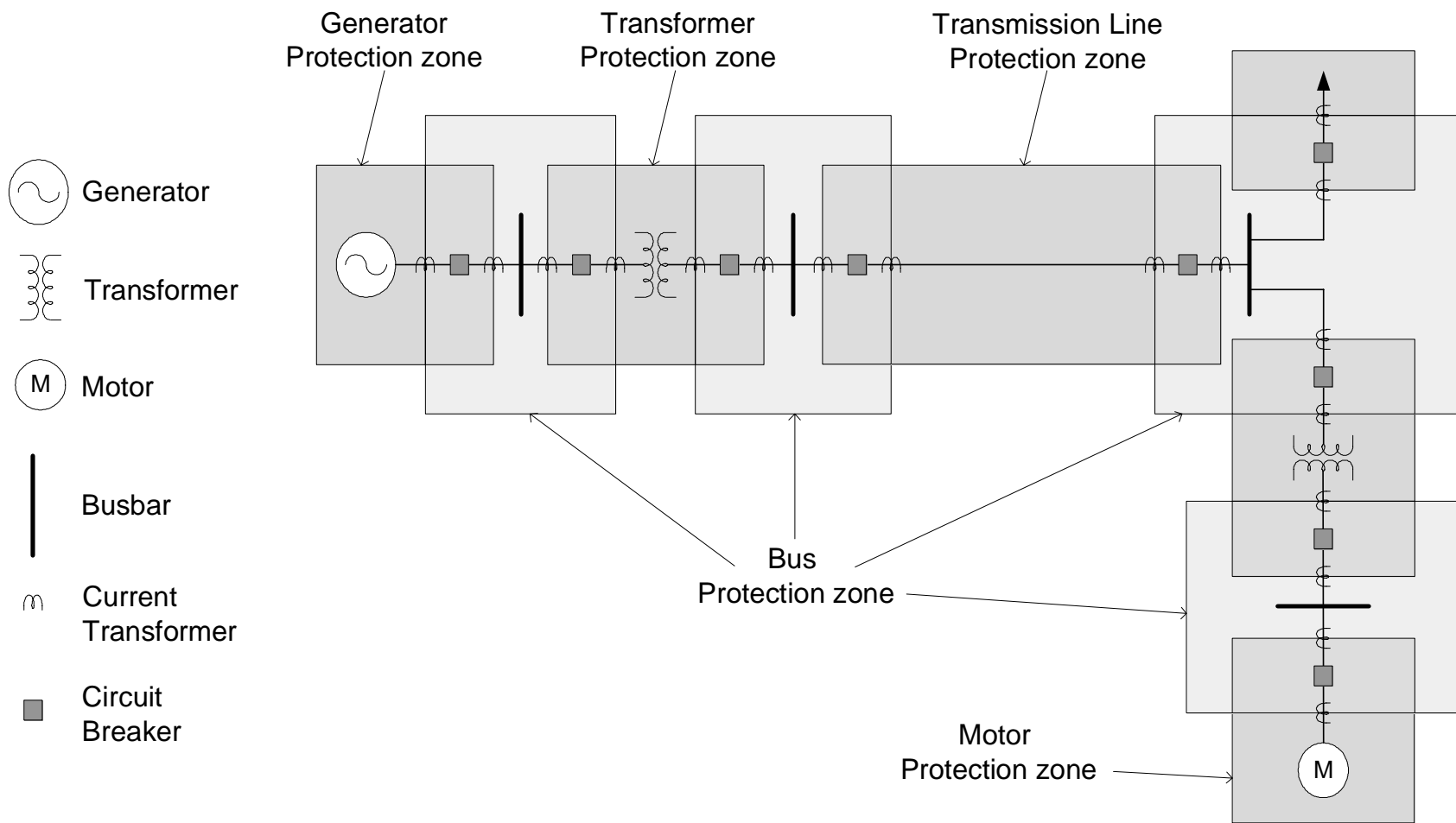
Figure 1.2: Protection zones in a sample power system

tear of the moving parts; therefore, maintenance is required at short intervals.

Electromagnetic relays are not seriously affected by voltage transients. These relays have clean on and off states due to substantial distance between the contacts. Experience has shown that well maintained electromagnetic relays give reliable performance but, the probability of failure increases rapidly as these relays approach the end of their useful life.

1.3.2 Solid-State Relays

Solid-state relays are semiconductor devices composed of electronic components like resistors, diodes, transistors etc. These relays do not have moving parts which make them lighter and smaller than electromagnetic relays. Solid-state relays perform the same functions as electromagnetic relays except that they need less voltage to operate and switching can be performed in very short times. However, these relays are affected by transients, which, if present in the inputs, may cause them to malfunction. Solid-state relays are reliable but electronic components may drift due to high ambient temperature and aging.

Solid-state relays energize trip circuits using electronic devices such as silicon controller rectifiers and, therefore, there is no arcing during switching. Switches in solid-state relays always have leakage currents irrespective of the fact whether the switches are open or closed.

1.3.3 Digital Relays

Power system protection has changed a lot since the evolution of microprocessors. Very large scale integration has made it possible to put together numerous components in a single chip. Digital technology has made its place in the field of power system protection. Today, digital techniques are implemented to protect almost all components of power systems. Basically digital techniques use the same logic that is used in electromechanical and solid-state relays. Digital relays have many advantages over electromechanical relays.

1. Economical: The major reason for the acceptance of digital relays is that they present many features at reasonable price.

2. Fast operation: There are two reasons for fast operation of digital relays. One, digital relays barely use any mechanical parts. Two, the use of high speed processors have made these relays very fast.

3. Self monitoring: Digital relays monitor themselves continuously. On the other hand, electromechanical relays must be tested by personnel at regular intervals. Self monitoring feature saves time as well as money.

4. Multiple functions: Relays, meters, control switches, indicators, and communication devices can be integrated into a single microprocessor-based protective relay. Substation/system schematics and wiring diagrams are easy to generate due to the reduced number of devices and related wiring.

5. Reduced commissioning time: Commissioning is a process of verifying the performance of an equipment before it is put into operation. Microprocessor-based relays have metering features and remote capabilities, which makes commissioning, simple and less time consuming.

6. Less outage time: Fast operation and fault location capability of microprocessor-based relays for transmission line protection reduce the power outage time considerably. When relays, without a fault location capability, detect a fault, crew spends a lot of time in finding the location of the fault by patroling the line.

7. Flexibility: Digital relays can be designed and built using general purpose hardware. A relay can be used to protect different power system components by loading different software programs.

8. Small size: Digital relays are lighter in weight and need less space than the electromechanical and solid-state relays. For this reason, digital relays are easy to transport.

9. Easy replacement: Due to economical advantage, digital relays, if fail, can be replaced in full. This saves time and labor needed for repairs.

1.4 Transmission Line Protection

A power transmission line can be protected by fuses, overcurrent relays, distance relays, pilot protection schemes or by a combination of these relays.

Fuses and overcurrent relays are generally used for the protection of distribution lines because these devices are simple and inexpensive. Another reason is that fault currents are generally greater than load currents in distribution circuits; selectivity is achieved by time grading.

Overcurrent relays are also applicable, where a large impedance component such as a transformer, is involved. Currents due to a fault on the load end of a transformer are considerably less than the currents due to a fault on the source end. Therefore it is possible to current grade the relays.

With the passage of time and increase in demand of electric energy, power systems have grown to large areas. The EHV transmission lines connect the generating sources and load points located at long distance. Due to the long lengths of EHV transmission lines and networking of the transmission systems, overcurrent relays cannot be used to protect EHV lines.

Distance relays are the most often used to protect transmission lines. Distance relays take voltages and currents as inputs from the power system and calculate impedance. If the calculated impedance lies in a pre-defined operating region on the impedance plane, distance relays operate to isolate the faulted part.

A pilot protection scheme is a unit type of protection, which compares the direction of power flow, or phase relation of currents, at both ends of the line. Information exchange between relays provided at the two ends of a transmission line is done by a wire, a carrier, or a microwave pilot channel. These schemes provide protection for 100 percent of the line. The cost of the wire pilot schemes increases with the increase in length of the transmission line, because of the increased length of the pilot wire length.

Digital relays, used in the transmission line protection, are based on the same protection logic as is used in analog relays but, the physical structure and operation of the digital relays are different. Most digital relays, presently in practice, use the fundamental frequency components of the voltages and currents to protect the transmission line.
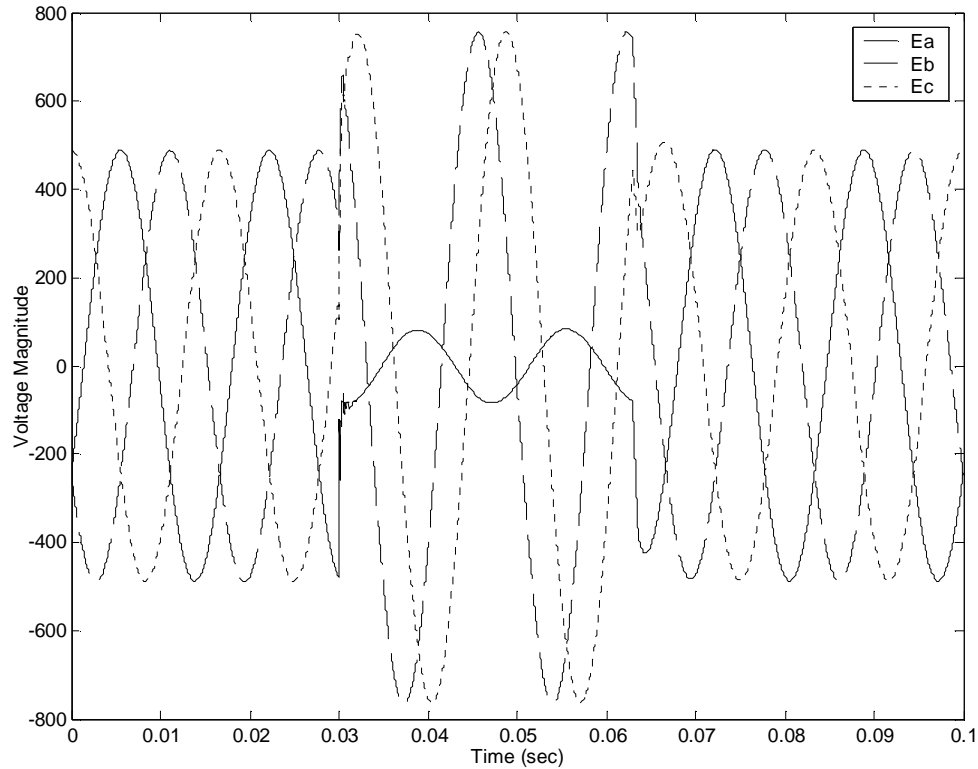
Figure 1.3: Three phase voltage waveforms in steady state, during a fault and after a fault on phase-a

Voltages and currents on a transmission line contain high frequency components at the occurrence of a fault. These components, generated by faults in the voltages are shown in Figure 1.3. The same phenomenon is observed in currents also. The high frequency components contain traveling waves, which originate at the fault and travel away from it. The information contained in the waves can be extracted and used to detect and locate faults. In this thesis, the digital techniques, which use traveling waves to protect transmission lines, are proposed.

1.5 Objective of the Thesis

Following are the major objectives of the work reported in this thesis.

1. To develop a digital technique for detecting the occurrence of a fault on a transmission line and extract traveling waves from the voltages and currents.

2. To determine the distance of a fault on the protected line from the information contained in the traveling waves.

3. To implement the fault detection and location logic in a Texas Instruments Digital Signal Processor (DSP), TMS320C6201 [2]. And to check the performance of the techniques on data generated from the Electromagnetic Transient program (EMTDC) simulations.

1.6 Outline of the Thesis

This thesis is organized in five chapters and five appendices. The first chapter provides a brief review of areas relevant to the project and outlines the material presented in the thesis. Numerical relays are also introduced in this chapter.

The second chapter introduces the subject of traveling waves. This chapter also describes the properties and behavior of traveling waves.

The third chapter presents a technique which can be used to detect the arrival of traveling waves from a fault. Optimal number of samples required to detect traveling waves is also determined. This chapter also presents the techniques for calculating the distance of a fault from the relaying point.

The fourth chapter introduces the hardware and software used in the project. The hardware includes the Texas Instruments DSP TMS320C6201 and the software includes the real time operating system, Diamond, developed by 3L Limited. This chapter also describes the programming logic of the technique implemented in the selected DSP for detecting and locating faults on a transmission line.

The fifth chapter presents the test system, simulated in the electromagnetic transient simulation application, EMTDC [3], to generate data for testing the performance of the proposed techniques. Cases were run, in EMTDC, by varying different parameters like transmission line length, fault type, fault resistance and fault inception angle. Results of some cases, obtained by processing the data in the designed relay, are also discussed.

The summary of the thesis and the conclusions drawn from the work reported in the thesis are provided in Chapter six.

The Appendix A discusses the modal analysis. The test power system and its parameters are described in Appendix B. The code for the proposed protection techniques, written in linear assembly language and C language, is given in Appendix C

and Appendix D respectively. EMTDC, which was used to simulate the test power system, is discussed in Appendix E.

Chapter 2

Traveling Waves

2.1 Introduction

All conductors of a transmission line have resistances and inductances distributed uniformly along the length of the line. It is, however, assumed in most applications that the resistance and inductance of a conductor is lumped and is, therefore, replaced by a single value. This is also true for the conductance and capacitance of a conductor.

Transmission lines can not be analyzed with lumped parameters, when the length of the line is considerably small compared to the wavelength of the signal applied to the line. Power lines, which operate at 60Hz and are more than 50 km long, are considered to have distributed parameters. These lines have the following properties.

1. Voltages and currents travel on the line.
2. The velocity of propagation of these waves is finite.

One meter sections of a power transmission line can be represented by the circuits shown in Figure 2.1.
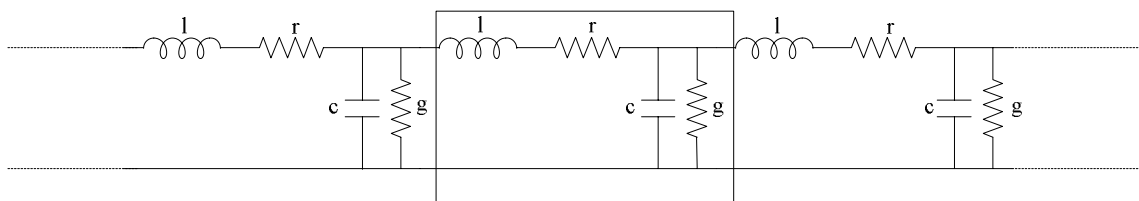
Figure 2.1: Transmission line equivalent circuit

2.2 Transmission Line Equations

Consider a small section of length, Δx of a transmission line, as shown in Figure 2.2. Assume that resistance, inductance, capacitance and conductance remain constant along the length of the transmission line and do not change with time.

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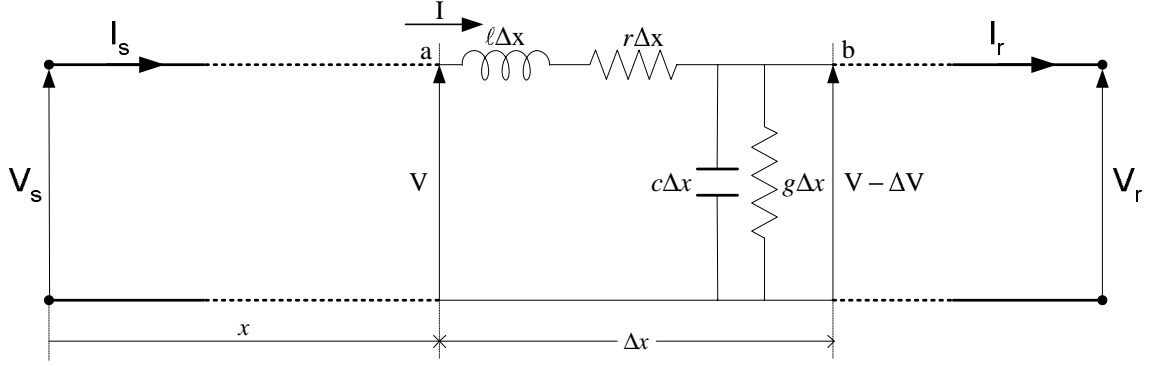
Figure 2.2: Small section of a transmission line

Due to distributed resistance and inductance, voltage at every point along the length of the line is different. The transmission line equations [4, 5] can be derived as follows.

Voltage drop per unit length of the line from location 'a' to location 'b' is

$$\frac{V - (V - \Delta V)}{\Delta x} = \frac{I(r\Delta x + j\omega \ell \Delta x)}{\Delta x}$$

where, r is resistance per unit length of the line, and

ℓ is inductance per unit length of the line.

Rearranging this equation provides,

$$\frac{\Delta V}{\Delta x} = (r + j\omega \ell)I$$

$$= zI \tag{2.1}$$

where, z is impedance per unit length of the line.

Similarly, $\dfrac{\Delta I}{\Delta x} = (g + j\omega c)V$

$$= yV \tag{2.2}$$

where, g is conductance per unit length of the line,

c is capacitance per unit length of the line, and

y is admittance per unit length of the line.

As Δx approaches zero, $\dfrac{\Delta V}{\Delta x}$ approaches $\dfrac{dV}{dx}$ and $\dfrac{\Delta I}{\Delta x}$ approaches $\dfrac{dI}{dx}$.

Now,

$$\frac{dV}{dx} = zI \text{, and} \qquad\qquad (2.3)$$

$$\frac{dI}{dx} = yV \qquad\qquad (2.4)$$

Differentiating Equation 2.3 with respect to x provides,

$$\frac{d^2V}{dx^2} = z\frac{dI}{dx} \qquad\qquad (2.5)$$

Substituting Equation 2.4 in Equation 2.5 provides,

$$\frac{d^2V}{dx^2} = zyV$$

$$= \gamma^2 V \qquad\qquad (2.6)$$

In this equation, γ is a complex quantity that is known as the *propagation constant* and is given by

$$\gamma = \sqrt{zy}$$

The propagation constant, γ, can also be expressed as

$$\gamma = \alpha + j\beta$$

where, α is the *attenuation constant*, and

β is the *phase constant.*

Similarly, differentiating Equation 2.4 with respect to x provides,

$$\frac{d^2I}{dx^2} = y\frac{dV}{dx} \qquad\qquad (2.7)$$

Substituting Equation 2.3 in Equation 2.7 provides,

$$\frac{d^2I}{dx^2} = zyI$$

$$= \gamma^2 I \qquad\qquad (2.8)$$

The solution of the differential Equation 2.6 can be written as

$$V = Ae^{\gamma x} + Be^{-\gamma x} \qquad\qquad (2.9)$$

A and B are constants that are usually complex quantities. At the sending end, $x = 0$, and therefore, the sending end voltage is

$$V_s = A + B \tag{2.10}$$

Equation 2.3 can be written as

$$I = \frac{1}{z}\frac{dV}{dx} \tag{2.11}$$

Differentiating Equation 2.9 with respect to x provides,

$$\frac{dV}{dx} = \gamma A e^{\gamma x} - \gamma B e^{-\gamma x} \tag{2.12}$$

Substituting the value of $\dfrac{dV}{dx}$ in Equation 2.11 provides,

$$I = \frac{1}{z}\gamma[A e^{\gamma x} - B e^{-\gamma x}]$$

Also,

$$I = \frac{1}{Z_o}[A e^{\gamma x} - B e^{-\gamma x}] \tag{2.13}$$

Z_o, called the *Characteristic impedance* of the line and is given by

$$Z_o = \sqrt{\frac{z}{y}} \tag{2.14}$$

At the sending end, $x = 0$, therefore, Equation 2.13 provides,

$$I_s = \frac{1}{Z_o}[A - B] \tag{2.15}$$

The constants, A and B, determined from Equations 2.10 and 2.15, are

$$A = \frac{1}{2}[V_s + Z_o I_s] \tag{2.16}$$

$$B = \frac{1}{2}[V_s - Z_o I_s] \tag{2.17}$$

Substituting A and B in Equation 2.9 provides,

$$V = \frac{1}{2}[(V_s + Z_o I_s)e^{\gamma x} + (V_s - Z_o I_s)e^{-\gamma x}]$$

$$= [V_s \frac{(e^{\gamma x} + e^{-\gamma x})}{2} + Z_o I_s \frac{(e^{\gamma x} - e^{-\gamma x})}{2}]$$

$$= [V_s \cosh(\gamma x) + Z_o I_s \sinh(\gamma x)] \tag{2.18}$$

Similarly,

$$I = \frac{1}{2Z_o}[(V_s + Z_o I_s)e^{\gamma x} - (V_s - Z_o I_s)e^{-\gamma x}]$$

$$= \frac{1}{Z_o}[V_s \sinh(\gamma x) + Z_o I_s \cosh(\gamma x)] \qquad (2.19)$$

These equations provide the voltage and current at a location on the transmission line that is x meters away from the sending end.

2.3 Interpretation

Equation 2.9 indicates that there are two components of the voltage at any location on the transmission line. Both components represent traveling waves; $Be^{-\gamma x}$ represents the wave travelling in the forward direction and $Ae^{\gamma x}$ represents the wave travelling in the backward direction. The voltage and current can also be expressed as

$$V = V^+ + V^- \qquad (2.20)$$

$$I = I^+ + I^- \qquad (2.21)$$

where, V^+ and I^+ are the voltage and current waves traveling in the forward direction, and V^- and I^- are the voltage and current waves traveling in the backward direction. The voltage wave traveling in the forward direction can be expressed as

$$V^+ = Z_o I^+ \qquad (2.22)$$

Similarly, the voltage wave traveling in the backward direction can be expressed as

$$V^- = -Z_o I^- \qquad (2.23)$$

A typical positive traveling wave, as shown in Figure 2.3, has the following properties [6].

- Crest: This is the maximum amplitude attained by the wave.
- Front: This is the part of wave before crest, when the wave is rising to attain the maximum value.
- Tail: This is part of the wave beyond crest. In this portion, the wave gradually decreases in amplitude.
- Polarity: Polarity of a traveling wave, positive or negative, is the polarity of crest of the wave.

- The rate of rise of the wave is higher than the rate at which the wave dies.
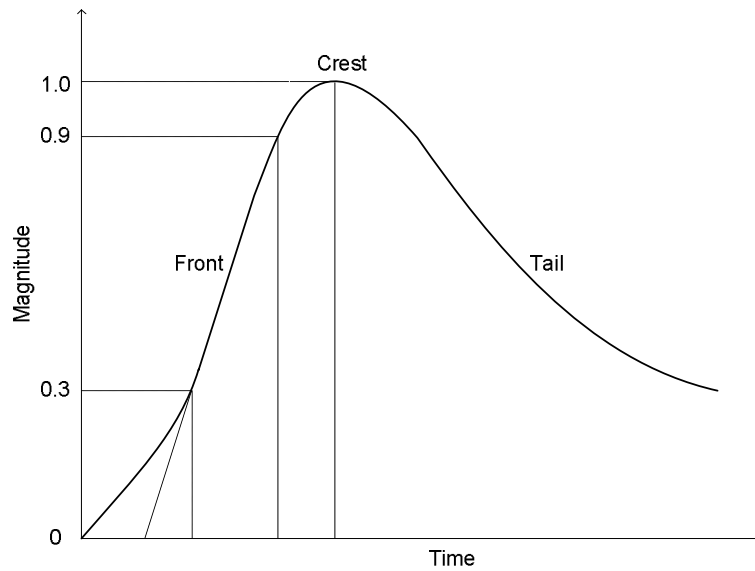
Figure 2.3: A positive traveling wave

2.4 Propagation Constant

The amplitude and phase variation of traveling waves along the transmission line is controlled by γ, the propagation constant of the line.

$$\gamma = \alpha + j\beta \tag{2.24}$$

Attenuation of traveling waves depends on α, the attenuation constant and phase variation depends on β, the phase constant. The velocity of propagation of traveling waves on overhead lines is close to the velocity of light, 3×10^8 m/s.

2.5 Reflection and Refraction of Traveling Waves

Traveling waves travel along the transmission line and encounter discontinuities, such as buses and transformers. When traveling waves reach a discontinuity, part of it is reflected back and the remaining part passes through. The magnitude of the reflected and refracted waves depends on the characteristic impedance of the transmission line and the impedance beyond the discontinuity. The amplitude of the reflected and refracted waves is such that the proportionality of the voltage and current is preserved. The phenomenon of the reflection and refraction of traveling waves is shown in the Bewley's Lattice diagram [6], which is reproduced in Figure 2.4. This diagram shows the propagation of

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traveling waves that originates at a fault location that is 80 km from bus A, on a transmission line of 100 km length.
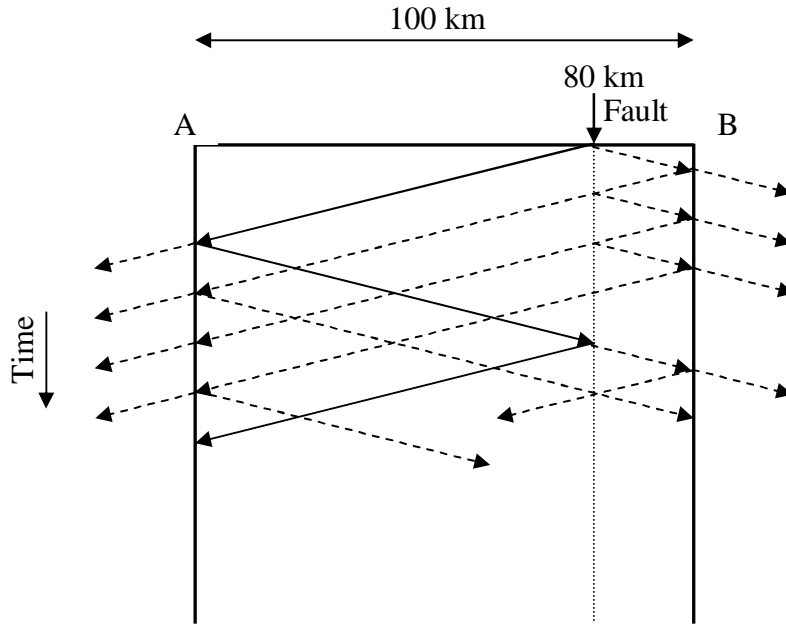
Figure 2.4: Bewley's Lattice diagram

At each discontinuity, the total energy of the incident wave is distributed among the reflected and refracted waves. This process lasts until the traveling waves loose all their energy and their amplitudes become negligible. Consider a transmission line with characteristic impedance, Z_o. From Equations 2.22 and 2.23,

$$Z_o = \frac{V^+}{I^+} \text{ and } \tag{2.25}$$

$$-Z_o = \frac{V^-}{I^-} \tag{2.26}$$

If the refracted voltage and current waves are V^t and I^t, the impedance of load, Z_t, at the termination of the line, is given by

$$Z_t = \frac{V^t}{I^t} \tag{2.27}$$

Because the voltage and current waves exist at the same time at a junction,

$$V^t = V^+ + V^-, \text{ and} \tag{2.28}$$

$$I^t = I^+ + I^- \tag{2.29}$$

Substituting Equations 2.28 and 2.29 in Equation 2.27 provides,

$$Z_t = \frac{V^+ + V^-}{I^+ + I^-} \qquad (2.30)$$

Substituting for I^+ and I^- from Equations 2.22 and 2.23 in this equation gives

$$\frac{Z_t}{Z_o} = \frac{V^+ + V^-}{V^+ - V^-}$$

Rearranging this equation provides,

$$\frac{V^-}{V^+} = \frac{Z_t - Z_o}{Z_t + Z_o} \qquad (2.31)$$

This ratio, called the voltage reflection factor, ρ_v, is given by

$$\rho_v = \frac{Z_t - Z_o}{Z_t + Z_o} \qquad (2.32)$$

Similarly, the current reflection factor, ρ_i, is given by

$$\rho_i = \frac{Z_o - Z_t}{Z_o + Z_t} \qquad (2.33)$$

2.6 Line Termination

A transmission line may be terminated in a short circuit, in an open circuit or with an impedance. These cases are discussed in the following sections.

2.6.1 Line Terminated in a Short Circuit

When a transmission line is terminated in a short circuit, the voltage at the termination is zero. Equation 2.28 now becomes

$$V^+ + V^- = 0$$

Rearranging the equation provides,

$$V^- = -V^+ \qquad (2.34)$$

Substituting for V^+ and V^- from Equations 2.22 and 2.23 in this equation, and rearranging provides,

$$I^+ = I^- \qquad (2.35)$$

Substituting Equations 2.34 and 2.35 in Equation 2.30 provides,

$$Z_t = 0 \qquad (2.36)$$

Substituting Z_t in Equations 2.32 and 2.33 provides,

$$\rho_v = -1, \text{ and} \tag{2.37}$$

$$\rho_i = +1 \tag{2.38}$$

Therefore, for a line terminated in a short circuit, the voltage of the backward (or reflected) wave is equal and opposite to the voltage of the forward (or incident) wave. Similarly, the current of the backward (or reflected) wave is equal and in phase with the current of the forward (or incident) wave.

2.6.2 Line Open Circuited at Receiving End

When a transmission line is open circuited at receiving end, the current flow out of the transmission line is zero.

Equation 2.29, in this case, becomes

$$I^+ + I^- = 0$$

Rearranging this equation provides,

$$I^+ = -I^- \tag{2.39}$$

Substituting for I^+ and I^- from Equations 2.22 and 2.23, and rearranging provides,

$$V^- = V^+ \tag{2.40}$$

Substituting Equations 2.39 and 2.40 in Equation 2.30 provides,

$$Z_t = \infty \tag{2.41}$$

Substituting Z_t in Equations 2.32 and 2.33 provides,

$$\rho_v = +1, \text{ and} \tag{2.42}$$

$$\rho_i = -1 \tag{2.43}$$

Therefore, for a line terminated by an open circuit, the current of the backward (or reflected) wave is equal and opposite to the current of the forward (or incident) wave. Similarly, the voltage of the backward (or reflected) wave is equal and in phase with the voltage of the forward (or incident) wave.

2.7 Traveling Wave Relays

Several traveling wave relays have been proposed in the past, but all of them use analog technology. Due to the limitations in detecting high frequency waves, these techniques have not been used in commercial devices.

The basic concept of previously proposed techniques is presented in this section. A fault on a transmission line can be replaced by a fictitious source [7] as shown in Figure 2.7. Let the voltage and current injected at the fault be v_f and i_f. These injected signals can be calculated by subtracting the pre-fault voltage and current from the post-fault voltage and current. Fault injected components; therefore, can be expressed in terms of the forward and backward traveling waves as [8, 9]

$$v_f(x,t) = f^+\left(t - \frac{x}{v}\right) + f^-\left(t + \frac{x}{v}\right) \tag{2.44}$$

$$i_f(x,t) = \frac{1}{Z_o}\left[f^+\left(t - \frac{x}{v}\right) - f^-\left(t + \frac{x}{v}\right)\right] \tag{2.45}$$

where, f^+ is a function representing the forward traveling wave,

f^- is a function representing the backward traveling wave,

v is velocity of propagation of traveling waves,

Z_o is surge impedance of the transmission line, and

x is the distance traveled by the traveling waves.

Rearranging Equations 2.44 and 2.45 provides,

$$2f^+\left(t - \frac{x}{v}\right) = v_f(x,t) + Z_o i_f(x,t) \tag{2.46}$$

$$2f^-\left(t + \frac{x}{v}\right) = v_f(x,t) - Z_o i_f(x,t) \tag{2.47}$$

Two traveling wave relays, proposed in the past, are described in the following sections.

2.7.1 Chamia and Liberman Technique

M. Chamia and S. Liberman proposed a traveling waves technique [7] for protecting transmission lines; the technique used directional comparison. To understand the technique, consider a two terminal power system [7], shown in Figure 2.5.

Figure 2.5: Voltage and current at fault inception

A transmission line connects the bus A to bus B and a fault is experienced at location F on the line. Post-fault voltage, v and current, i can be split into four components. Two components are the pre-fault voltage and current and the other two components are the changes in the voltage and current due to the fault. Figure 2.5 shows the voltage and current at the inception of the fault; Figure 2.6 shows the pre-fault voltage and current and Figure 2.7 shows the component of voltage and current injected by the fictitious source at the fault [7].

Figure 2.6: Voltage and current before fault

Figure 2.7: Voltage and current components injected by the fictitious source at the fault

If the pre-fault voltage and current are v' and i', and the fault injected voltage and current are v_f and i_f, then

$$v_f = v - v', \text{ and} \tag{2.48}$$

$$i_f = i - i' \tag{2.49}$$

v_f and i_f are directly related to the fault, therefore, they can be used to obtain information about the fault. The direction of motion of traveling waves can be determined by comparing polarities of the pre-fault voltage and current with the

polarities of the fault injected voltage and current. The internal and external faults can be distinguished by comparing polarities of the fault injected voltage and current.

2.7.2 Crossley and McLaren Technique

Crossley and McLaren proposed a traveling waves technique [10] to determine the location of a fault on the transmission line. The technique records samples of the incident traveling wave at the inception of a fault. The wave that returns after reflection from the fault is recognized by correlating the reflected signal with the recorded incident signal. The correlation is used to determine the degree of similarity between the signals. If ϕ_{ir} is the discrete correlation function [10] establishing a correlation between incident signal, i and reflected signal, r,

$$\phi_{ir}(\tau) = \frac{1}{N}\sum_{k=1}^{N} i(k\Delta t + \tau) \ . \ r(k\Delta t) \tag{2.50}$$

where, i is the incident signal,

r is the incident signal, and

τ is the time delay introduced in the reflected signal.

The time at the arrival of incident and reflected traveling waves is recorded. If T is the difference in time at the arrival of incident wave and time of arrival of reflected waves, then, twice the distance of fault from the relay is equal to T times velocity of propagation of traveling waves.

$$D = \frac{T \times v}{2} \tag{2.51}$$

2.8 Traveling Wave Relay Issues

The implementation of the techniques, developed by Chamia and Liberman, and Crossley and McLaren, was based on the analog signals and devices. Analog signal processing can not fully exploit the information, about the fault, carried by the traveling waves. The analog devices are slow in operation; therefore, the techniques, based on traveling waves, do not present realizable implementation on analog devices.

Digital techniques, proposed in this thesis, eliminate the drawbacks of the analog devices. The relays, based on the proposed techniques, provide high-speed detection and location of the faults.

2.9 Summary

Traveling wave theory is discussed in this chapter. Traveling waves originate at the fault and travel away from the fault. Buses act as discontinuities in the path of the traveling waves, which are reflected when they encounter a discontinuity. The fault location also acts as a discontinuity. The techniques proposed by Chamia and Liberman, and Crossley and McLaren are described. The problems associated with the implementation of traveling wave techniques using the analog technology are also discussed briefly.

Chapter 3
Proposed Protection Techniques

3.1 Introduction

Traveling waves are introduced in Chapter 2. A technique for extracting traveling waves from the modal components of voltages and currents is presented in this chapter. The modal analysis is briefly discussed in Appendix A. Two techniques, which utilize the information obtained from the traveling waves to detect and locate a fault on an EHV transmission line, are also presented. Application of the techniques on a single circuit line as well as on a double circuit line is discussed.

Tamije Selvy Munian studied the feasibility of traveling wave techniques for protecting transmission lines [11]. She proposed digital techniques, which are based on the traveling waves extracted from the phase voltages and currents. Two digital techniques are proposed in this thesis, which are based on the traveling waves extracted from the modal voltages and currents. The techniques are implemented in hardware and performance is tested on data generated by simulating cases using EMTDC.

3.2 Traveling Wave Extraction

Traveling waves can be extracted from the modal voltages and currents by using sequence filters. A sequence filter, basically, is an algorithm that uses a sequence of samples to obtain information about the changes in a signal.

Traveling waves result in step changes in voltages and currents, such as the changes shown in Figure 3.1. Step changes in voltages and currents can be detected by using sequence filters that are classified on the basis of the size of the data window and on the structure of the filter. The size of the data window is an important aspect in detecting traveling waves. The data-window size should be optimal for achieving accuracy without leaving any part of the line unprotected.
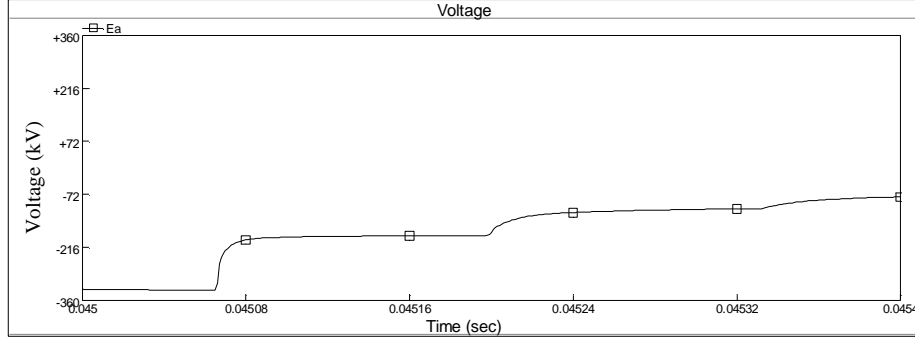
Figure 3.1: Step changes in voltage due to traveling waves

Increasing the data-window size increases the accuracy, but the length of the unprotected region increases. Various sequence filters with different number of samples and different structures were studied to detect the arrival of traveling waves at the relay location. The filters and their feasibility for detecting traveling waves are discussed in the following sections.

3.2.1 Sequence Filter with Data-Window of Two Samples

A two-sample sequence filter is proposed in Reference 11. This filter is based on the first differences [12] of the voltage and current samples. The first differences of the voltage samples can be expressed as

$$\Delta v_n = v_{n+\frac{1}{2}} - v_{n-\frac{1}{2}} \tag{3.1}$$

where, $v_{n+\frac{1}{2}}$ is $\left(n+\frac{1}{2}\right)^{\text{th}}$ sample of the voltage, and

$v_{n-\frac{1}{2}}$ is $\left(n-\frac{1}{2}\right)^{\text{th}}$ sample of the voltage.

Taking z-transform of Equation 3.1 provides,

$$H(z) = z^{+\frac{1}{2}} - z^{-\frac{1}{2}} \tag{3.2}$$

Equation 3.2, in frequency domain, becomes

$$H(\omega) = e^{+j\frac{1}{2}\omega\Delta T} - e^{-j\frac{1}{2}\omega\Delta T}$$

$$= 2j\sin\left(\frac{\omega\Delta T}{2}\right) \tag{3.3}$$

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The frequency response of the filter for a sampling rate of 1MHz is shown in Figure 3.2. This sequence filter is the simplest of all and uses minimum number of samples, but this filter does not provide adequate accuracy. The output of this filter, when traveling waves are present in the voltage, is shown in Figures 3.3 and 3.4. These figures show that the output of the filter has clear spikes when a traveling wave arrives at the measuring device.
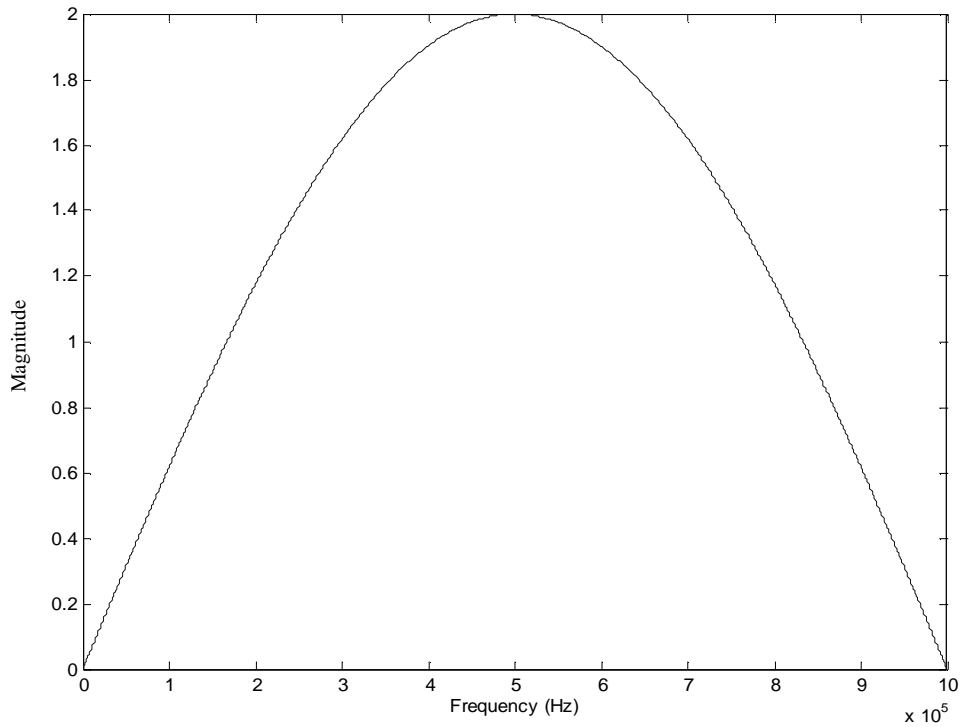
Figure 3.2: Frequency response of a two-sample sequence filter
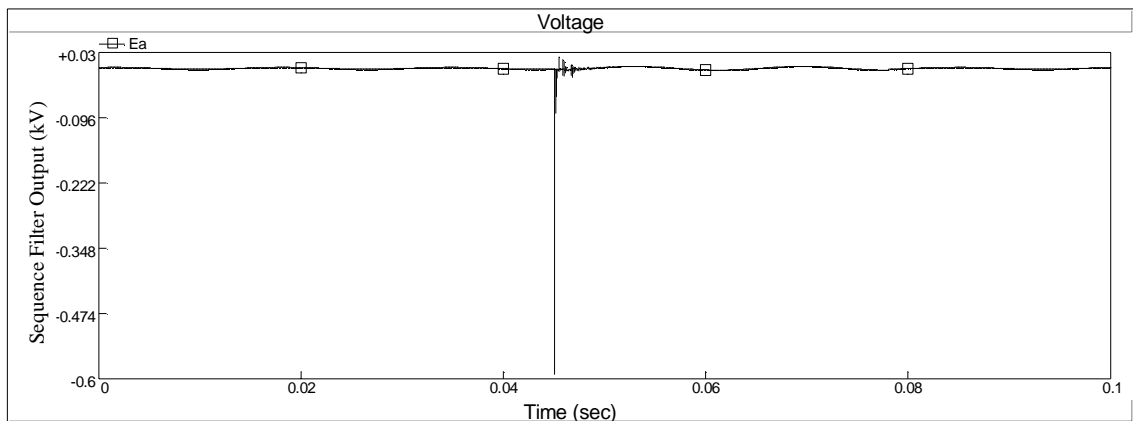
Figure 3.3: Output of a two-sample sequence filter

The output of the filter is, however, not zero when signal is a sinusoidal waveform as shown in Figures 3.3 and 3.4. Also, low level traveling waves due to the

occurrence of faults at low instantaneous values, can not be detected. Therefore, this filter is not appropriate for detecting traveling waves.
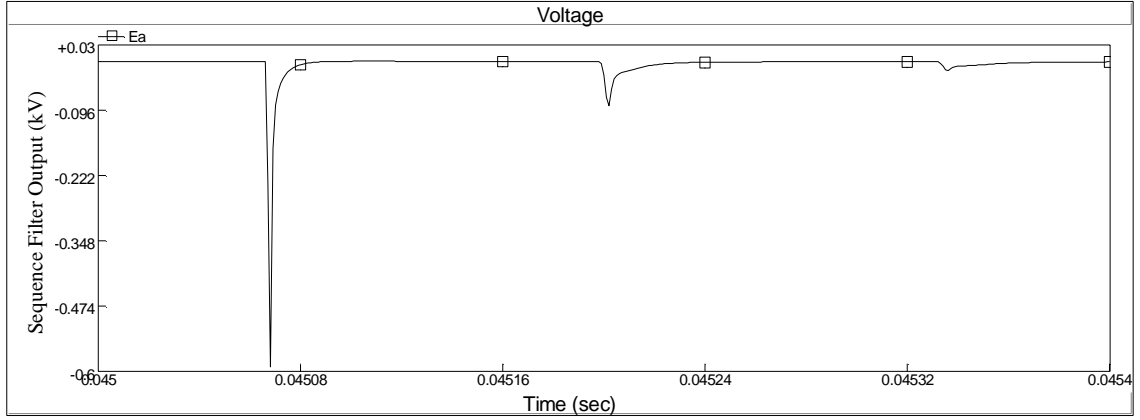
Figure 3.4: Zoomed output of a two-sample sequence filter

3.2.2 Sequence Filter with Data-Window of Three Samples

Consider a three-sample sequence filter, which is based on the second differences of the voltage and current samples. The second differences of the voltage samples can be expressed as

$$\Delta v_n = v_{n+1} - 2v_n + v_{n-1} \tag{3.4}$$

where, v_{n+1} is $(n+1)^{th}$ sample of the voltage,

v_n is n^{th} sample of the voltage, and

v_{n-1} is $(n-1)^{th}$ sample of the voltage.

Taking z-transform of Equation 3.4 provides,

$$H(z) = z^{+1} - 2z^0 + z^{-1} \tag{3.5}$$

Equation 3.5, in frequency domain, becomes

$$H(\omega) = e^{+j\omega\Delta T} - 2e^0 + e^{-j\omega\Delta T}$$

$$= 2(\cos(\omega\Delta T) - 1) \tag{3.6}$$

The frequency response of the filter for a sampling rate of 1MHz is shown in Figure 3.5.
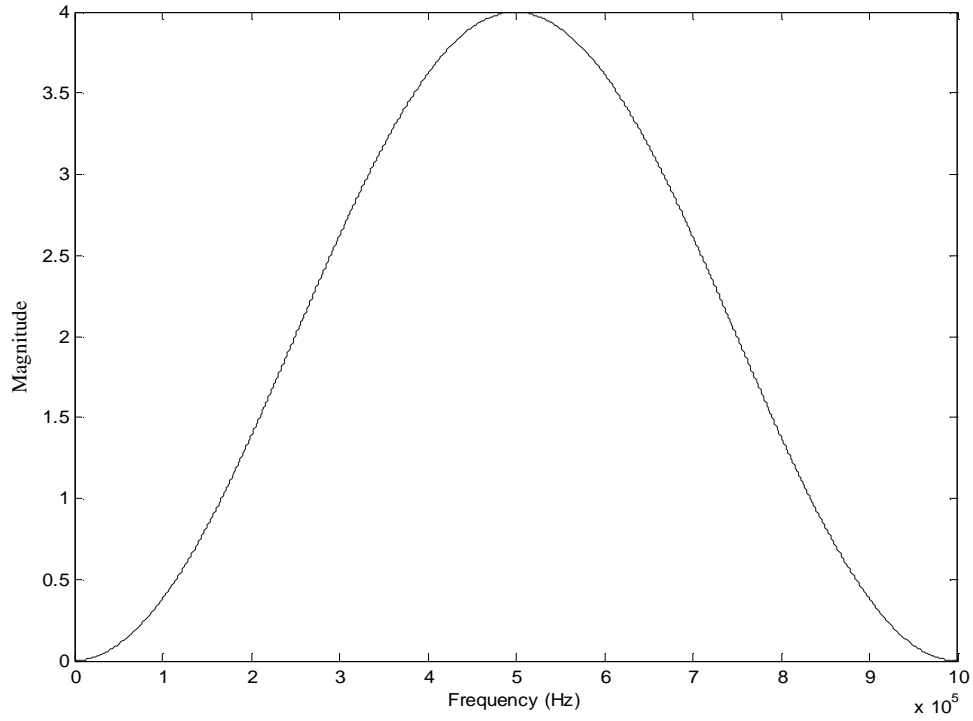
Figure 3.5: Frequency response of a three-sample sequence filter

The output of this filter, when the input voltage contains traveling waves, is shown in Figures 3.6 and 3.7. Sets of up-down spikes confirm the presence of traveling waves.
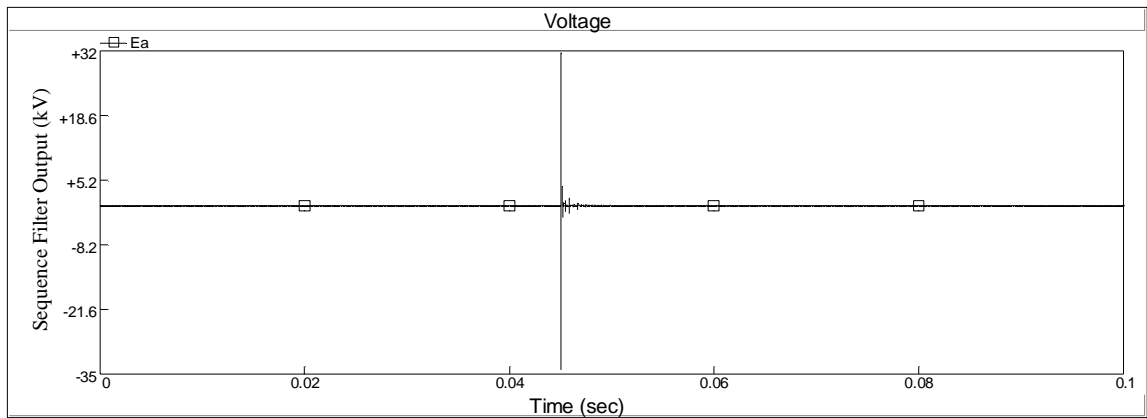
Figure 3.6: Output of a three-sample sequence filter

Figure 3.6 also shows that when a traveling wave is not present in the signal, the output is zero. This feature helps in recognizing traveling waves with low intensity. Also, using a set of up and down spikes for detecting the arrival of a traveling wave adds to dependability and security of the detection process.

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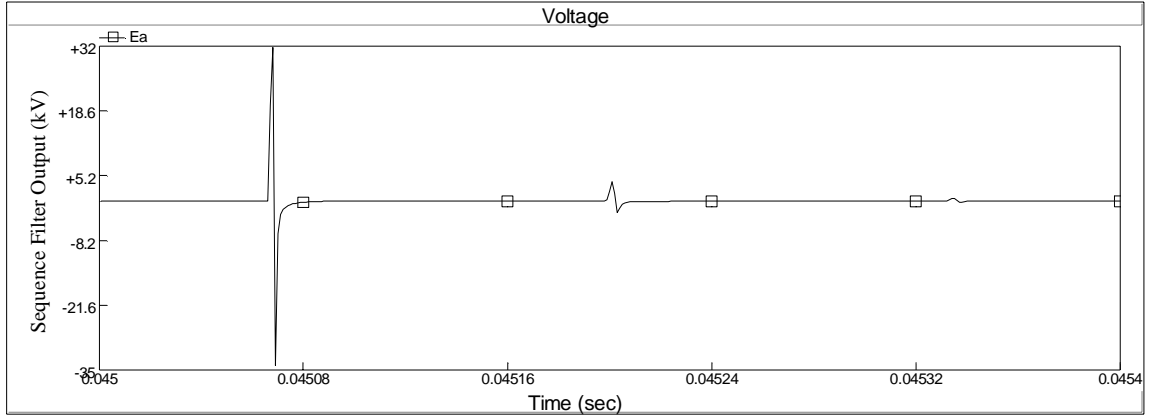
Figure 3.7: Zoomed output of a three-sample sequence filter

3.2.3 Sequence Filter with Data-Window of Five Samples

Two sequence filters, which take five samples as input, are discussed in the following sections.

3.2.3.1 Filter 1

Consider a five-sample sequence filter, which is based on the following difference equation

$$\Delta v_n = v_{n+2} - 2v_{n+1} + 2v_n - 2v_{n-1} + v_{n-2} \tag{3.7}$$

where, v_{n+2} is $(n+2)^{th}$ sample of the voltage,

v_{n+1} is $(n+1)^{th}$ sample of the voltage,

v_n is n^{th} sample of the voltage,

v_{n-1} is $(n-1)^{th}$ sample of the voltage, and

v_{n-2} is $(n-2)^{th}$ sample of the voltage.

The z-transform of Equation 3.7 provides,

$$H(z) = z^2 - 2z^1 + 2z^0 - 2z^{-1} + z^{-2} \tag{3.8}$$

Equation 3.8, in frequency domain, becomes

$$H(\omega) = e^{+j2\omega\Delta T} - 2e^{+j\omega\Delta T} + 2e^{j0} - e^{-j\omega\Delta T} + e^{-j2\omega\Delta T}$$

$$= 2\cos(2\omega\Delta T) - 4\cos(\omega\Delta T) + 1 \tag{3.9}$$

The frequency response of the sequence filter for a sampling rate of 1MHz is shown in Figure 3.8. The output of this filter is shown in Figure 3.9. The filter does not

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give a consistent pattern, when traveling waves arrive at the relay; therefore, this filter can not be used for detecting faults on transmission lines.
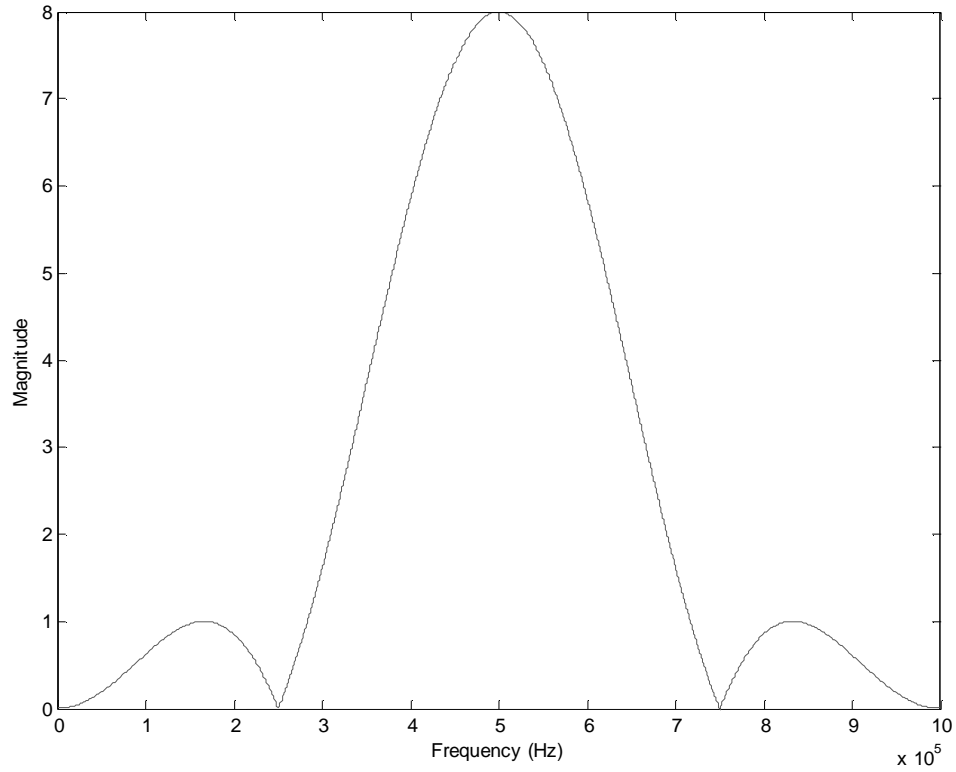
Figure 3.8: Frequency response of a five-sample filter defined in Equation 3.7
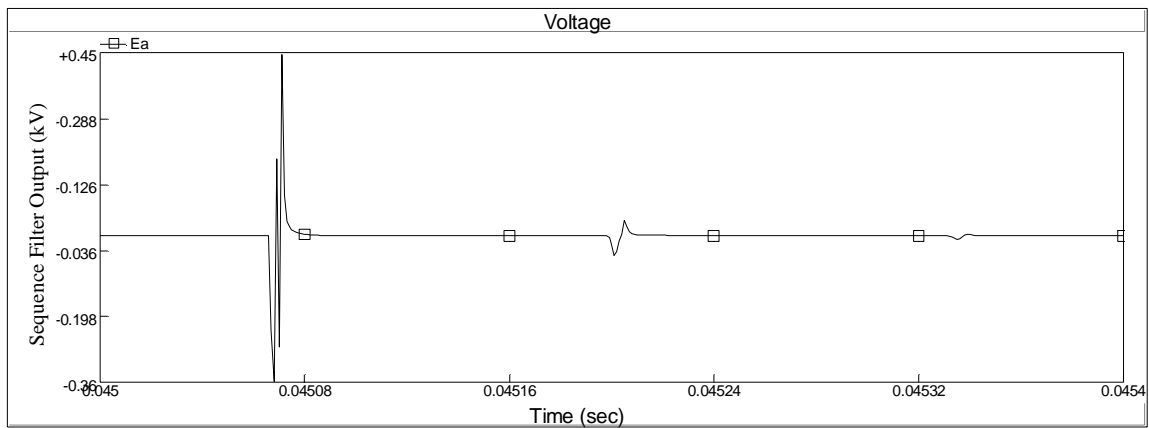
Figure 3.9: Output of a five-sample sequence filter defined in Equation 3.7

3.2.3.2 Filter 2

Consider a five-sample sequence filter, which is based on the following difference equation

$$\Delta v_n = 2v_{n+2} - v_{n+1} - 2v_n - v_{n-1} + 2v_{n-2} \qquad (3.10)$$

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where, v_{n+2} is (n+2)th sample of the voltage,

v_{n+1} is (n+1)th sample of the voltage,

v_n is nth sample of the voltage,

v_{n-1} is (n–1)th sample of the voltage, and

v_{n-2} is (n–2)th sample of the voltage.

The z-transform of Equation 3.10 provides,

$$H(z) = 2z^2 - z^1 - 2z^0 - z^{-1} + 2z^{-2} \qquad (3.11)$$

Equation 3.11, in frequency domain, becomes

$$H(\omega) = 2e^{+j2\omega\Delta T} - e^{+j\omega\Delta T} - 2e^{j0} - e^{-j\omega\Delta T} + 2e^{-j2\omega\Delta T}$$

$$= 4\cos(2\omega\Delta T) - 2\cos(\omega\Delta T) - 2 \qquad (3.12)$$

The frequency response of the sequence filter for a sampling rate of 1MHz is shown in Figure 3.10.
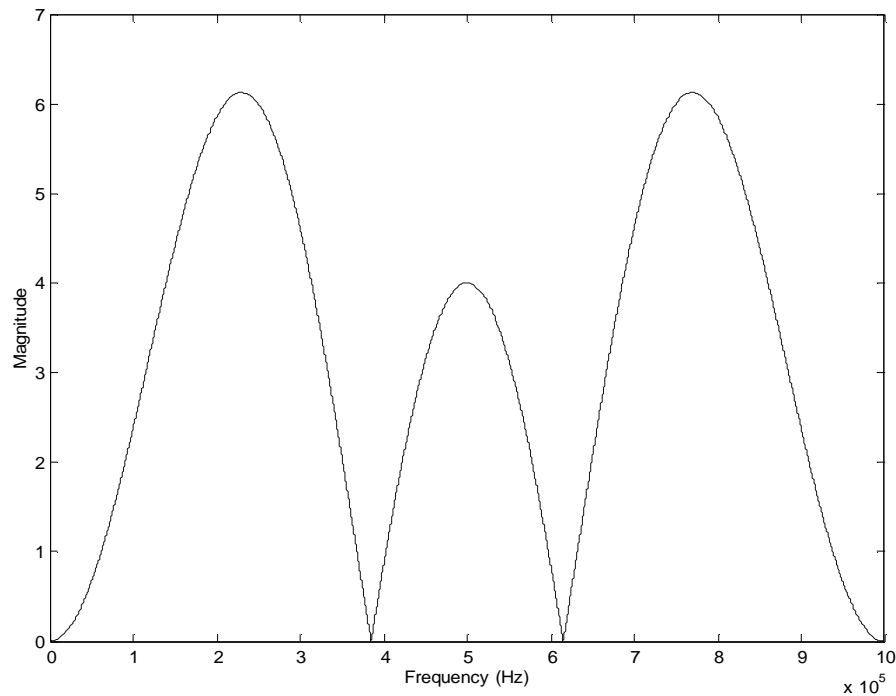
Figure 3.10: Frequency response of a five-sample filter defined in Equation 3.10

The output of this filter is shown in Figure 3.11, which clearly depicts the arrival of traveling waves. But this filter does not have any additional advantages over the three-sample filter discussed in section 3.2.1.2. Therefore, the sequence filter, which uses three samples, was used for detecting traveling waves.
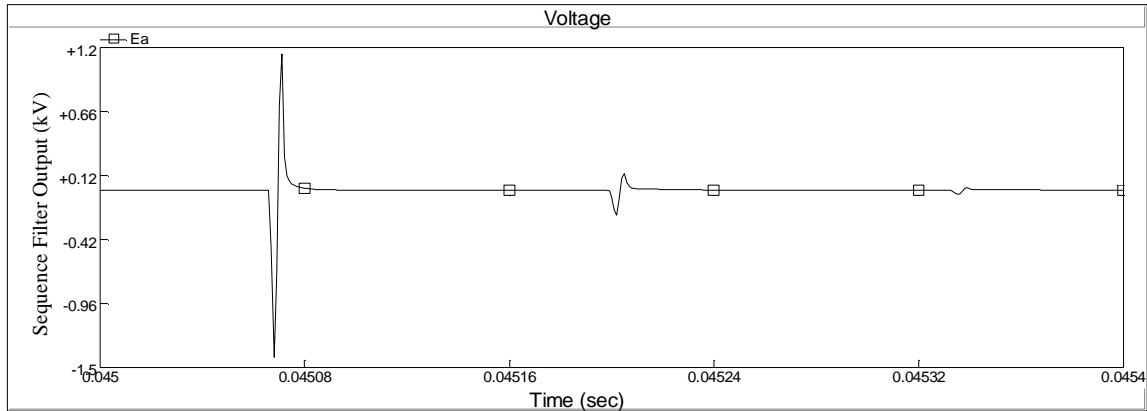
Figure 3.11: Output of a five-sample sequence filter defined in Equation 3.10

3.3 Sequence Filter Inputs

The proposed techniques use modal voltages and currents as inputs to the sequence filters instead of the phase voltages and currents. The modal components simplify the logic for detecting the traveling waves.

When the phase signals are used, voltages and currents of all three phases are checked for the presence of traveling waves. When modal components of the signals are used, aerial modes are checked for the presence of traveling waves. The calculations required for detecting traveling waves by using modal components of voltages and currents are less than the calculations required for detecting traveling waves by using phase voltages and currents.

3.4 Fault Location Techniques

The two digital techniques, single-ended and double-ended, for detecting and locating faults on transmission lines are described in the following sections. The single-ended technique takes voltage and current inputs from one end of the transmission line. The double-ended technique takes voltage and current inputs from both ends of the transmission line; the information from the remote end is obtained over a communication channel between the two ends of the transmission line.

3.4.1 Single-Ended Technique: Single Circuit Line

Consider a power system, shown in Figure 3.12, with a single circuit transmission line connecting bus A and bus B. A traveling wave digital relay, $R_{a,}$ is located at the bus A terminal of the line. This relay takes input voltages and currents

from the local terminal and calculates modal voltages and currents. The aerial modes, 1 and 2, of the voltages and currents are passed through the sequence filters.
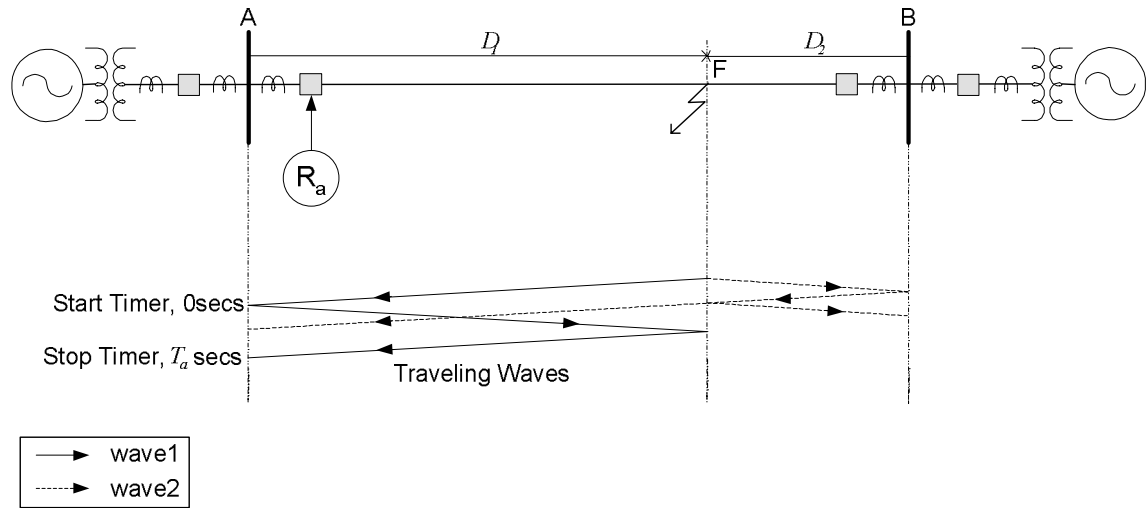
Figure 3.12: Traveling waves on a single circuit transmission line in sample power system

When a fault occurs on the transmission line, the voltage and current traveling waves originate and propagate on the line away from the fault. One wave travels towards bus A and the other wave travels towards bus B. The traveling waves, after a few microseconds, arrive at bus A. When the traveling waves are detected by the relay, R_a, the timer is turned on. The spikes corresponding to the voltage and current incident waves are shown as V_{S1} and I_{S1} in the outputs of sequence filters, in Figure 3.13. The opposite polarities of the voltage and current spikes confirm the occurrence of
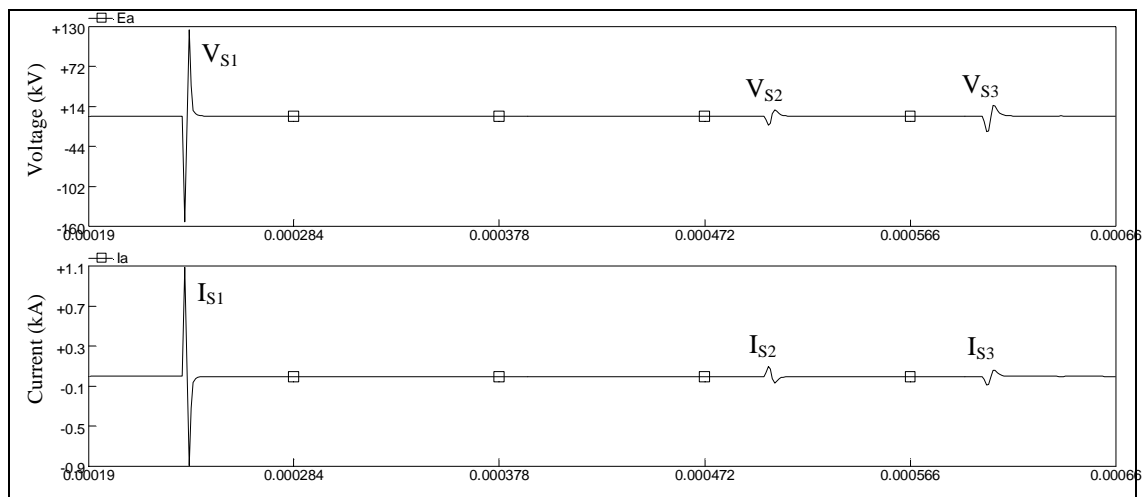
Figure 3.13: Sequence filter output at relay R_a

a fault. A bus acts as a discontinuity in the path of the traveling waves. On reaching a bus, a part of the voltage wave and a part of the current traveling wave is reflected, and rest passes through. The reflected waves arrive at the fault, where a part of the voltage wave and a part of the current wave is reflected. These waves arrive at bus A, the second time. The arrival of the waves is detected by the relay, R_a. The spikes, corresponding to these voltage and current waves are shown as V_{S2} and I_{S2}, in Figure 3.13. The timer is stopped and the time is noted as T_a.

The distance traveled by the traveling waves is twice the distance of the fault from bus A. Therefore, the distance of the fault can be calculated as

$$D = \frac{T_a}{2} \times v \tag{3.13}$$

where, v is the velocity of propagation of the traveling waves.

If the distance, D is less than the length of the protected transmission line, the relay sends trip signals to the circuit breakers to isolate the faulted line from the rest of the system. If the value of D is greater than the length of the protected line, the relay is reset and normal operation is resumed.

When the traveling waves arrive at bus B, part of the waves is reflected back to the fault. Again a part of the voltage wave and a part of the current wave gets reflected at the fault, and the rest passes through. When the waves, which pass through the fault, arrive at bus A, are detected by the relay, R_a. The spikes, corresponding to these voltage and current waves are shown as V_{S3} and I_{S3} in Figure 3.13. The same polarities of the spikes of these waves, distinguish them from the initial traveling waves, which propagated from the fault to bus A.

3.4.2 Single-Ended Technique: Double Circuit Line

Consider a power system, shown in Figure 3.14, with a double circuit transmission line connecting bus A and bus B. The traveling wave digital relays are located at bus A terminal of both circuits. The relays take the input voltages and currents from the local terminals and transform them into modal components. The aerial modes, 1 and 2, of the voltages and currents are passed through the sequence filters.
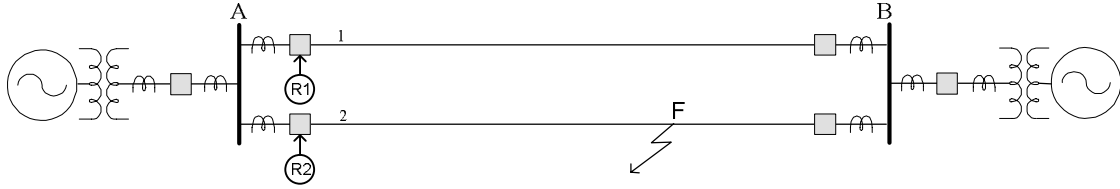
Figure 3.14: Power system with a double circuit transmission line

When a fault occurs on one of the circuits of the transmission line, the voltage and current traveling waves originate and propagate away from the fault. The traveling waves also exist on the healthy circuit due to magnetic induction. The voltage and current traveling waves, which arrive at bus A, are detected by the relays, R1 and R2. The first set of spikes corresponding to the initial voltage and current traveling waves at relay R2 are shown as V_{C21} and I_{C21} in Figures 3.15. The polarity of the voltage spike is opposite than the polarity of the current spike, which indicates that the fault is on circuit 2. The timer in Relay, R2, is turned on.
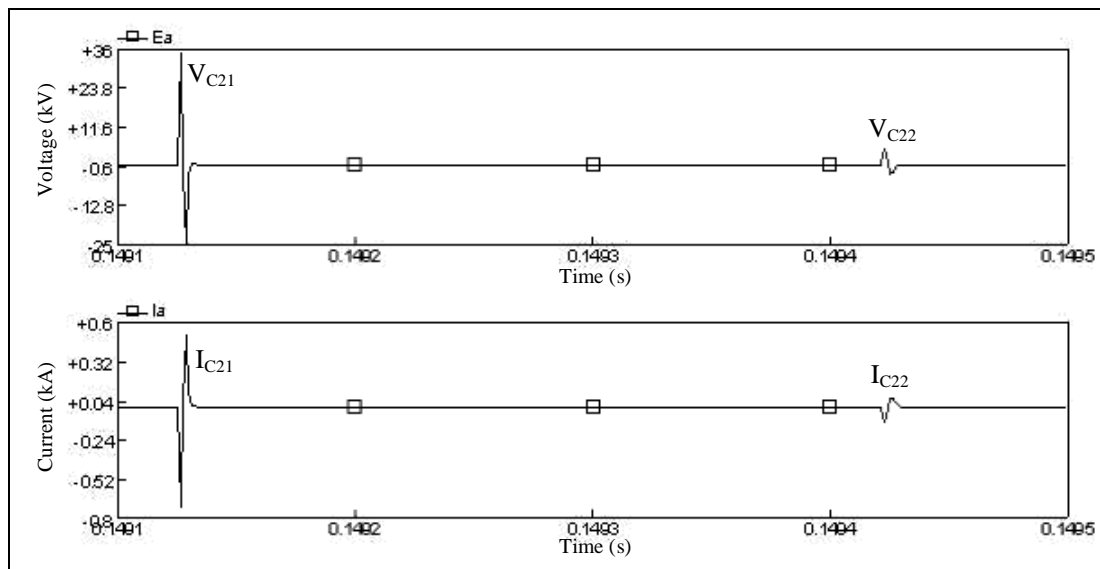
Figure 3.15: Voltage and current sequence filter outputs at relay on circuit 2 at bus A

The first set of spikes in voltage and current detected by the relay, R1, on circuit 1 are shown as V_{C11} and I_{C11} in Figure 3.16. The polarities of these spikes are same; therefore, fault is not on circuit 1.
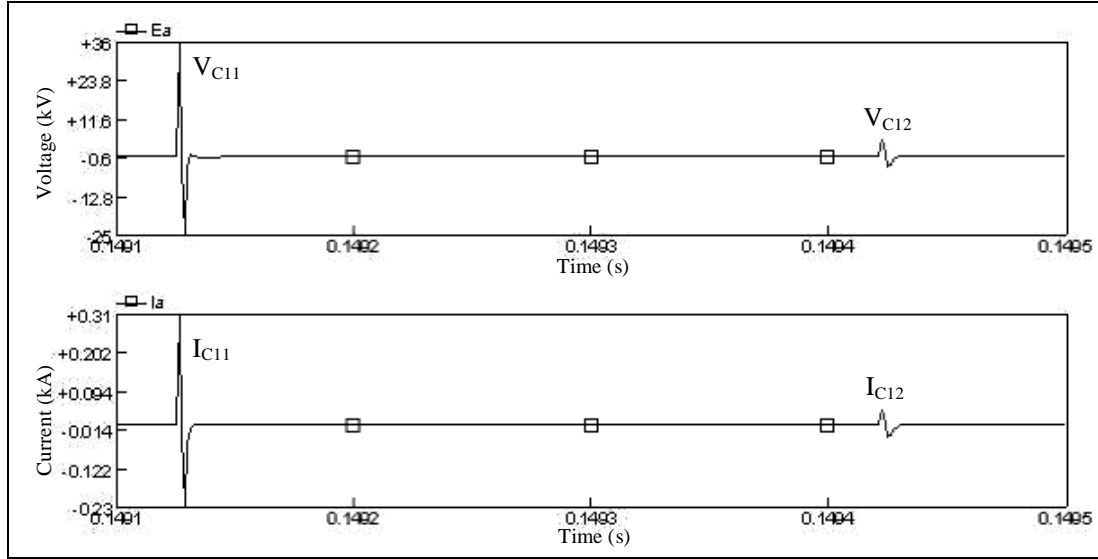
Figure 3.16: Voltage and current sequence filter outputs at relay on circuit 2 at bus A

The bus A reflects a part of the traveling waves, which travel back to the fault, where a part of the waves again gets reflected. The reflected voltage and current waves travel towards the bus A, where they are detected by the relays. The second set of voltage and current waves detected by relay R2 is represented as V_{C22} and I_{C22} in Figure 3.15. The timer is stopped. If, the time recorded by the relay is T_a, the distance of the fault from bus A can be calculated as

$$D = \frac{T_a}{2} \times v \qquad\qquad (3.14)$$

where, v is the velocity of propagation of the traveling waves.

If the value of D is less than the length of the protected transmission line, the fault is on the line. Relay sends the trip signals to circuit breakers to isolate the faulted line. If the value of D is greater than the length of the protected line, the relays are reset and normal operation is resumed.

3.4.3 Double-Ended Technique: Single Circuit Line

Consider a power system, shown in Figure 3.17, with a single circuit transmission line connecting bus A and bus B. The traveling wave digital relays are located at each terminal of the line. The relays take the input voltages and currents from the local terminals of the line and calculate modal components. The aerial modes, 1 and 2, of the voltages and currents are passed through the sequence filters. The relays can

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send and receive information from each other through the communication channel. A Global Positioning System (GPS) is used to time-stamp the incoming samples.
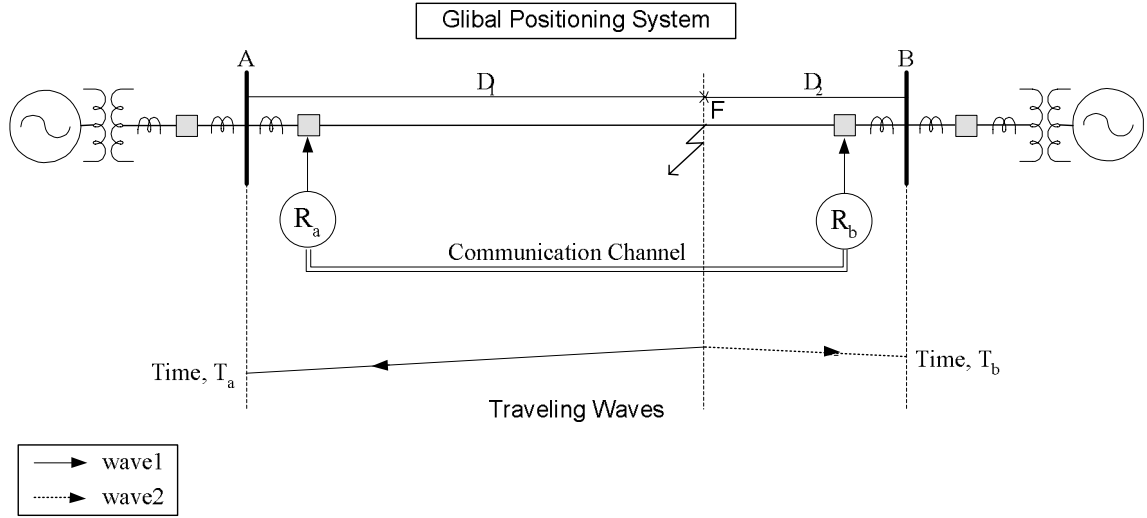
Figure 3.17: Traveling waves on a single circuit transmission line protected with double-ended technique

In case of a fault on the transmission line, traveling waves originate on the line and propagate away from the fault. These waves arrive at the buses after a few microseconds. Traveling waves present up-down spikes in the outputs of the voltage and current sequence filters. The polarities of the spikes in voltages are opposite to the polarities of the spikes in currents. The traveling waves are detected by the relays and the time corresponding to the arrival of the waves is recorded. The relay at each terminal sends the recorded time to the relay at the other terminal. Let the difference of the times recorded by the relays be T_d, therefore,

$$T_d = |T_a - T_b| \qquad\qquad (3.15)$$

where, T_a is the time recorded by the relay, R_a, at the arrival of the waves, and

T_b is the time recorded by the relay, R_b, at the arrival of the waves.

The time taken by a traveling wave to travel the length of the line can be calculated as

$$T = \frac{L}{v} \qquad\qquad (3.16)$$

where, L is the total length of the transmission line, and

v is the velocity of propagation of the traveling waves.

Now the time, T_d is compared with the time, T. If, T_d is smaller than T, fault is on the transmission line. Therefore, the trip signals are issued by the relays to the circuit breakers to isolate the faulted line. If, T_d is equal to T, fault is beyond the remote end of the line, therefore the relays are reset and no action is taken.

If, fault is on the transmission line, the relay, R_a, calculates the distance of the fault as

$$D_1 = \left(T_a - T_b + \left(\frac{L}{v}\right)\right) \times \frac{v}{2} \qquad (3.17)$$

The relay, R_b, calculates the distance of the fault as

$$D_2 = \left(\left(\frac{L}{v}\right) - \left(T_a - T_b\right)\right) \times \frac{v}{2} \qquad (3.18)$$

3.4.4 Double-Ended Technique: Double Circuit Line

In case of a double circuit transmission line, the traveling wave relays are located at each terminal of the circuits. The relays can transfer information to the relays at the remote terminal through a communication channel. A GPS system is used to time-stamp the incoming samples. The relays take input voltages and currents from the local terminals of the line and transform them into modal components. The aerial modes, 1 and 2, of the voltages and currents are passed through the sequence filters.

When a fault occurs on one of the circuits, traveling waves originate on the line and propagate away from the fault. The traveling waves also exist on the healthy circuit due to magnetic induction. When the voltage and current waves arrive at the terminals of the lines, the relays compare the polarities of spikes in the outputs of the voltage and current sequence filters. In case, the polarities of the spikes in voltages are opposite to the polarities of the spikes in currents, the time corresponding to the arrival of the waves is recorded by the relays. The relay at each terminal sends the recorded time to the relay at the other terminal via the communication channel. The difference in the values of time recorded by the relays is compared with the time, T, calculated by using Equation 3.16.

If the fault is on the circuit, the distance of fault from bus A and bus B is calculated by using Equations 3.17 and 3.18 respectively.

In case, polarities of the spikes in the outputs of the voltage and current sequence filters are same, fault is not on the circuit.

3.5 The Algorithm for Single-Ended Technique

The flowchart for the single-ended technique is shown in Figure 3.18. The steps involved in the algorithm are as follows

1. Initialize variables, CV and CI, to zero.
2. Fetch the voltage and current samples.
3. Calculate aerial modes of the voltages and currents.
4. Pass samples through the sequence filters.
5. Check if spikes are present in the outputs of the sequence filters.
6. If spikes are detected, compare polarities of the voltage and current spikes.
7. If polarities of the spikes are different, increment the variables, VC and VI, by one.
8. Compare the values of the variables with 2.
9. If values of the variables are not equal to 2, turn the timer on.
10. If values of the variables are equal to 2, compare the polarities of the second set of voltage and current spikes with the polarities of the first set of voltage and current spikes respectively.
11. If the compared polarities are same, stop the timer and record the time.
12. Calculate the distance of the fault.
13. If the calculated distance is less than the length of the protected transmission line, send trip signals to the circuit breakers.
14. Otherwise, the fault is external to the line. Reset the variables to zero.
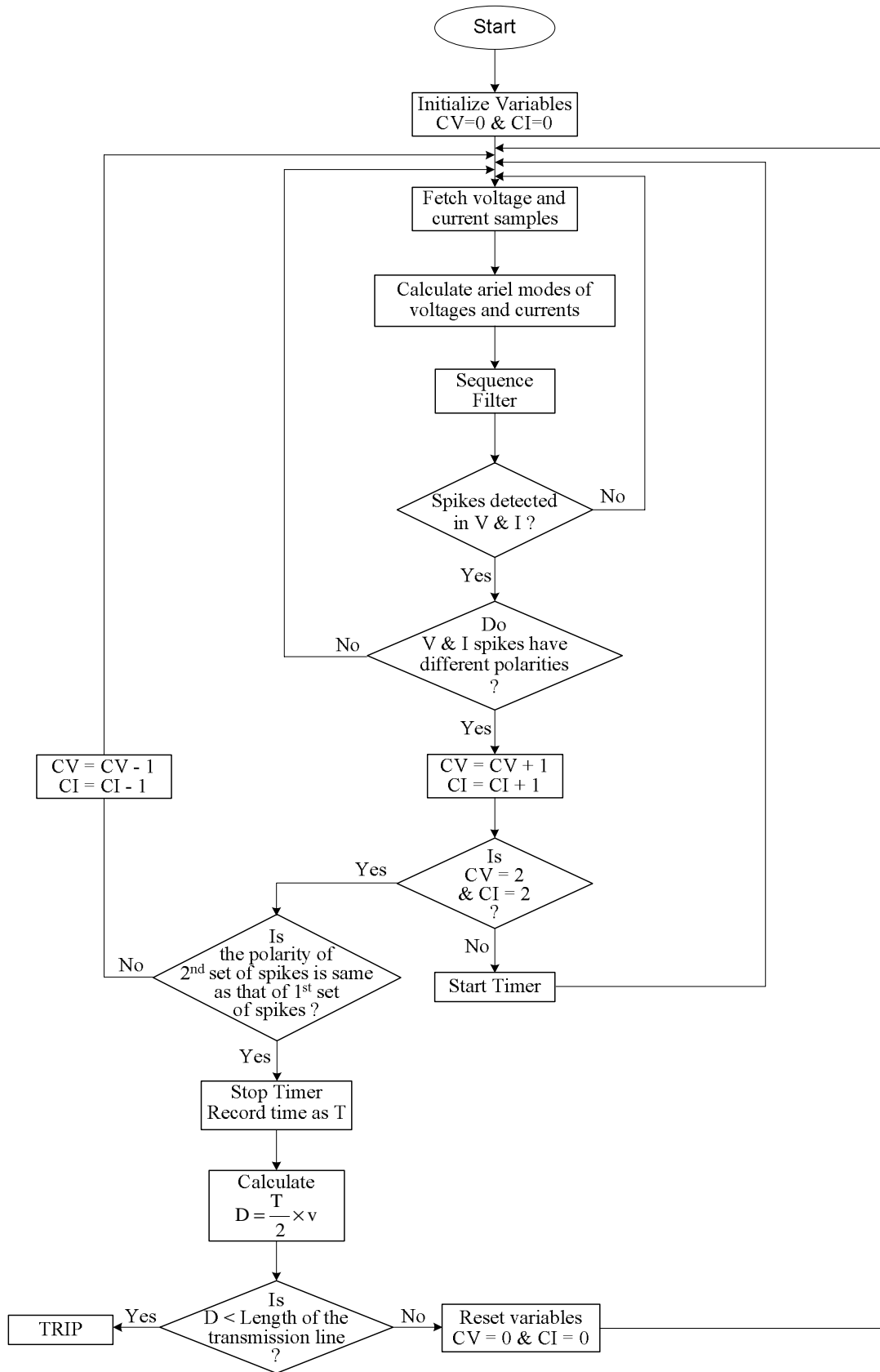
Figure 3.18: Flowchart for the single-ended technique

3.6 The Algorithm for Double-Ended Technique

The flowchart for the double-ended technique is shown in Figure 3.19. The steps involved in the algorithm are as follows

1. Fetch the voltage and current samples.
2. Calculate aerial modes of the voltages and currents.
3. Pass samples through the sequence filters.
4. Check if spikes are present in the outputs of the sequence filters.
5. If spikes are detected, compare polarities of the voltage and current spikes.
6. If polarities of the spikes are different, record the time and send this value to relay at the other end.
7. Calculate difference of the times recorded by the relays. Record the value as T_d.
8. Calculate the time that a traveling wave takes to travel the full length of the transmission line. Record this value as T.
9. If T_d is less than T, fault is on the protected line.
10. Send trip signals to the circuit breakers and calculate the distance of the fault.
11. Otherwise, fault is external to the line. Normal operation of the relay is resumed.

3.7 Features of Single-Ended Technique and Double-Ended Technique

Features of the proposed techniques are summarized as follows.

- The techniques are capable of distinguishing between faults, internal and external to the protected line.

- The techniques are applicable on single circuit lines as well as on double circuit lines for detecting and locating faults.

- Computational time is small in these techniques. For example, the time needed by the relay, based on single-ended technique, for detecting a fault on the remote end of a 150 km transmission line is

$$T_{max} = \frac{2 \times 150 \times 10^3}{3 \times 10^8} = 0.001 \text{ s} \qquad (3.19)$$

The total time required to isolate the faulted line is less than 3 ms. This time is very low in comparison to 16 ms, taken by the relays, which use fundamental component of the signal to detect faults.

Start

Fetch V and I samples at sending end

Calculate ariel modes of voltages and currents

Sequence Filter

Spike detected ? — No

Is the receiving end relay sending the time ? — No

Yes

Record time as T_b

Do V & I spikes have different polarities ? — No

Yes

Record time as T_a

Is time received from receiving end relay ? — No

Yes

Calculate $T_d = |T_a - T_b|$

Calculate $T = v \times L$

Is $T_d < T$? — Yes / No

Calculate
$$D_1 = \left(T_a - T_b + \left(\frac{L}{v} \right) \right) * \frac{v}{2}$$

TRIP

Fetch V and I samples at receiving end

Calculate ariel modes of voltages and currents

Sequence Filter

Spike detected ? — No

Do V & I spikes have different polarities ? — No

Yes

Record time and send to the sending end relay

Figure 3.19: Flowchart for the double-ended technique

3.8 Summary

Single-ended and double-ended techniques for detecting and locating faults on transmission lines are proposed in this chapter. The techniques use traveling waves of modal components of voltages and currents. The techniques and their algorithms for protection of single circuit transmission lines and double circuit transmission lines are described. Relays based on the proposed techniques are very fast in operation.

Chapter 4

Hardware, Software and Programming

4.1 Introduction

The hardware and software used to implement the digital techniques for transmission line protection is described in this chapter. The hardware used to implement the techniques is a DSP module and a personal computer. A real time operating system was used to load the code on the processor.

4.2 DSP Module

A DSP module, generally, contains a microprocessor, an external memory and various peripheral devices. The main components of the DSP module, SMT335 [13, 14], are shown in the block diagram in Figure 4.1.
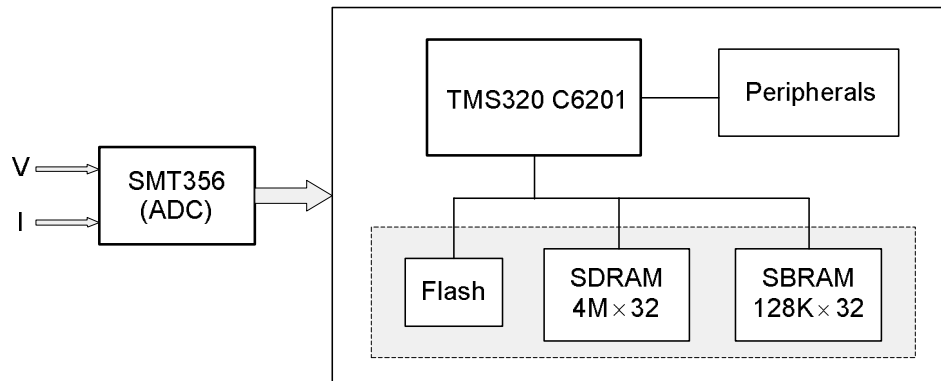
Figure 4.1: Block diagram of SMT335

The voltages and currents obtained from the power system are digitized by passing them through an analog to digital (A/D) converter unit, SMT356 [15], which consist of eight A/D converters (AD9240). This 14-bit A/D converter can process 10 million samples in a second. It has four-stage pipeline architecture with on-chip input sample and hold circuit, and voltage reference. The device utilizes one cycle to

acquire samples and three cycles to process them. The device also contains digital output error correction logic to guarantee no missing codes over the operating temperature range. All A/D converters, sample the inputs simultaneously using the same clock.

The protection techniques were coded in C language and linear assembly language. These programs were loaded and executed on a microprocessor. The DSP module, SMT335, was used in this project and has the following features.

- The module contains a fixed point processor, TMS320C6201 [2], running at 200 MHz.

- The module has six communication ports, which can transfer data at a maximum speed of 20 MB/s.

- The module has 512 KB of Synchronous Burst Static Random Access Memory (SBSRAM) and 16 MB of Synchronous Dynamic Random Access Memory (SDRAM).

  The Random Access Memory (RAM) provides very fast access speed, which is needed by the processor for temporary storage of the data during the program execution. The DRAM, composed of a transistor and a capacitor, requires periodic rewriting of the information in order for data to remain valid. On the other hand, Static Random Access Memory (SRAM) is made up of a flip-flop circuitry and the data stored in it does not need to be refreshed. The data remains in the device as long as the power is on. In synchronous mode, the device uses a clock to synchronize the signal input and the signal output. In burst mode, SRAM transmits a series of consecutive addresses when the processor requests a single address.

- The module has 512 KB of Flash memory, a Read Only Memory (ROM), reserved for the configuration (boot code) and field programmable gate array (FPGA) programming. Flash memory is a solid-state device, which is non-volatile and can be rewritten.

- The module is equipped with a global bus expansion connector, which allows the processor to access additional features like I/O expansion and memory.

- The module has two Sundance Digital Bus (SDB) interface ports. SDB is a 16-bit parallel communication link, which can transfer data between processors at the speed of 200 Mbps.

4.2.1 Digital Signal Processor

The main components of a DSP are shown in the block diagram in Figure 4.2. The central processing unit (CPU) is the heart of the processor, which performs all arithmetic and logic calculations. The memory on a microprocessor chip, called the on-chip memory, is used by the processor for temporary storage during execution of the program. CPU communicates with the internal memory and other peripheral devices via internal buses. The two types of buses are present in a processor. A control bus is used by the control unit of the CPU to control the flow of data among peripherals connected to the CPU. The other type of bus is a data bus, which transports data from memory to the CPU.

The external memory and other peripherals can also communicate with the processor through various ports available on the processor.
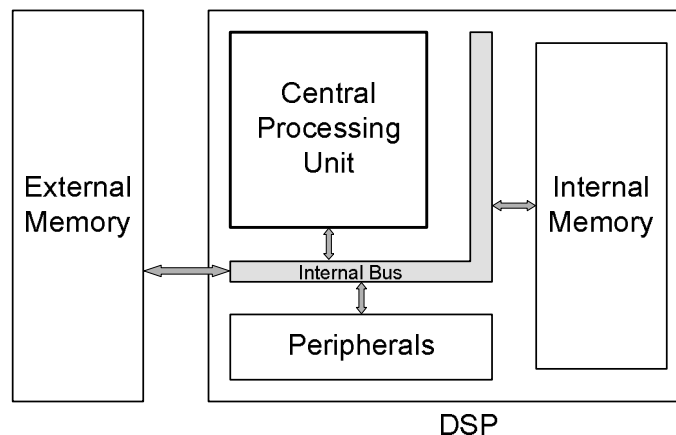
Figure 4.2: Block diagram of a digital signal processor

4.2.1.1 Digital Signal Processor C6201

TMS320C6201, a fixed point DSP, has the following features [2, 14].

1 High performance

   i. The processor has clock rate of 200 MHz, which provides 5 ns instruction cycle time.

  ii. The CPU contains eight functional units, which operate in parallel to execute up to eight 32-bit instructions in each clock cycle.

2 Very Long Instruction Word

   i. The functional units of the CPU are six Arithmetic and Logic Units (ALU) and two multipliers. The ALU can process 32-bit as well as 40-bit instructions. The multipliers can process two 16-bit instructions to produce a result of 32-bit. The eight functional units are placed on the chip in two identical sections; section A and section B. Each section has its general purpose registers, which allow the transfer of data between the sections.

  ii. The processor has thirty-two 32-bit general purpose registers, which are used to load and store instructions.

3 On-chip SRAM

  The on-chip SRAM is 1 MB in size, which is divided on the chip as 512 KB of program memory and 512 KB of data memory. The program memory and the data memory are used by the processor to load the instructions and data, temporarily, during the execution.

4 Peripherals

   i. External Memory Interface (EMIF): The processor has a 32-bit external memory interface, which transfers data between the processor and the external memory.

  ii. Direct Memory Access (DMA): It is a feature that allows the transfer of data from the external devices to the memory located on the processor, without the intervention of the processor.

 iii. Host Port Interface (HPI): 16-bit HPI provides access of the entire memory map to the host processor.

 iv. Timers: The processor has two 32-bit general purpose timers.

4.3 Real Time Operating System: Diamond

The Diamond [16] is a real time operating system, which gives high performance with simplified structure. Diamond loads a program on the processor, and displays the results after the execution of the program. Diamond has the following features:

- It has a graphical user interface for interaction with the user. It can take user inputs and displays the results.

- It has a microkernel with multi-tasking and multi-threading ability to handle multiple processors efficiently. Multi-tasking is an ability by virtue of which multiple tasks can be handled concurrently. Multi-threading is an ability that allows processor to process multiple simultaneous requests.

- It includes a configuration software, which optimizes the system performance by moving tasks around a multi-processor network.

4.4 Programming

The code for the proposed techniques was written in linear assembly language and C language. The logic of the proposed techniques was implemented in a linear assembly program. Linear assembly language code [17, 18] used along with the assembly optimizer, efficiently generates the assembly language code without worrying about register usage, pipelining, functional units and delay slots. The C program was made to fetch data from the files stored on personal computer. The samples were scaled and stored in arrays and pointers to these arrays were passed to the assembly language program by the C program. C program also provided results to the real time operating system, Diamond, which displays them on a graphical interface.

Data collected by running simulated cases in EMTDC was stored in a personal computer. The C language program and the linear assembly language program were compiled and linked using code composer studio compiler and linker. The resulting task files were configured by using Diamond configurer. The configurer, interlinked the tasks and specified the processor on which program was to be loaded. Configurer produced an application file, which was loaded on the processor by using Diamond.

The execution of the program was controlled from the Diamond's user interface. When the program was executed, the DSP accessed the data files stored on the personal

computer. The program checked the data for the presence of traveling waves and detects the fault. It calculates the location of the fault on the transmission line. The linear assembly program saved the results in an array. The C program provides the results to the Diamond. The results include; time of arrival of the traveling waves and distance of the fault. The Diamond shows the results on the graphical user interface. Application execution sequence is shown in Figure 4.7.
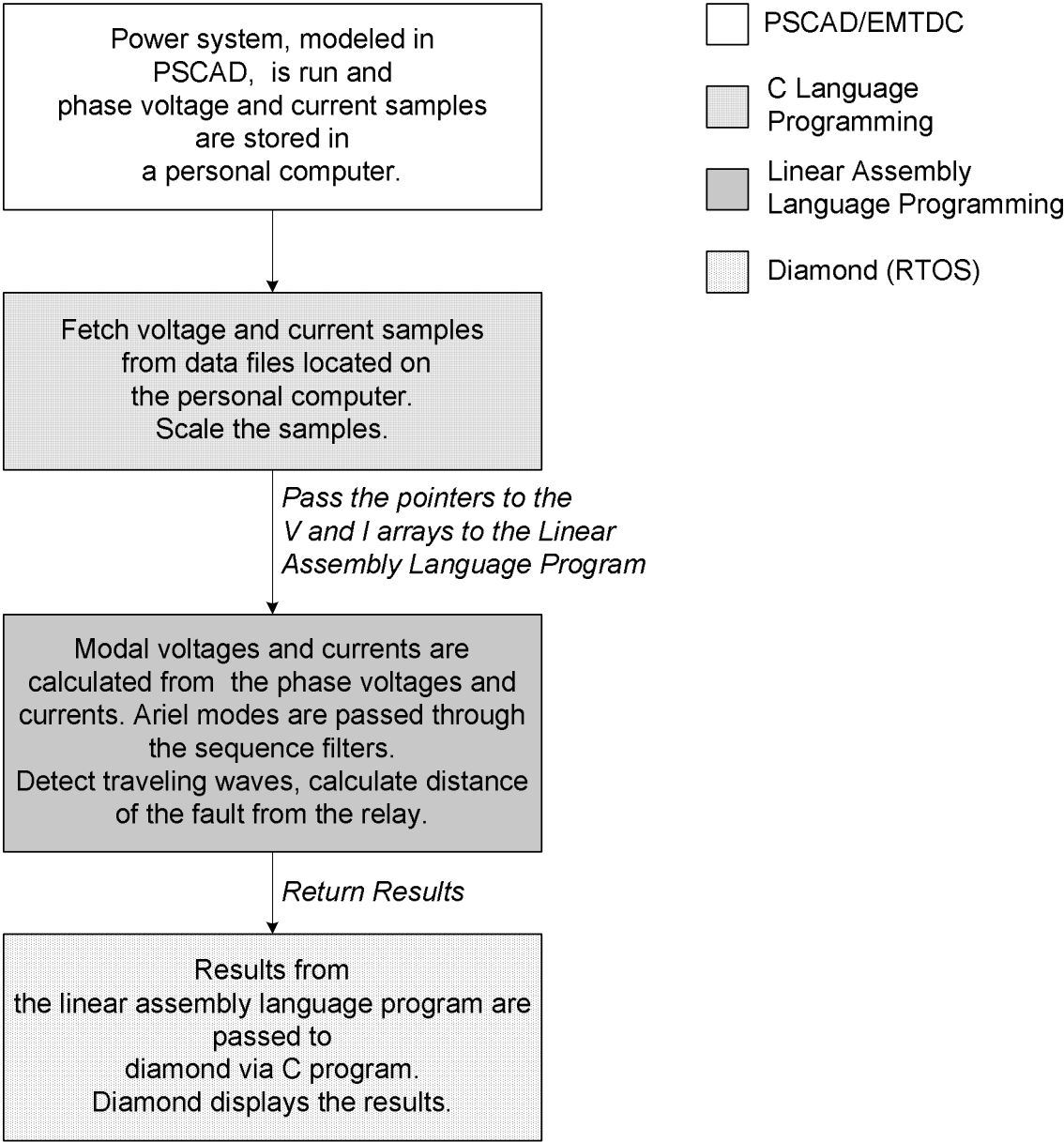
Figure 4.3: Program execution sequence

4.5 Summary

High performance hardware is required to implement the traveling wave techniques for fast and reliable performance of the relay. Linear assembly language programming is used to implement the protection logic in the relay for better optimization of the code. Diamond is used for loading and connecting multiple tasks on the microprocessor.

Chapter 5

System Studies

5.1 Introduction

The two proposed techniques for detecting and locating faults on transmission lines are introduced in Chapter 4. This chapter describes the test power system, which was simulated in EMTDC to generate data. The parameters, which affect the properties of the traveling waves, are described. The results obtained by implementing the techniques in a DSP are also discussed.

5.2 Test Power System

A test power system was modeled in the EMTDC program. A case of the modeled power system is shown in Figure 5.1. Model of a source, a transformer, a transmission line, an induction motor and a load are shown in Figures 5.2, 5.3, 5.4 and 5.5 respectively. Test power system consists of 17 buses, 8 transformers, 14 transmission lines, 2 sources, 2 induction motors and 4 loads. The transmission lines; T5, and T7a and T7b in parallel configuration, were considered for applying faults. The line to line voltage of T5 is 500 kV and that of T7a and T7b is 735 kV. The transmission line, T5, is 100 km long and T7a and T7b are 130 km long. The single-ended and double-ended techniques were implemented to find the distance of faults on the transmission lines.

5.3 Simulated Cases

A total of 1250 different cases were simulated in EMTDC by applying different types of faults on transmission lines and by assuming different values of fault location, fault resistance and fault inception angle. The cases were run with the time-step of 1 μs. The data generated by running these cases was saved in a personal computer.
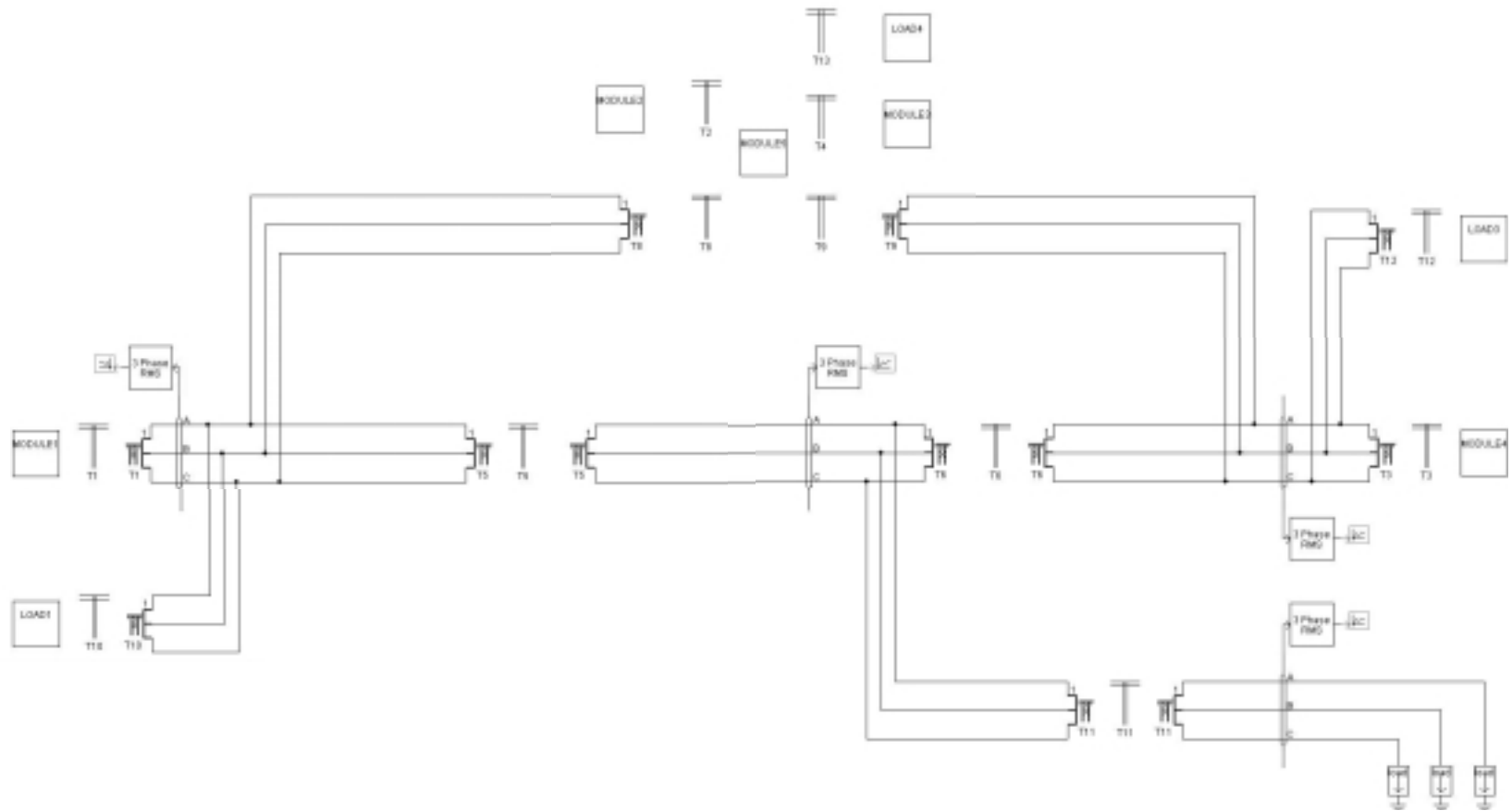
Figure 5.1: Model of the test power system in EMTDC
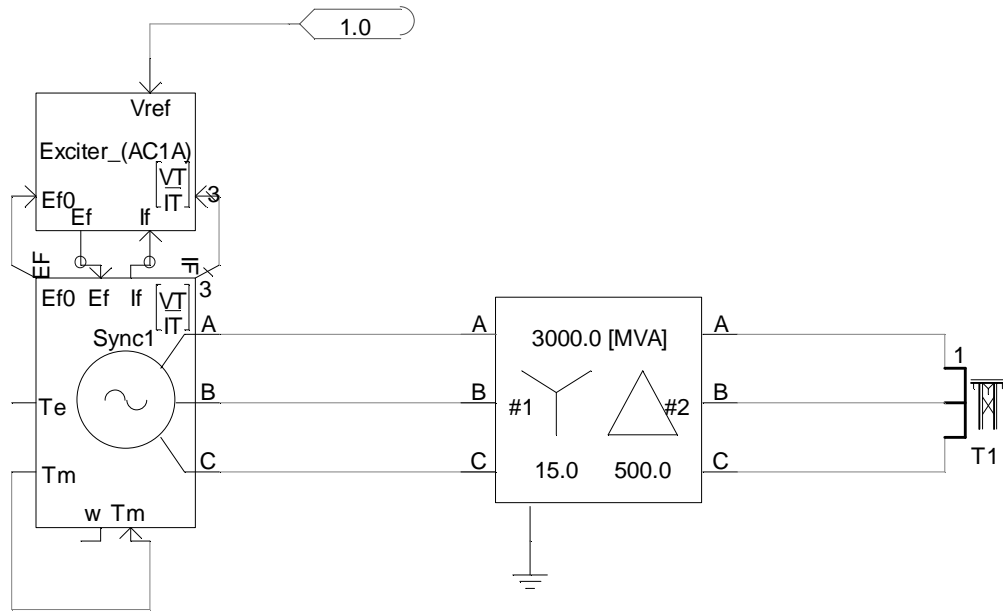
Figure 5.2: Model of a source and a transformer in EMTDC
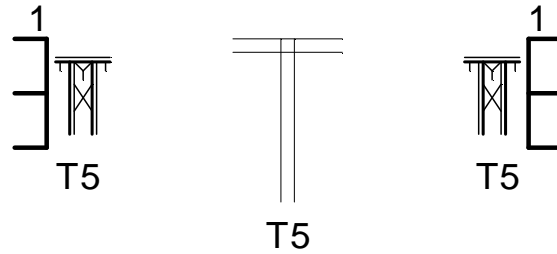
Figure 5.3: Model of a transmission line in EMTDC
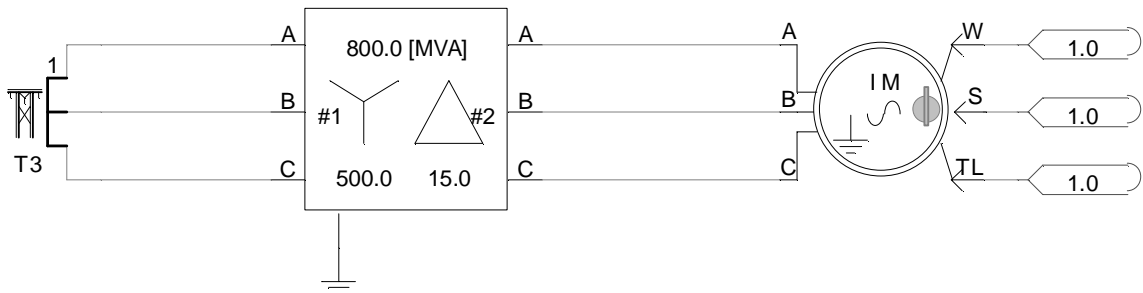
Figure 5.4: Model of a transformer and a machine in EMTDC
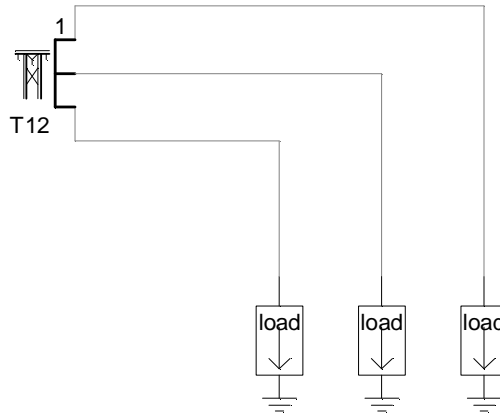
Figure 5.5: Model of a load in EMTDC

5.3.1 Fault Distance

Different types of faults ware applied at one km intervals on the 10 km sections adjacent to the terminals of the transmission lines. Faults were also applied at 10 km intervals on the remaining length of the lines. The traveling waves propagate with a finite velocity and their intensity decreases as the distance traveled increases. A traveling wave originated at a farther location takes longer time to reach the relay than a wave originated at a nearer location.

5.3.2 Fault Types

The types of faults applied on the transmission lines are

1. single phase to ground fault,
2. double phase fault,
3. double phase to ground fault, and
4. three phase fault.

When a fault occurs, the traveling waves also exist on the healthy phases due to the mutual coupling between the conductors of the transmission line.

5.3.3 Fault Resistance

The intensity of the traveling waves decreases with the increase in the value of fault resistance. The cases were simulated by assuming the following values of fault resistance.

1. 3 ohm,

2. 15 ohm,

3. 50 ohm, and

4. 100 ohm.

5.3.4 Fault Inception Angle

The intensity of a traveling wave largely depends on the angle of the voltage wave at the time of occurrence of the fault. When the fault inception angle is close to 90º, the intensity of a generated traveling wave is highest. The intensity of a traveling wave decreases with the deviation of the fault inception angle from 90º. No traveling waves are generated, if, the voltage angle is close to 0º at the time of occurrence of a fault. Cases were developed with the fault inception angle equal to 90º, 60º, 30º and 0º.

5.4 Effect of Transformer on Traveling Waves

When a traveling wave encounters an inductance at a terminal of a line, the inductance appears to be an open circuit initially because the initial current in the inductor is zero. Gradually, the current starts increasing, and ultimately, the inductance appears to be a short circuit. The wave reflected by the inductor initially has the same polarity as the polarity of the incident wave [6]. The transformers have high inductive reactance and therefore, the voltage and current traveling waves reflected by a transformer have initially the same polarities as the polarities of the incident waves. The traveling waves reflected from a transformer, therefore, do not exhibit the up-down pattern in the outputs of the current sequence filters as observed in the waves reflected from buses on which no transformers connected to them. The EHV transmission line, T7a, has transformers at its terminals. The sample of the output of a sequence filter at T7a is shown in Figure 5.6.

A capacitance in the path of traveling waves appears to the wave as a short circuit initially. Gradually, the charge builds up on the capacitor and the capacitor acts as an open circuit [6].

5.5 Case Discussion

The cases with the single-ended and double-ended techniques, implemented for protecting EHV transmission lines, T5, T7a and T7b, are discussed in the following sections.

5.5.1 Single-Ended Technique Cases

The six cases with the single-ended technique are discussed. In three of the six cases, a fault is applied on the transmission line, T7a, and in other three, a fault is applied on the transmission line, T5.

5.5.1.1 Phase 'a' to Ground Fault at 10 km on Transmission Line T7a

A phase 'a' to ground fault, at a distance of 10 km from bus B7, is applied on the transmission line, T7a. The high-speed digital relays, located at bus B7 and B9, take phase voltages and currents as inputs from the system. The aerial modes, 1 and 2, of the voltages and currents are calculated and then, passed through the sequence filters. The outputs of the sequence filters are shown in Figures 5.6, 5.7, 5.8 and 5.9. The spikes in the outputs indicate the arrival of traveling waves at the relays. The different polarities of the spikes in the outputs of the voltage and current sequence filters at bus B7 confirm the occurrence of a fault. The spikes are not present in the outputs of the sequence filters on line T7b; therefore, the line is healthy. The time recorded by the relay on line T7a, at the arrival of the first set of traveling waves, is 133 μs. The set of traveling waves, which arrived after reflection from the fault, is recorded by the relay at the time, 199 μs. The distance of fault, calculated by the relay, is as follows

$$D = \frac{(0.000199 - 0.000133)}{2} \times v = 9.89 \text{ km}$$

where, v, the velocity of propagation of the traveling waves = 299792.468 km/s.

The calculated distance is less than the length of the transmission line; therefore, a fault has occurred on the transmission line, T7a. Relay sends a trip signal to the circuit breakers and the line is isolated from the rest of the system.

5.5.1.2 Phase 'a' to 'b' to Ground Fault at 60 km on Transmission Line T7a

A phase 'a' to 'b' to ground fault, at a distance of 60 km from bus B7, is applied on the transmission line, T7a. The high-speed digital relays, located at bus B7 and B9, take phase voltages and currents as inputs from the system. The aerial modes, 1 and 2, of the voltages and currents are calculated and then, passed through the sequence filters. The outputs of the sequence filters are shown in Figures 5.14, 5.15, 5.16 and 5.17. The spikes in the outputs indicate the arrival of traveling waves at the relays. The different polarities of the spikes in the outputs of the voltage and current sequence filters in relays, on line T7a, confirm the occurrence of a fault. The spikes are not present in the outputs of the sequence filters of relays on line T7b; therefore, the line is healthy. The time recorded by the relay on line T7a, at the arrival of the first set of traveling waves, is 300 μs. The set of traveling waves, which arrived after reflection from the fault, is recorded by the relay at the time, 700 μs. The distance of fault, calculated by the relay, is as follows

$$D = \frac{(0.000700 - 0.000300)}{2} \times 299792.458 = 59.96 \text{ km}$$

The calculated distance is less than the length of the transmission line; therefore, a fault has occurred on the transmission line, T7a. Relay sends a trip signal to the circuit breakers and the line is isolated from the rest of the system.

5.5.1.3 Phase 'b' to 'c' Fault at 110 km on Transmission Line T7a

A phase 'b' to 'c' fault, at a distance of 110 km from bus B7, is applied on the transmission line, T7a. The relays calculate the aerial modes of the voltages and currents and pass them through the sequence filters. The outputs of the filters are shown in Figures 5.22, 5.23, 5.24 and 5.25. The different polarities of the spikes in the outputs of the voltage and current sequence filters of relays on line T7a confirm the occurrence of a fault. The time recorded by the relay, at the arrival of the first set of traveling waves, is 467 μs. The time, when the set of traveling waves, arrived after the reflection from the fault, is recorded by the relay as 1201 μs. The distance of the fault is calculated as follows

$$D = \frac{(0.001201 - 0.000467)}{2} \times 299792.458 = 110.02 \text{ km}$$

The calculated distance is less than the length of the transmission line; therefore, a fault has occurred on the transmission line, T7a. Relay sends a trip signal to the circuit breakers and the line is isolated from the rest of the system.

5.5.1.4 Phase 'b' to Ground Fault at 20 km on Transmission Line T5

A phase 'b' to ground fault, at a distance of 20 km from bus B3, is applied on the transmission line, T5. The relays calculate the aerial modes of the voltages and currents and pass them through the sequence filters. The outputs of the filters are shown in Figures 5.30 and 5.31. The different polarities of the spikes in the outputs of the voltage and current sequence filters confirm the occurrence of a fault. The time recorded by the relay, at the arrival of the first set of traveling waves, is 167 μs. The time, when the set of traveling waves, arrived after the reflection from the fault, is recorded by the relay as 300 μs. The distance of the fault is calculated as follows

$$D = \frac{(0.000300 - 0.000167)}{2} \times 299792.458 = 19.94 \text{ km}$$

The calculated distance is less than the length of the transmission line; therefore, a fault has occurred on the transmission line, T5. Relay sends a trip signal to the circuit breakers and the line is isolated from the rest of the system.

5.5.1.5 Phase 'a' to 'b' to 'c' to Ground Fault at 70 km on Transmission Line T5

A phase 'a' to 'b' to 'c' to ground fault, at a distance of 70 km from bus B3, is applied on the transmission line, T5. The relays calculate the aerial modes of the voltages and currents and pass them through the sequence filters. The outputs of the filters are shown in Figures 5.34 and 5.35. The different polarities of the spikes in the outputs of the voltage and current sequence filters confirm the occurrence of a fault. The time recorded by the relay, at the arrival of the first set of traveling waves, is 334 μs. The time, when the set of traveling waves, arrived after the reflection from the fault, is recorded by the relay as 801 μs. The distance of the fault is calculated as follows

$$D = \frac{(0.000801 - 0.000334)}{2} \times 299792.458 = 70.00 \text{ km}$$

The calculated distance is less than the length of the transmission line; therefore, a fault has occurred on the transmission line, T5. Relay sends a trip signal to the circuit breakers and the line is isolated from the rest of the system.

5.5.1.6 Phase 'c' to 'a' Fault at 90 km on Transmission Line T5

A phase 'c' to 'a' fault, at a distance of 90 km from bus B3, is applied on the transmission line, T5. The relays calculate the aerial modes of the voltages and currents and pass them through the sequence filters. The outputs of the filters are shown in Figures 5.38 and 5.39. The different polarities of the spikes in the outputs of the voltage and current sequence filters confirm the occurrence of a fault. The time recorded by the relay, at the arrival of the first set of traveling waves, is 400 μs. The time, when the set of traveling waves, arrived after the reflection from the fault, is recorded by the relay as 1002 μs. The distance of the fault is calculated as follows

$$D = \frac{(0.001002 - 0.000400)}{2} \times 299792.458 = 90.24 \text{ km}$$

The calculated distance is less than the length of the transmission line; therefore, a fault has occurred on the transmission line, T5. Relay sends a trip signal to the circuit breakers and the line is isolated from the rest of the system.

5.5.2 Double-Ended Technique Cases

The cases, given in the previous section, are discussed in this section with the double-ended technique implementation.

5.5.2.1 Phase 'a' to Ground Fault at 10 km on Transmission Line T7a

A phase 'a' to ground fault, at a distance of 10 km from bus B7, is applied on the transmission line, T7a. The high-speed digital relays, located at the terminals of the transmission lines, T7a and T7b, take phase voltages and currents as inputs from the system. The aerial modes, 1 and 2, of the voltages and currents are calculated and then, passed through the sequence filters. The outputs of the sequence filters are shown in Figures 5.6, 5.7, 5.8, 5.9, 5.10, 5.11, 5.12 and 5.13. The first spikes in the outputs of sequence filters on line T7a indicate the arrival of initial traveling waves at the relays. The different polarities of the voltage and current spikes confirm the occurrence of a

fault. The spikes are not present in the outputs of the sequence filters of relays on line T7b; therefore, the line is healthy. The time recorded by the relays at bus B7 and bus B8 on arrival of the first set of traveling waves is 133 μs and 500 μs respectively. The relay, at bus B8, sends the recorded time to the relay at bus B7. The difference of the time recorded by the relay is

$$T_d = |133 - 500|$$

$$T_d = 367 \, \mu s$$

The time taken by a traveling wave to cover the full length of the line can be calculated as

$$T = \frac{L}{v}$$

where, L, the length of the transmission line = 130 km, and

v, the velocity of propagation of the traveling waves = 299792.468 km/s.

Therefore,

$$T = 434 \, \mu s$$

Since, $T_d < T$, the fault is on the protected line. The relays send the trip signals to the circuit breakers to isolate the faulted line from the rest of the system.

The distance of the fault is calculated by using Equation 3.17 as

$$D = \left(0.000133 - 0.000500 + \left(\frac{130}{299792.458} \right) \right) \times \frac{299792.458}{2}$$

$$= 9.99 \, \text{km}$$

5.5.2.2 Phase 'a' to 'b' to Ground Fault at 60 km on Transmission Line T7a

A phase 'a' to 'b' to ground fault, at a distance of 60 km from bus B7, is applied on the transmission line, T7a. The high-speed digital relays, located at the terminals of the transmission lines, T7a and T7b, take phase voltages and currents as inputs from the system. The aerial modes, 1 and 2, of the voltages and currents are calculated and then, passed through the sequence filters. The outputs of the sequence filters are shown in Figures 5.14, 5.15, 5.16, 5.17, 5.18, 5.19, 5.20 and 5.21. The first spikes in the outputs of filters on the line T7a indicate the arrival of initial traveling waves at the relays. The different polarities of the spikes in the outputs of the voltage and current sequence filters

confirm the occurrence of a fault. The spikes are not present in the outputs of the sequence filters of relays on line T7b; therefore, the line is healthy. The time recorded by the relays at bus B7 and bus B8 on arrival of the first set of traveling waves is 300 μs and 333 μs respectively. The relay, at bus B8, sends the recorded time to the relay at bus B7. The difference of the time recorded by the relay is

$$T_d = |300 - 333|$$

$$T_d = 33\,\mu s$$

The time taken by a traveling wave to cover the full length of the line is

$$T = 434\,\mu s$$

Since, $T_d < T$, the fault is on the protected line. The relays send the trip signals to the circuit breakers to isolate the faulted line from the rest of the system.

The distance of the fault, calculated by the relay at bus B7, is as follows

$$D = \left(0.000300 - 0.000333 + \left(\frac{130}{299792.458}\right)\right) \times \frac{299792.458}{2}$$

$$= 60.05\ \text{km}$$

5.5.2.3 Phase 'b' to 'c' Fault at 110 km on Transmission Line T7a

A phase 'b' to 'c' fault, at a distance of 110 km from bus B7, is applied on the transmission line, T7a. The high-speed digital relays calculate the aerial modes, 1 and 2, of the voltages and currents and pass them through the sequence filters. The outputs of the filters are shown in Figures 5.22, 5.23, 5.24, 5.25, 5.26, 5.27, 5.28 and 5.29. The different polarities of the spikes in the outputs of the voltage and current sequence filters on line T7a confirm the occurrence of a fault. The time recorded by the relays at bus B7 and bus B8 on arrival of the first set of traveling waves is 467 μs and 166 μs respectively. The relay, at bus B8, sends the recorded time to the relay at bus B7. The difference of the time recorded by the relay is

$$T_d = |467 - 166|$$

$$T_d = 301\,\mu s$$

The time taken by a traveling wave to cover the full length of the line is

$$T = 434\,\mu s$$

Since, $T_d < T$, the fault is on the protected line. The relays send the trip signals to the circuit breakers to isolate the faulted line from the rest of the system.

The distance of the fault, calculated by the relay at bus B7, is as follows

$$D = \left(0.000467 - 0.000166 + \left(\frac{130}{299792.458}\right)\right) \times \frac{299792.458}{2}$$

$$= 110.12 \text{ km}$$

5.5.2.4 Phase 'b' to Ground Fault at 20 km on Transmission Line T5

A phase 'b' to ground fault, at a distance of 20 km from bus B3, is applied on the transmission line, T5. The high-speed digital relays calculate the aerial modes, 1 and 2, of the voltages and currents and pass them through the sequence filters. The outputs of the filters are shown in Figures 5.30, 5.31, 5.32 and 5.33. The different polarities of the spikes in the outputs of the voltage and current sequence filters on the line confirm the occurrence of a fault. The time recorded by the relays at bus B3 and bus B4 on arrival of the first set of traveling waves is 167 μs and 367 μs respectively. The relay, at bus B4, sends the recorded time to the relay at bus B3. The difference of the time recorded by the relay is

$$T_d = |167 - 367|$$

$$T_d = 200 \text{ μs}$$

The time taken by a traveling wave to cover the full length of the line is

$$T = 334 \text{ μs}$$

Since, $T_d < T$, the fault is on the protected line. The relays send the trip signals to the circuit breakers to isolate the faulted line from the rest of the system.

The distance of the fault, calculated by the relay at bus B3, is as follows

$$D = \left(0.000167 - 0.000367 + \left(\frac{100}{299792.458}\right)\right) \times \frac{299792.458}{2}$$

$$= 20.02 \text{ km}$$

5.5.2.5 Phase 'a' to 'b' to 'c' to Ground Fault at 70 km on Transmission Line T5

A phase 'a' to 'b' to 'c' to ground fault, at a distance of 70 km from bus B3, is applied on the transmission line, T5. The high-speed digital relays calculate the aerial modes, 1 and 2, of the voltages and currents and pass them through the sequence filters. The outputs of the filters are shown in Figures 5.34, 5.35, 5.36 and 5.37. The different polarities of the spikes in the outputs of the voltage and current sequence filters confirm the occurrence of a fault. The time recorded by the relays at bus B3 and bus B4 on arrival of the first set of traveling waves is 334 μs and 200 μs respectively. The relay, at bus B4, sends the recorded time to the relay at bus B3. The difference of the time recorded by the relay is

$$T_d = |334 - 200|$$

$$T_d = 134\,\mu s$$

The time taken by a traveling wave to cover the full length of the line is

$$T = 334\,\mu s$$

Since, $T_d < T$, the fault is on the protected line. The relays send the trip signals to the circuit breakers to isolate the faulted line from the rest of the system.

The distance of the fault, calculated by the relay at bus B3, is as follows

$$D = \left(0.000334 - 0.000200 + \left(\frac{100}{299792.458} \right) \right) \times \frac{299792.458}{2}$$

$$= 70.09\,km$$

5.5.2.6 Phase 'c' to 'a' Fault at 90 km on Transmission Line T5

A phase 'c' to 'a' fault, at a distance of 90 km from bus B3, is applied on the transmission line, T5. The high-speed digital relays calculate the aerial modes, 1 and 2, of the voltages and currents and pass them through the sequence filters. The outputs of the filters are shown in Figures 5.38, 5.39, 5.40 and 5.41. The different polarities of the spikes in the outputs of the voltage and current sequence filters confirm the occurrence of a fault. The time recorded by the relays at bus B3 and bus B4 on arrival of the first set

of traveling waves is 400 μs and 133 μs respectively. The relay, at bus B4, sends the recorded time to the relay at bus B3. The difference of the time recorded by the relay is

$$T_d = |400 - 133|$$

$$T_d = 267 \, \mu s$$

The time taken by a traveling wave to cover the full length of the line is

$$T = 334 \, \mu s$$

Since, $T_d < T$, the fault is on the protected line. The relays send the trip signals to the circuit breakers to isolate the faulted line from the rest of the system.

The distance of the fault, calculated by the relay at bus B3, is as follows

$$D = \left(0.000400 - 0.000133 + \left(\frac{100}{299792.458} \right) \right) \times \frac{299792.458}{2}$$

$$= 90.02 \, km$$

5.6 Summary

The type of fault, fault location, fault inception angle and fault resistance were the parameters, which were changed in EMTDC cases and data was generated. The performance of the high speed digital techniques was verified on the input data, obtained from the EMTDC by simulating a power system. A set of cases and their results are reported and discussed. Results show that the single-ended and double-ended techniques are suitable for protecting EHV transmission lines.
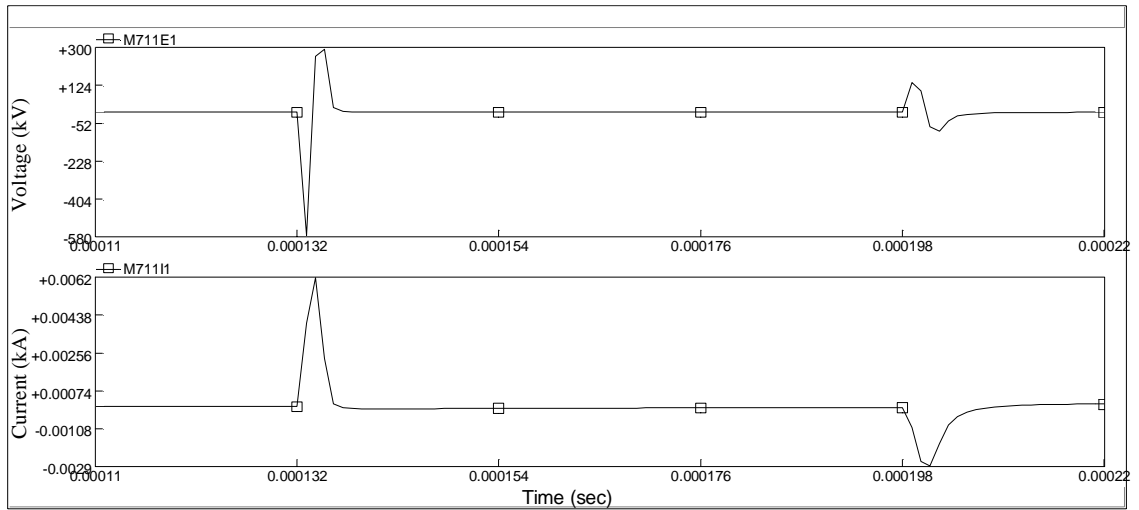
Figure 5.6: Output of mode 1 voltage and current sequence filters at bus B7 for phase 'a' to ground fault at 10 km on T7a
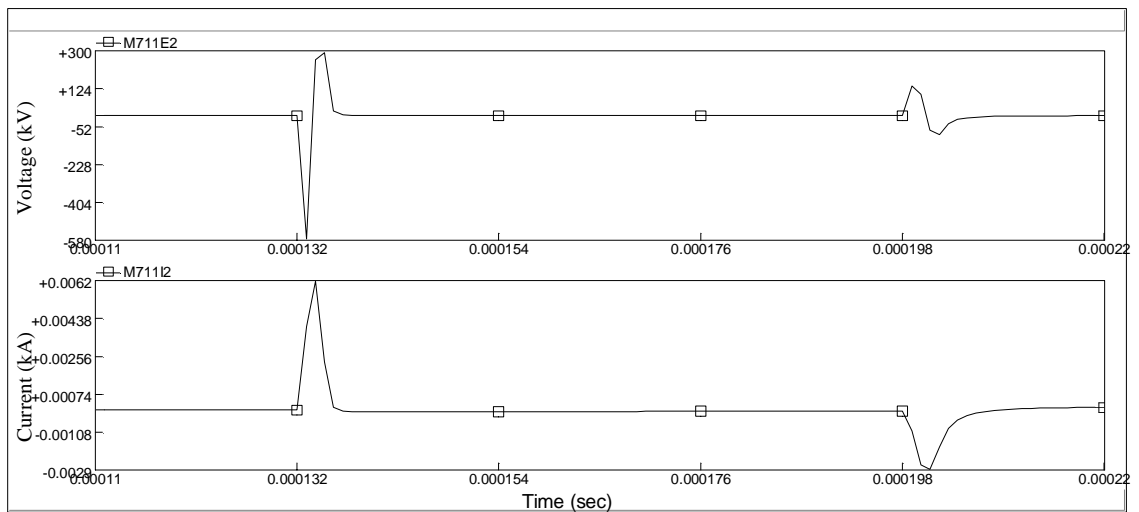
Figure 5.7: Output of mode 2 voltage and current sequence filters at bus B7 for phase 'a' to ground fault at 10 km on T7a
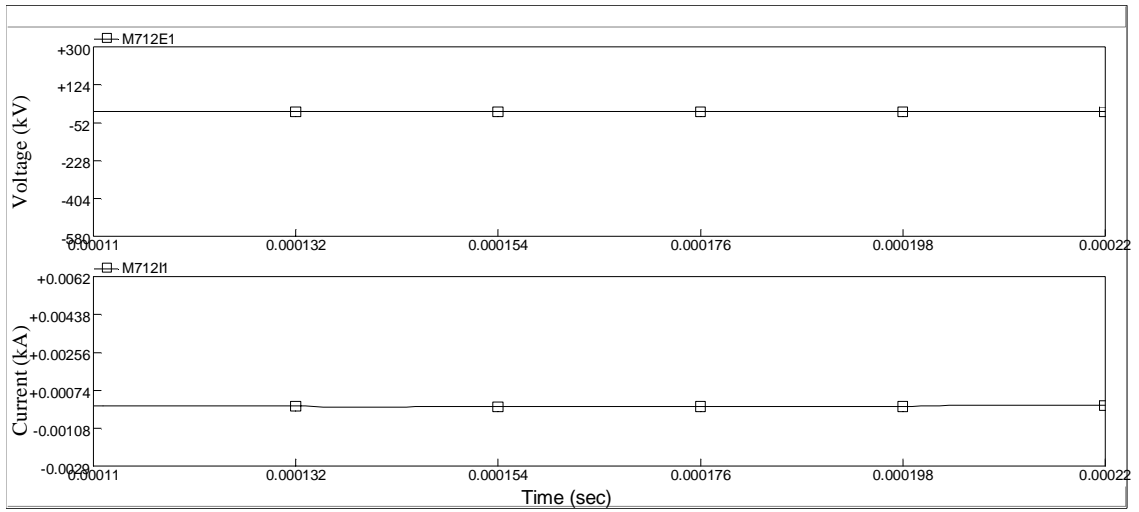
Figure 5.8: Output of mode 1 voltage and current sequence filters at bus B9 for phase 'a' to ground fault at 10 km on T7a
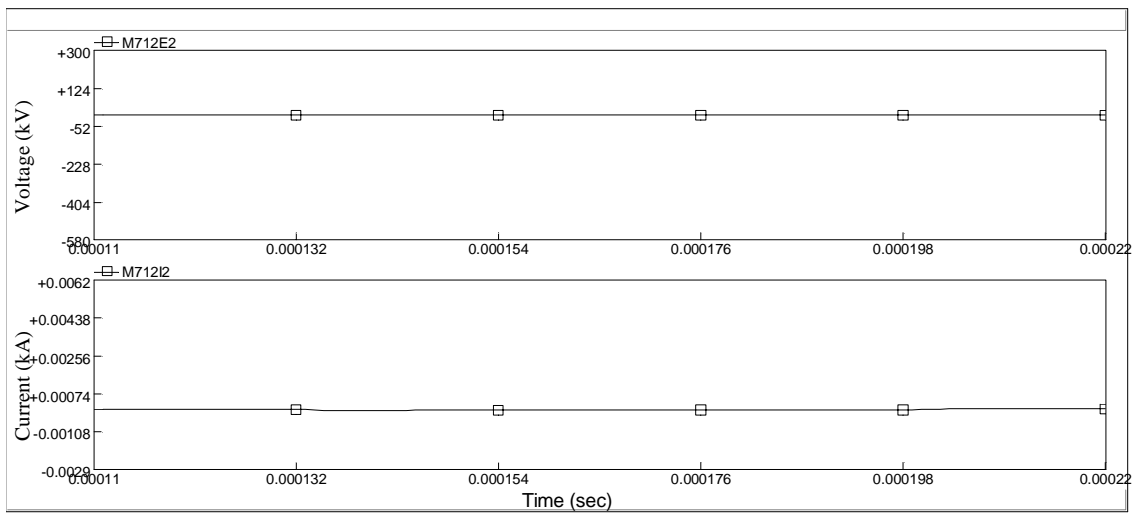
Figure 5.9: Output of mode 2 voltage and current sequence filters at bus B9 for phase 'a' to ground fault at 10 km on T7a
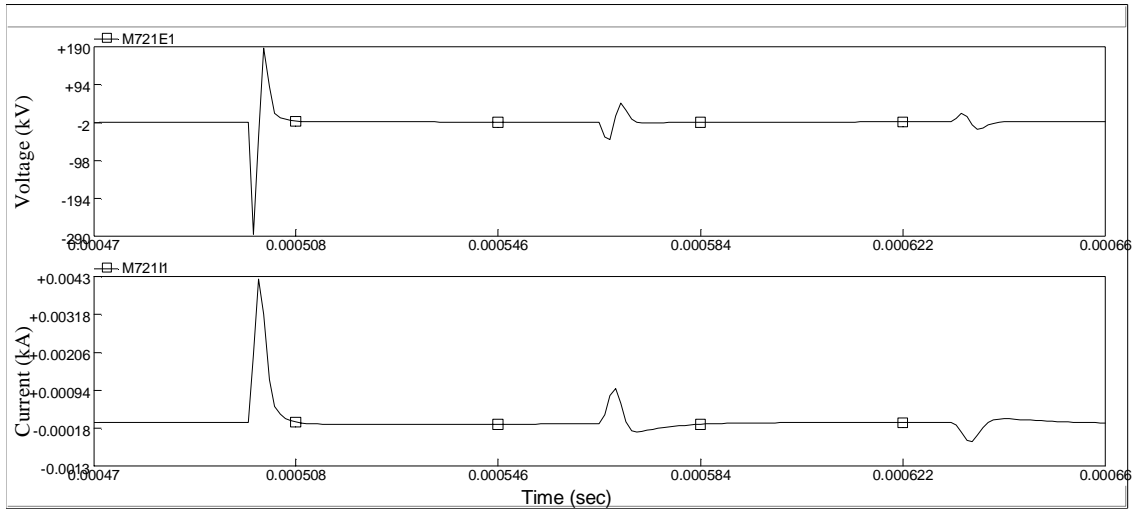
Figure 5.10: Output of mode 1 voltage and current sequence filters at bus B8 for phase 'a' to ground fault at 10 km on T7a
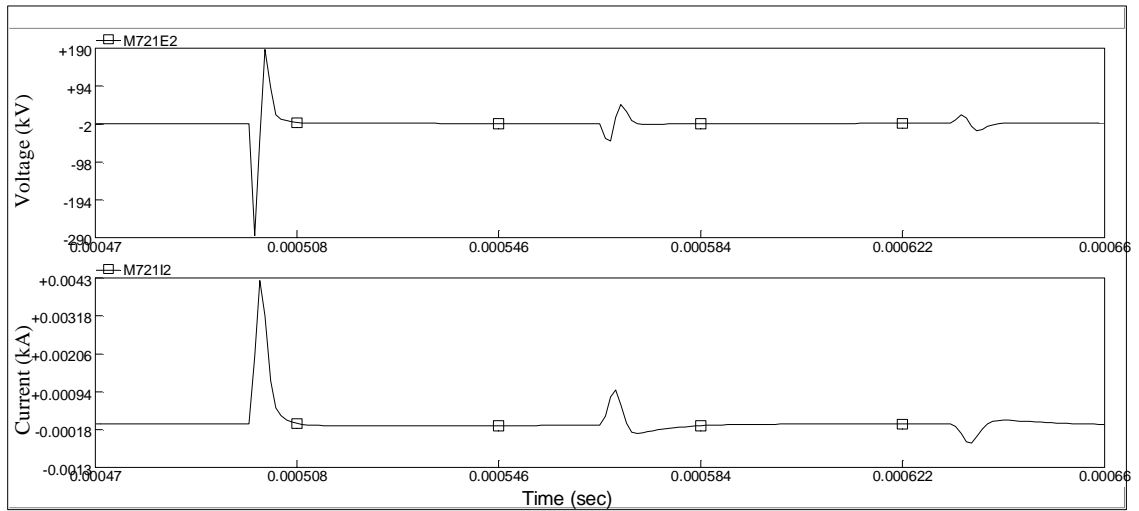
Figure 5.11: Output of mode 2 voltage and current sequence filters at bus B8 for phase 'a' to ground fault at 10 km on T7a
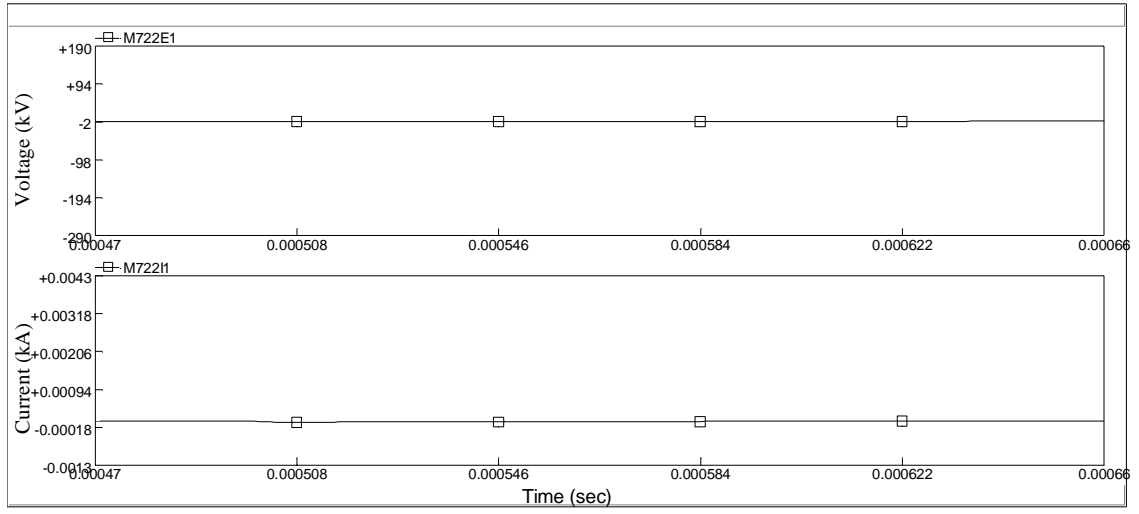
Figure 5.12: Output of mode 1 voltage and current sequence filters at bus B10 for phase 'a' to ground fault at 10 km on T7a
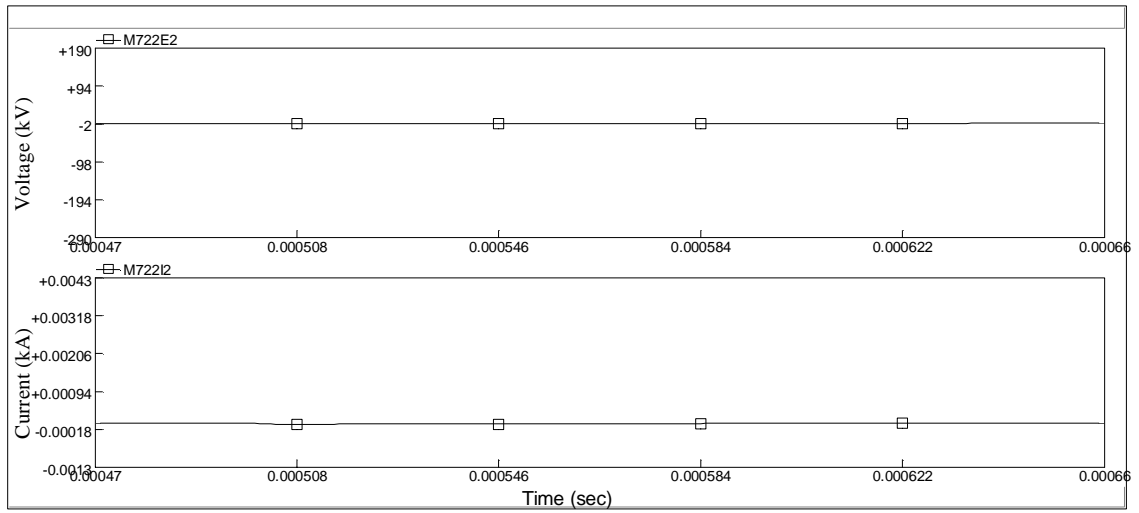
Figure 5.13: Output of mode 2 voltage and current sequence filters at bus B10 for phase 'a' to ground fault at 10 km on T7a
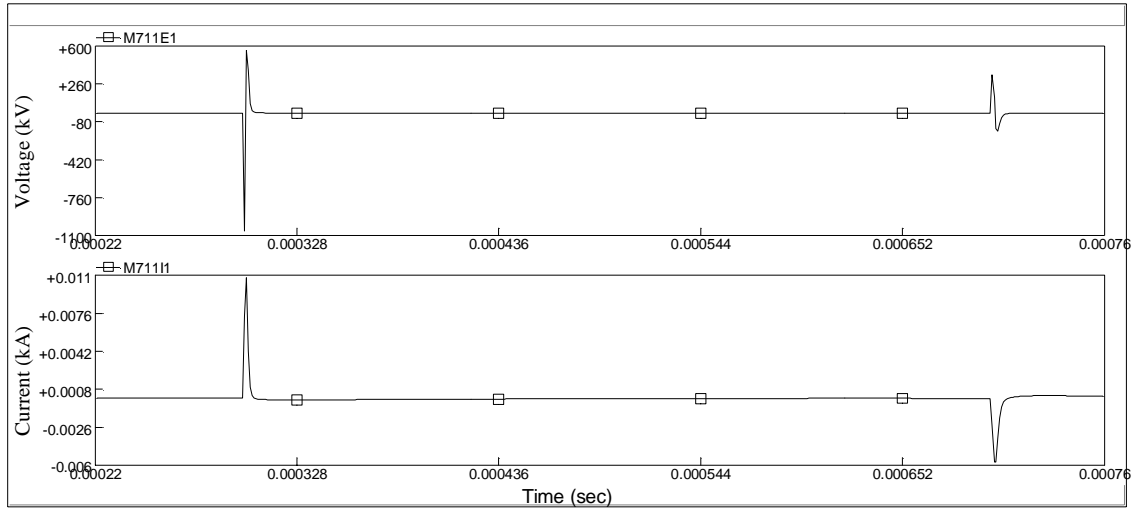
Figure 5.14: Output of mode 1 voltage and current sequence filters at bus B7 for phase 'a' to 'b' to ground fault at 60 km on T7a
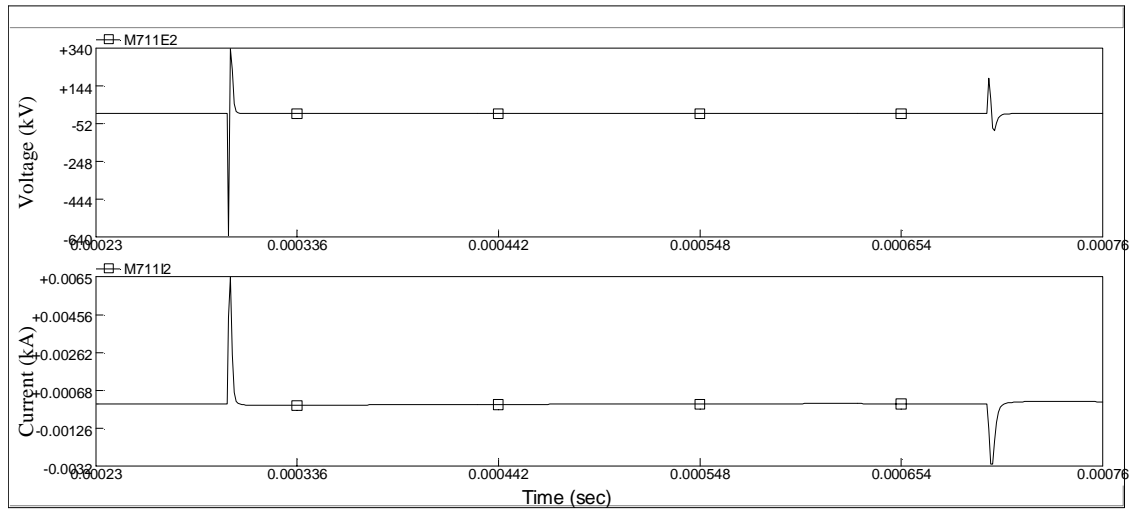
Figure 5.15: Output of mode 2 voltage and current sequence filters at bus B7 for phase 'a' to 'b' to ground fault at 60 km on T7a
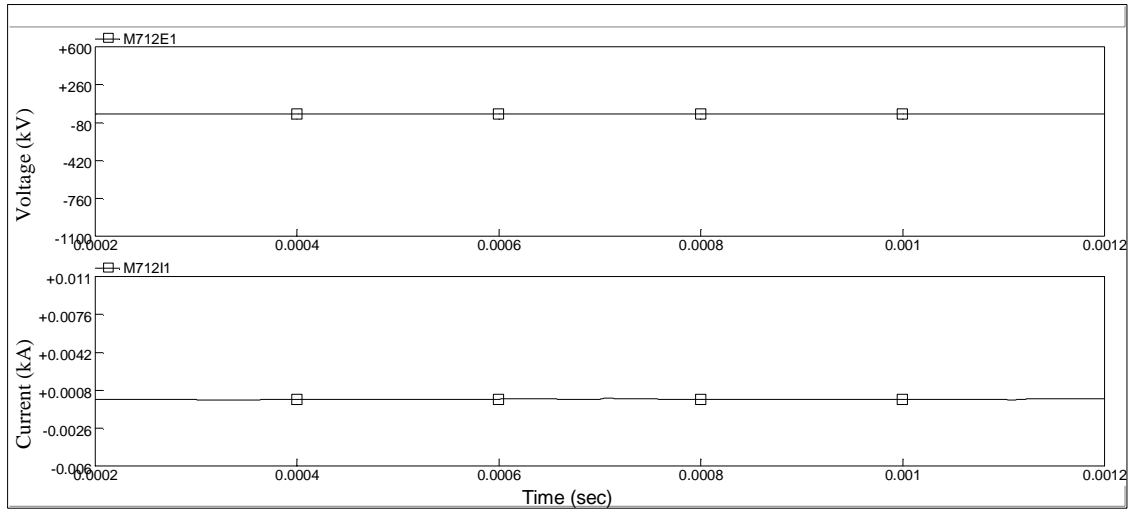
Figure 5.16: Output of mode 1 voltage and current sequence filters at bus B9 for phase 'a' to 'b' to ground fault at 60 km on T7a
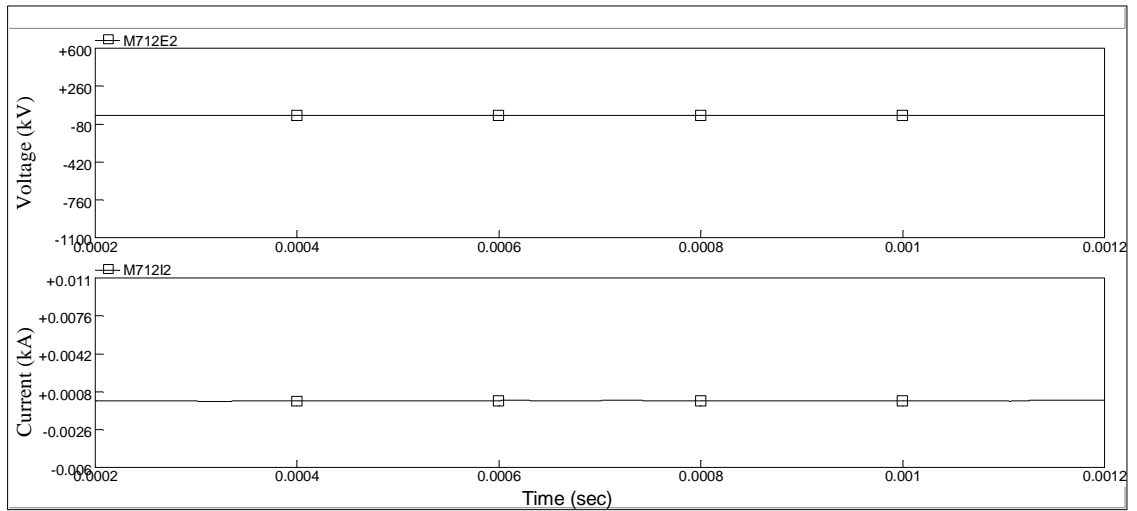
Figure 5.17: Output of mode 2 voltage and current sequence filters at bus B9 for phase 'a' to 'b' to ground fault at 60 km on T7a
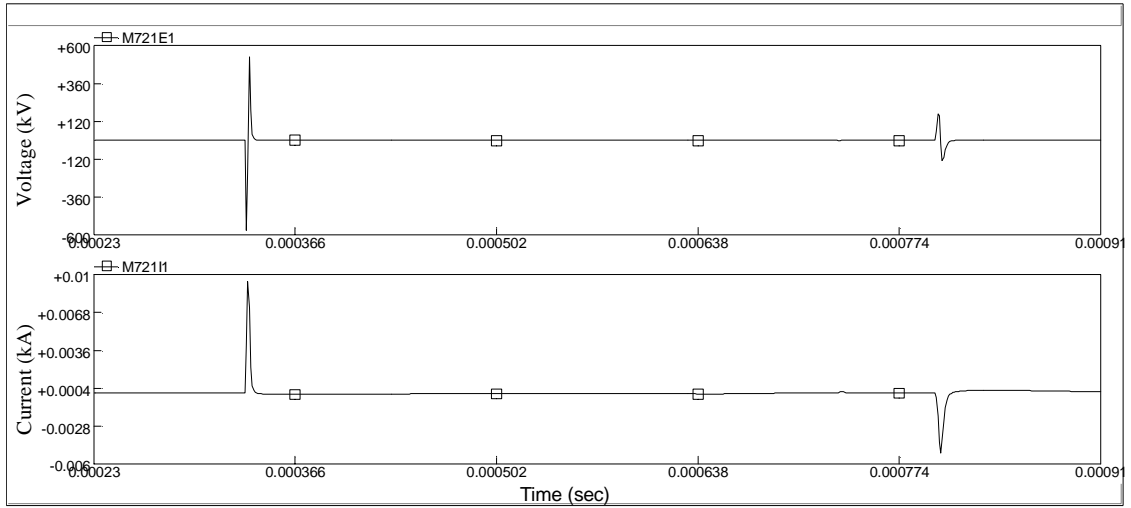
Figure 5.18: Output of mode 1 voltage and current sequence filters at bus B8 for phase 'a' to 'b' to ground fault at 60 km on T7a
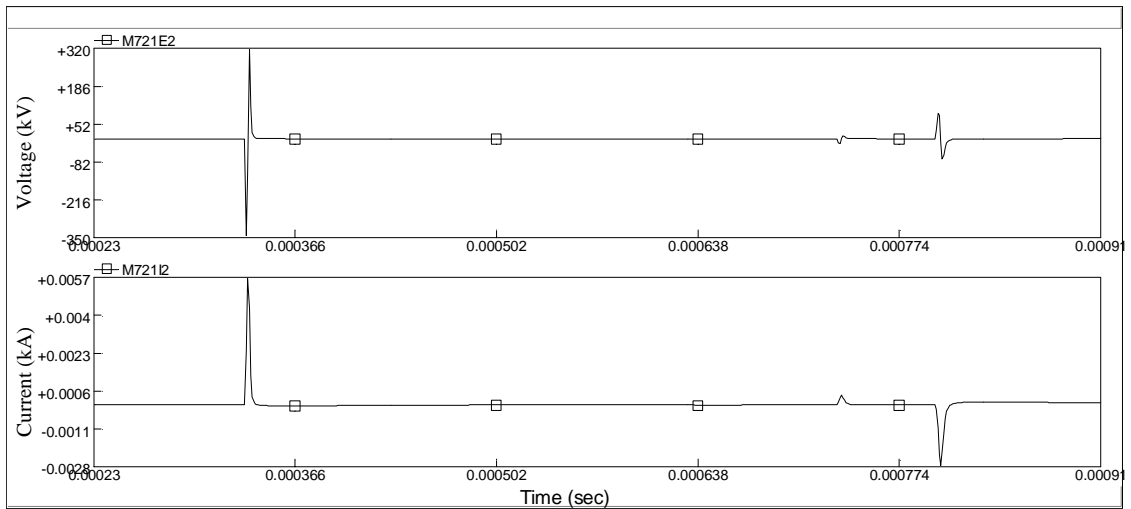
Figure 5.19: Output of mode 2 voltage and current sequence filters at bus B8 for phase 'a' to 'b' to ground fault at 60 km on T7a

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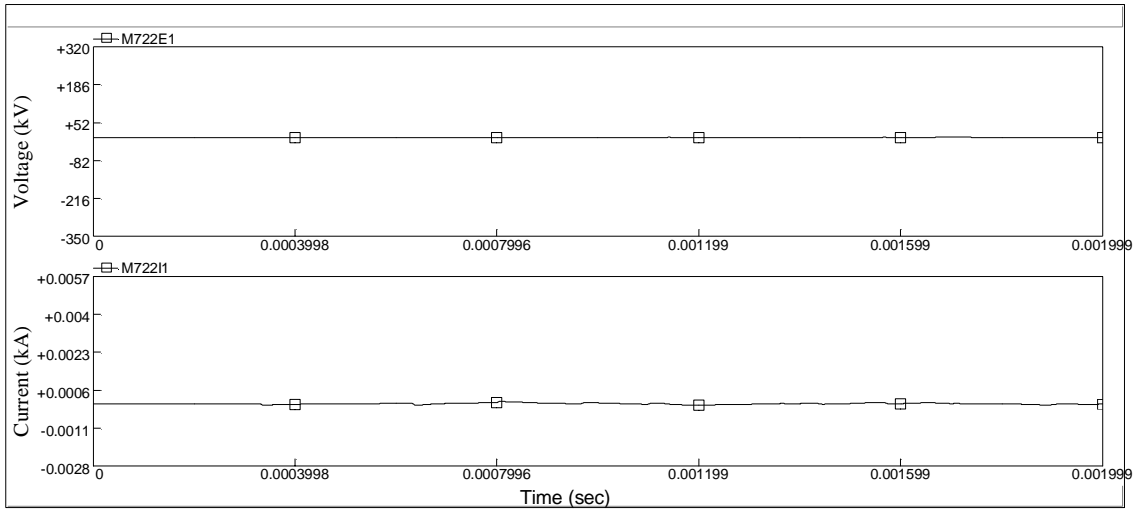
Figure 5.20: Output of mode 1 voltage and current sequence filters at bus B10 for phase 'a' to 'b' to ground fault at 60 km on T7a
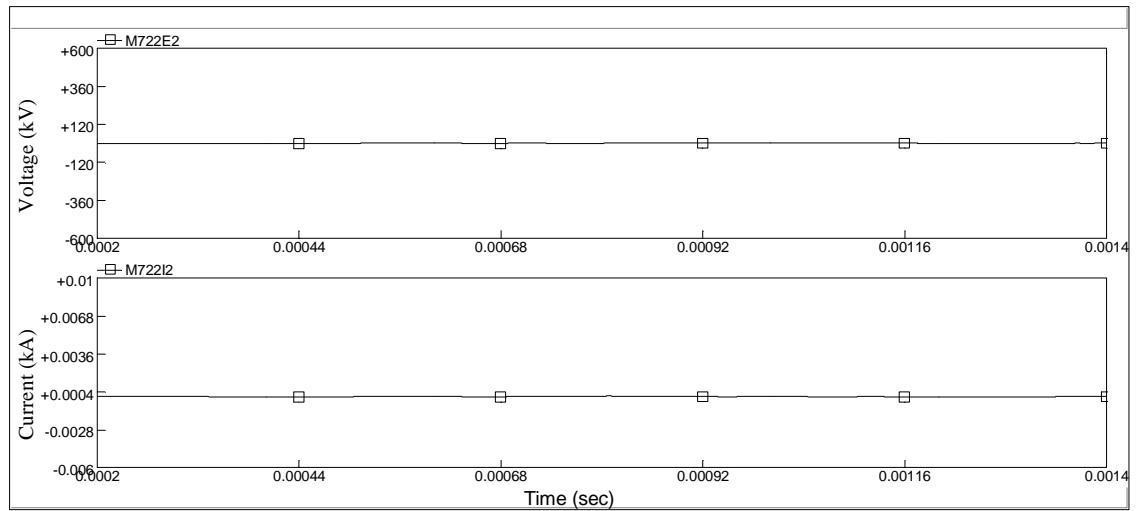
Figure 5.21: Output of mode 2 voltage and current sequence filters at bus B10 for phase 'a' to 'b' to ground fault at 60 km on T7a
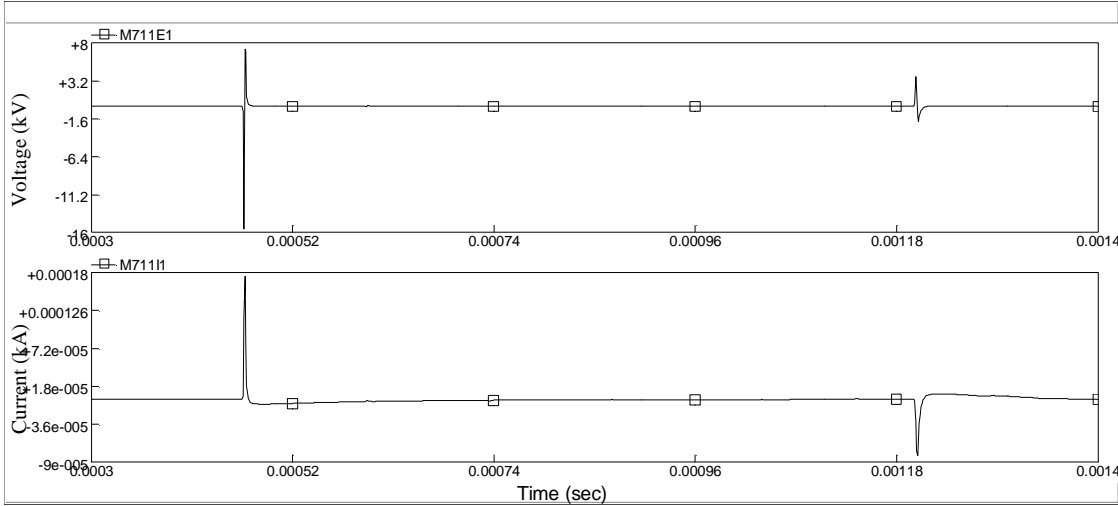
Figure 5.22: Output of mode 1 voltage and current sequence filters at bus B7 for phase 'b' to 'c' fault at 110 km on T7a
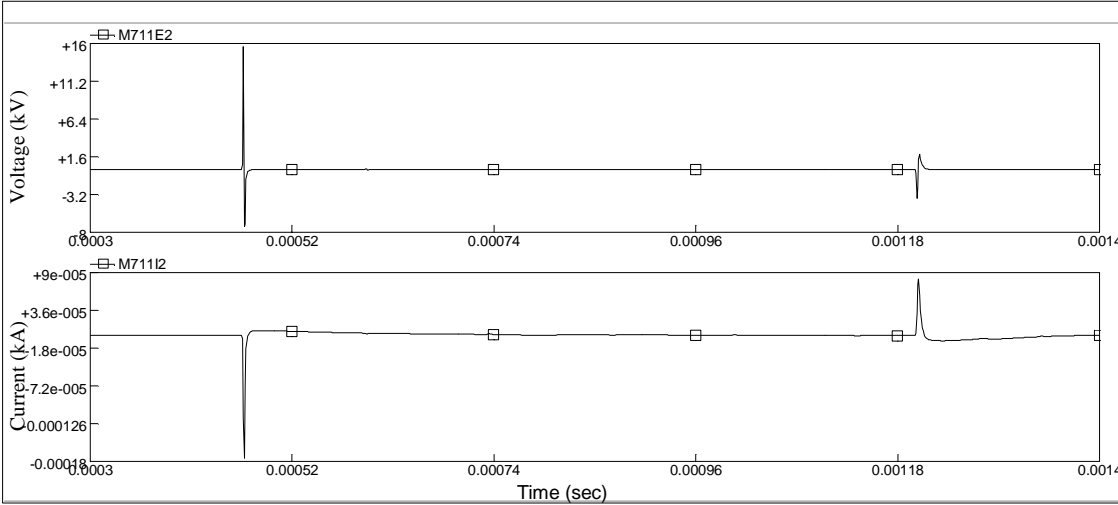
Figure 5.23: Output of mode 2 voltage and current sequence filters at bus B7 for phase 'b' to 'c' fault at 110 km on T7a
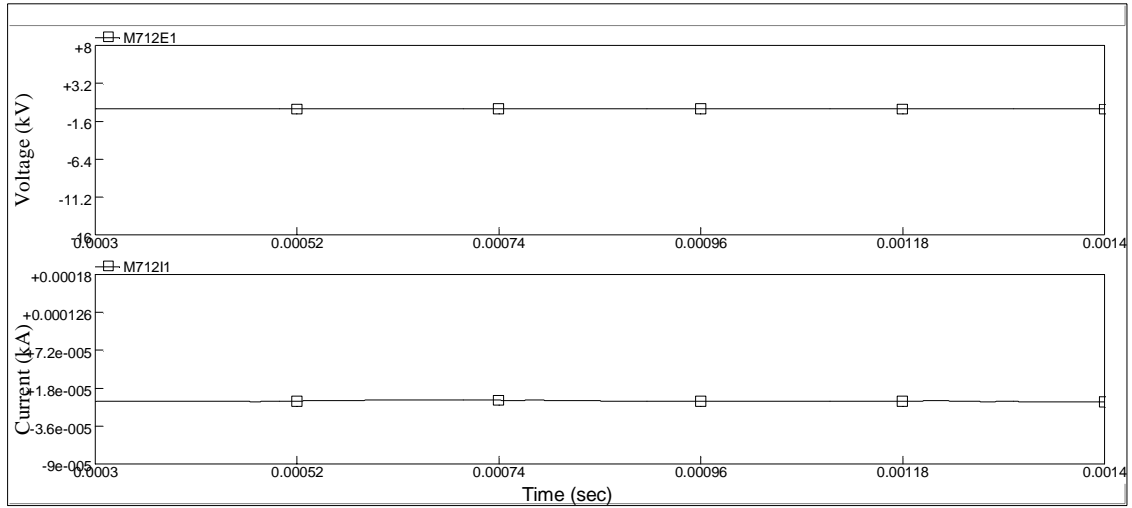
Figure 5.24: Output of mode 1 voltage and current sequence filters at bus B9 for phase 'b' to 'c' fault at 110 km on T7a
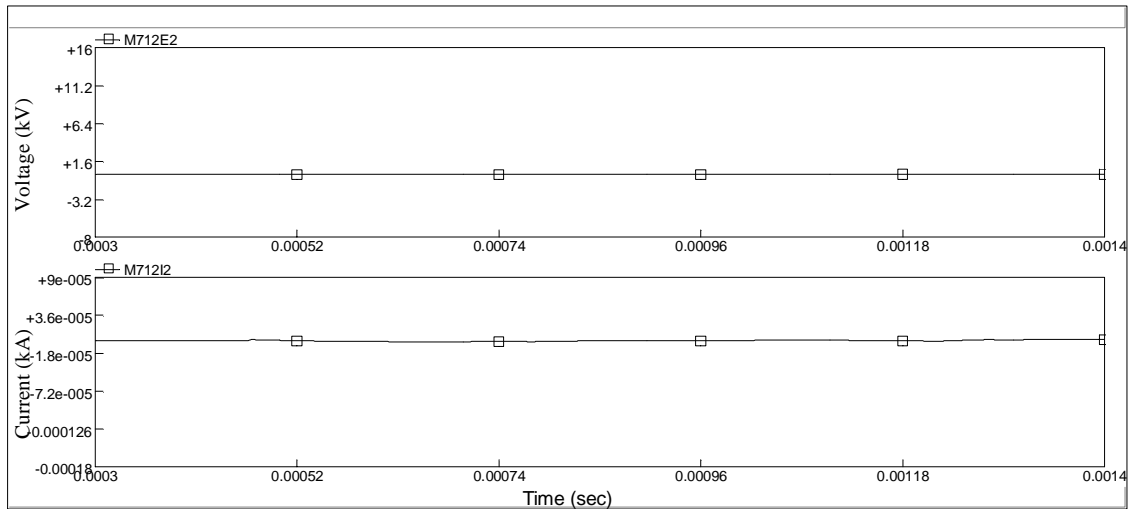
Figure 5.25: Output of mode 2 voltage and current sequence filters at bus B9 for phase 'b' to 'c' fault at 110 km on T7a
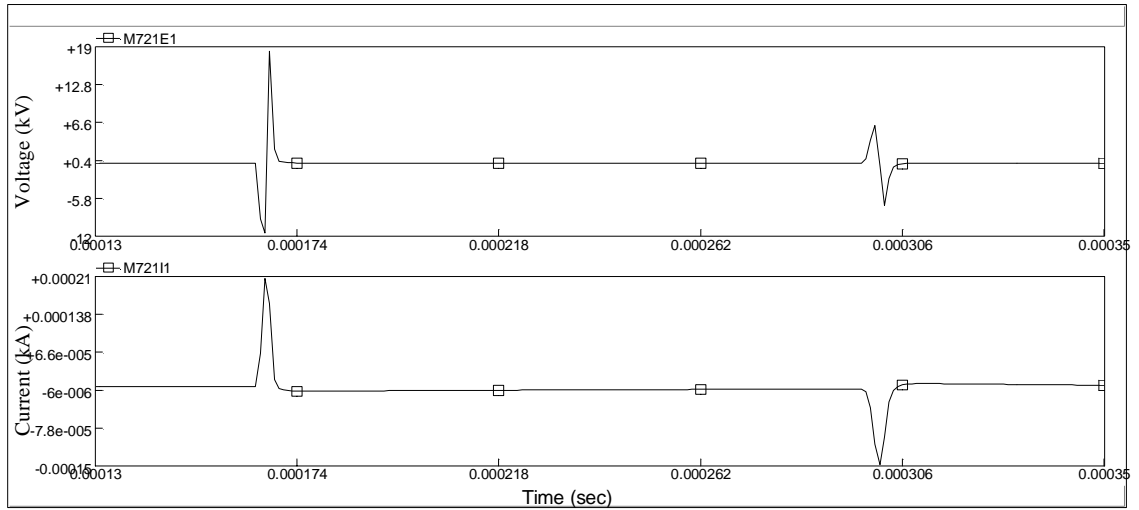
Figure 5.26: Output of mode 1 voltage and current sequence filters at bus B8 for phase 'b' to 'c' fault at 110 km on T7a
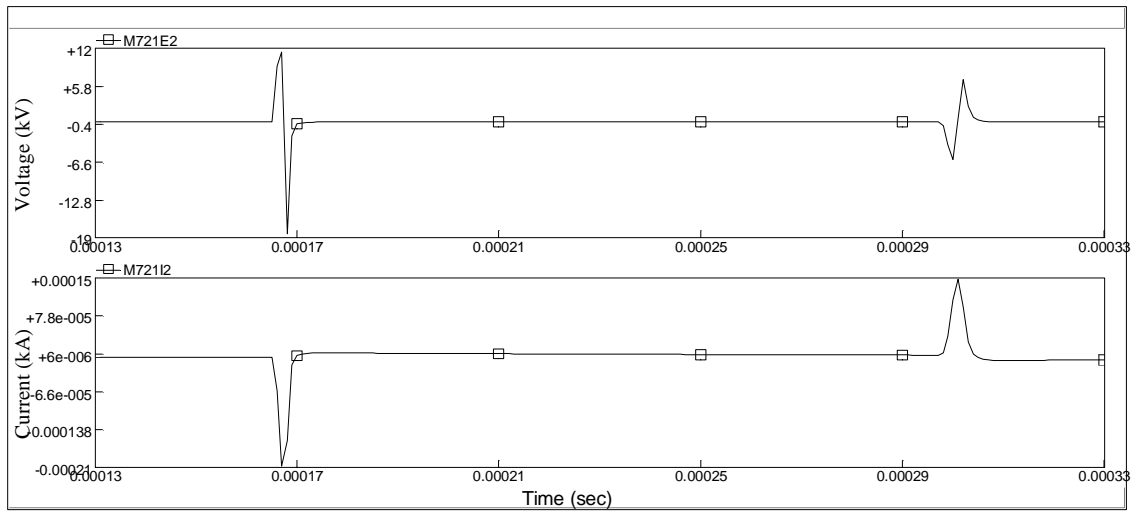
Figure 5.27: Output of mode 2 voltage and current sequence filters at bus B8 for phase 'b' to 'c' fault at 110 km on T7a
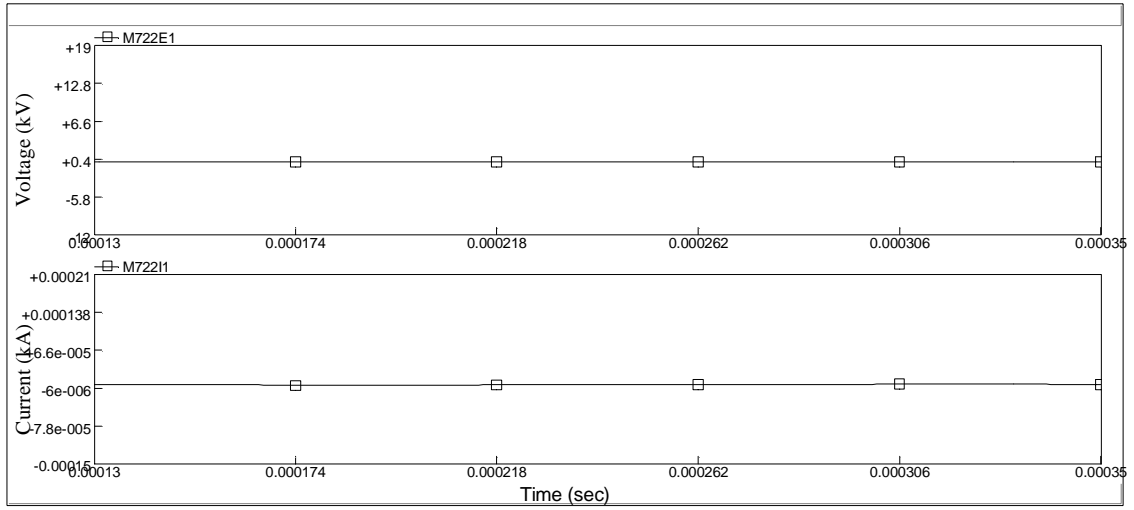
Figure 5.28: Output of mode 1 voltage and current sequence filters at bus B10 for phase 'b' to 'c' fault at 110 km on T7a
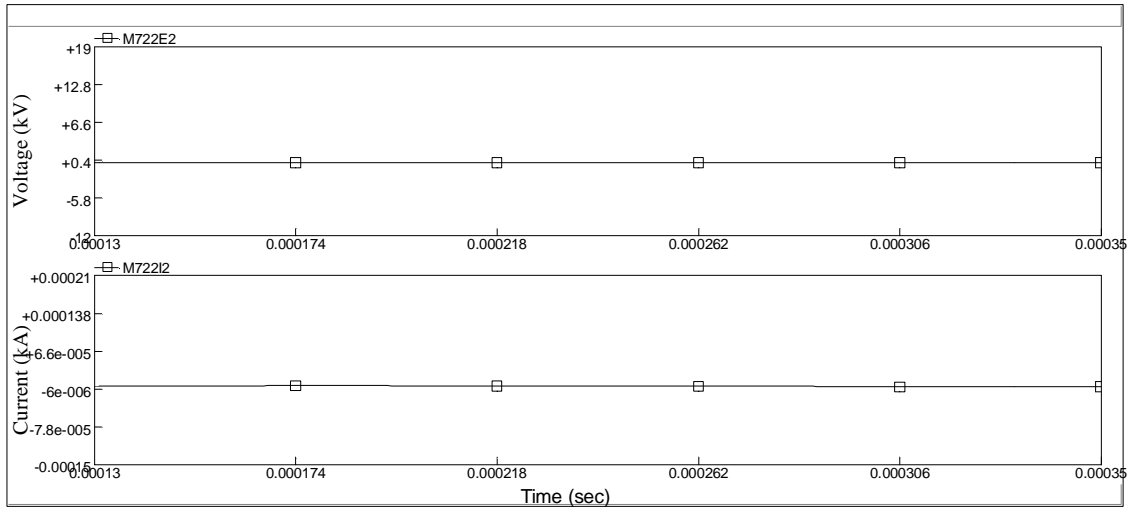
Figure 5.29: Output of mode 2 voltage and current sequence filters at bus B10 for phase 'b' to 'c' fault at 110 km on T7a
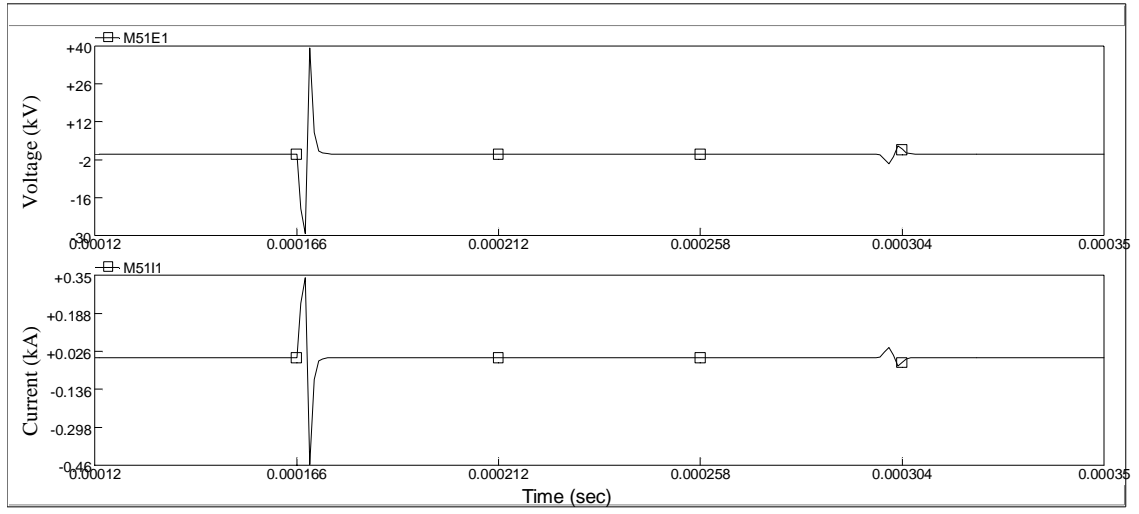
Figure 5.30: Output of mode 1 voltage and current sequence filters at bus B3 for phase 'b' to ground fault at 20 km on T5
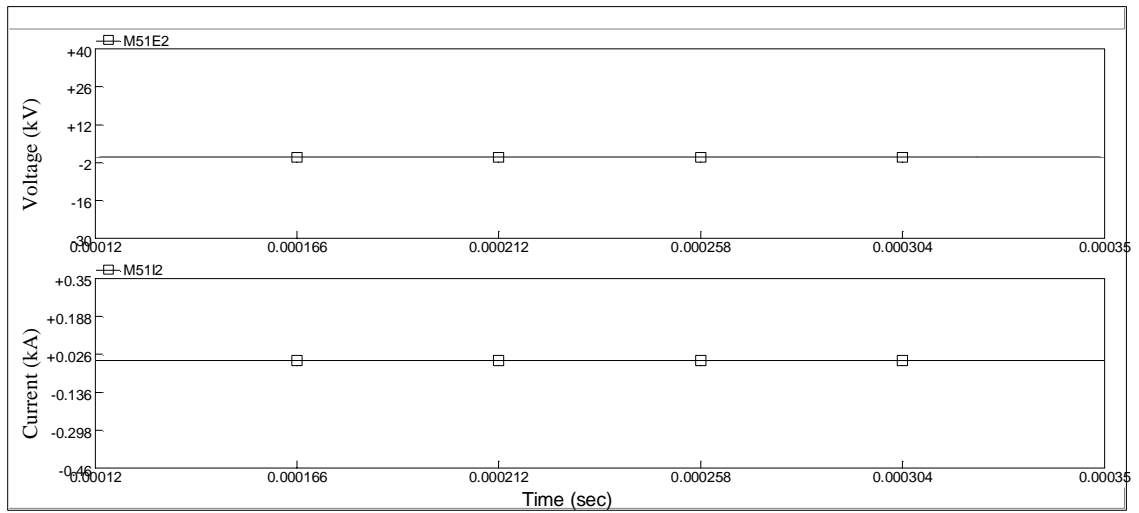
Figure 5.31: Output of mode 2 voltage and current sequence filters at bus B3 for phase 'b' to ground fault at 20 km on T5
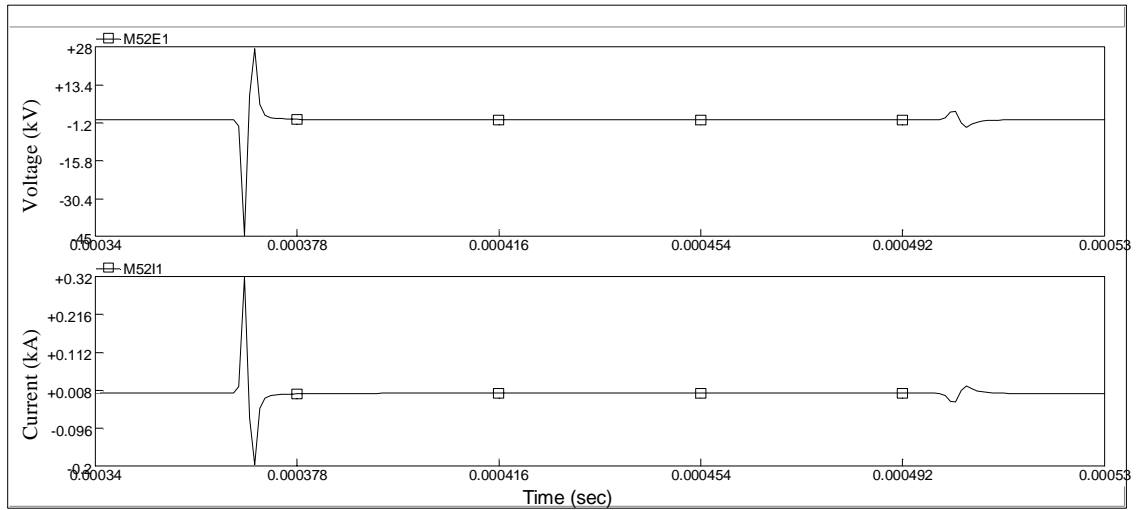
Figure 5.32: Output of mode 1 voltage and current sequence filters at bus B4 for phase 'b' to ground fault at 20 km on T5
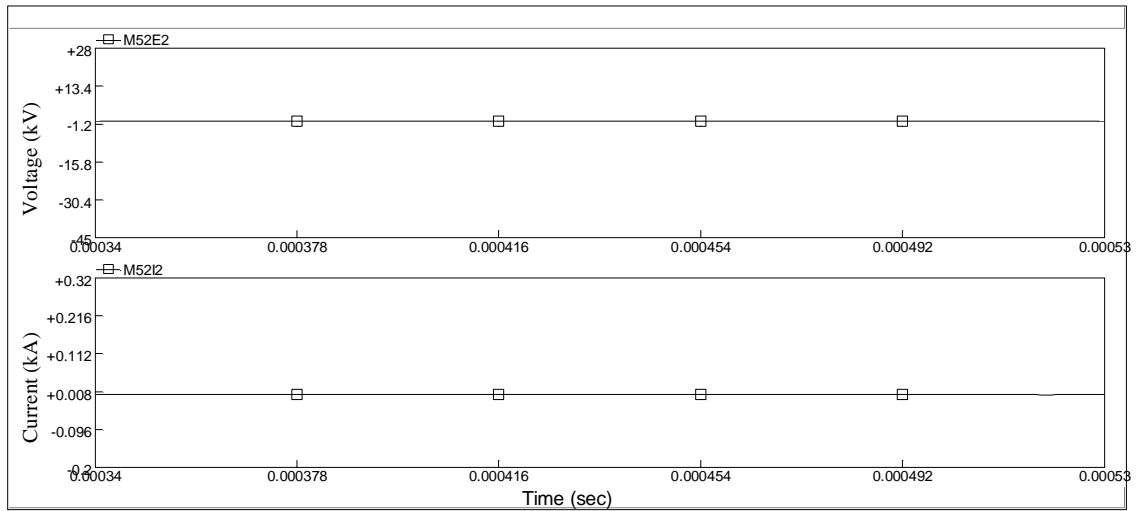
Figure 5.33: Output of mode 2 voltage and current sequence filters at bus B4 for phase 'b' to ground fault at 20 km on T5
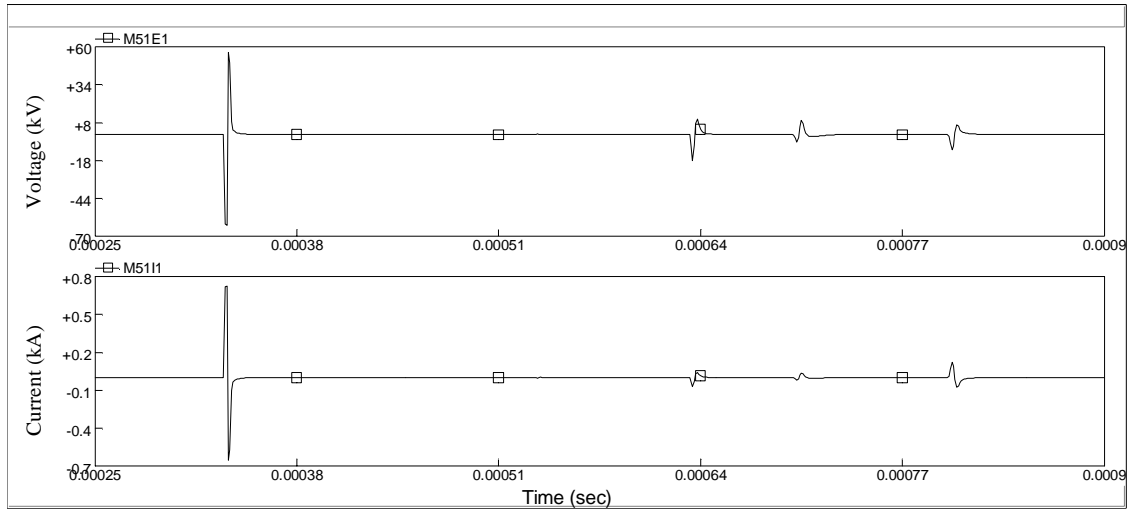
Figure 5.34: Output of mode 1 voltage and current sequence filters at bus B3 for phase 'a' to 'b' to 'c' to ground fault at 70 km on T5
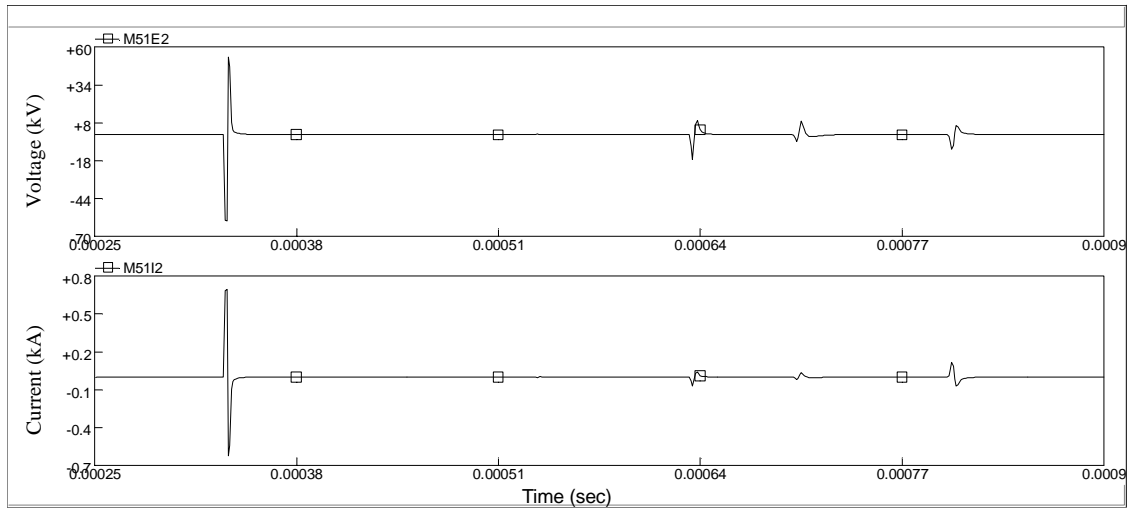
Figure 5.35: Output of mode 2 voltage and current sequence filters at bus B3 for phase 'a' to 'b' to 'c' to ground fault at 70 km on T5
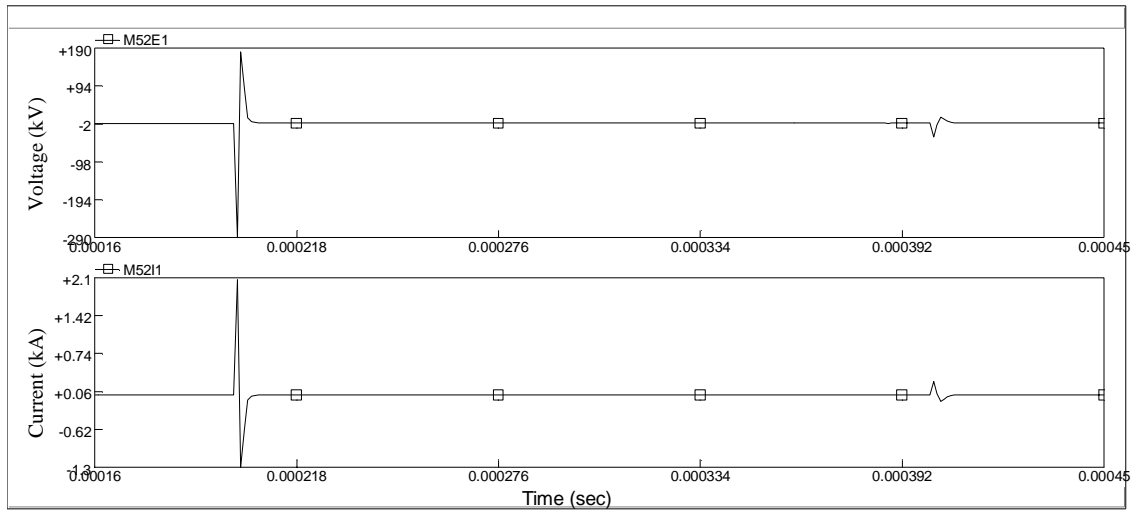
Figure 5.36: Output of mode 1 voltage and current sequence filters at bus B4 for phase 'a' to 'b' to 'c' to ground fault at 70 km on T5
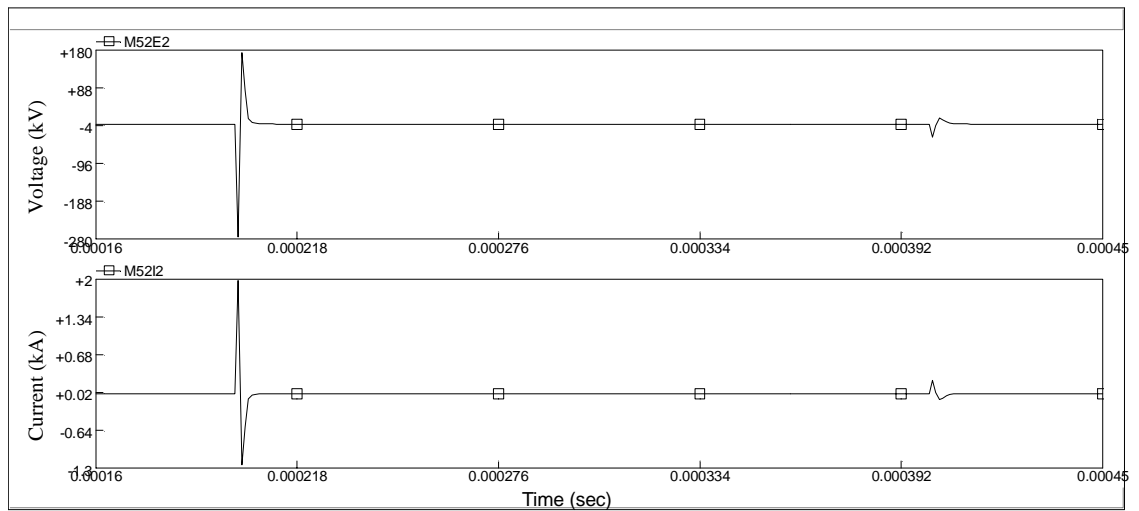
Figure 5.37: Output of mode 2 voltage and current sequence filters at bus B4 for phase 'a' to 'b' to 'c' to ground fault at 70 km on T5
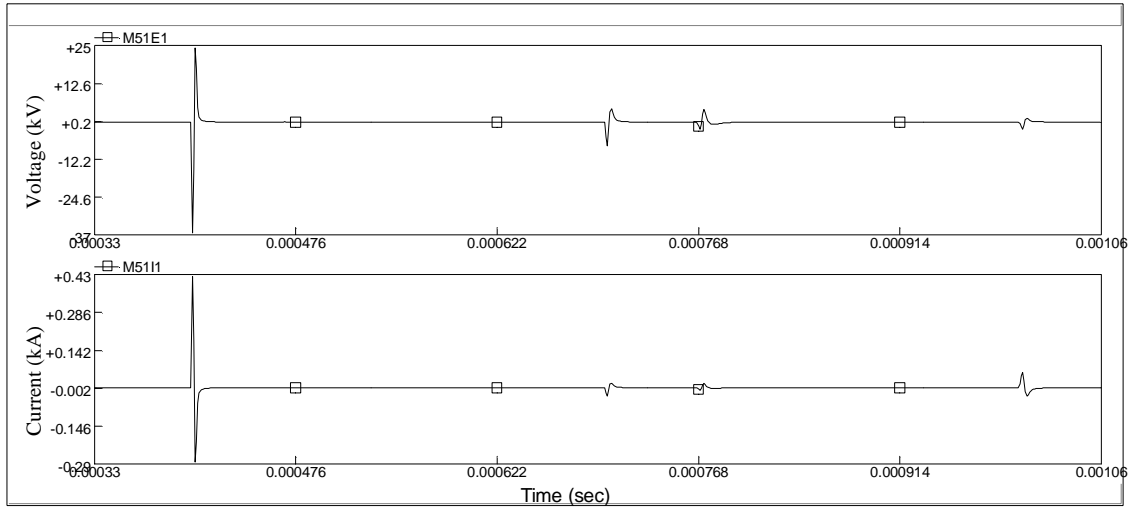
Figure 5.38: Output of mode 1 voltage and current sequence filters at bus B3 for phase 'c' to 'a' fault at 90 km on T5
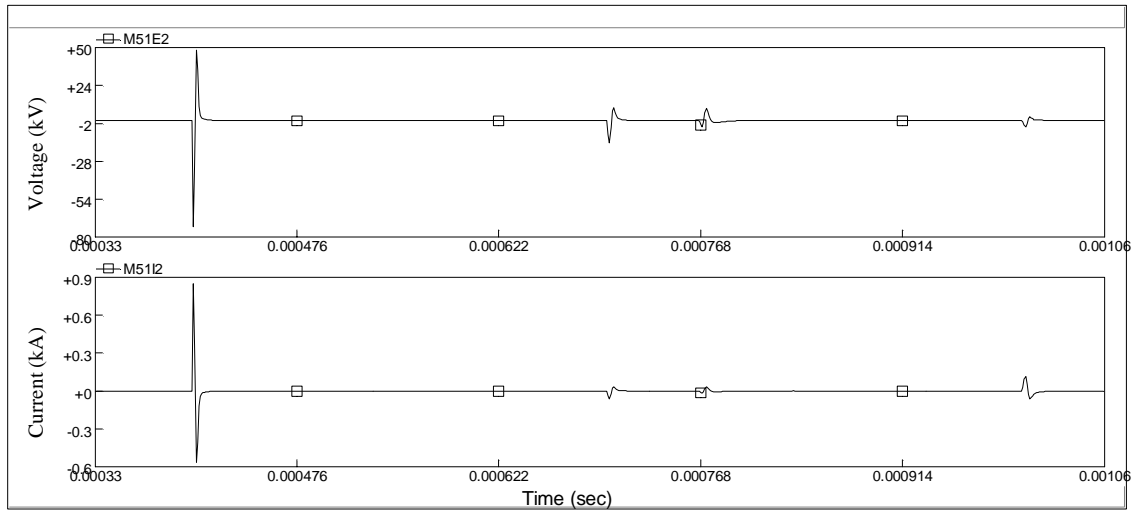
Figure 5.39: Output of mode 2 voltage and current sequence filters at bus B3 for phase 'c' to 'a' fault at 90 km on T5
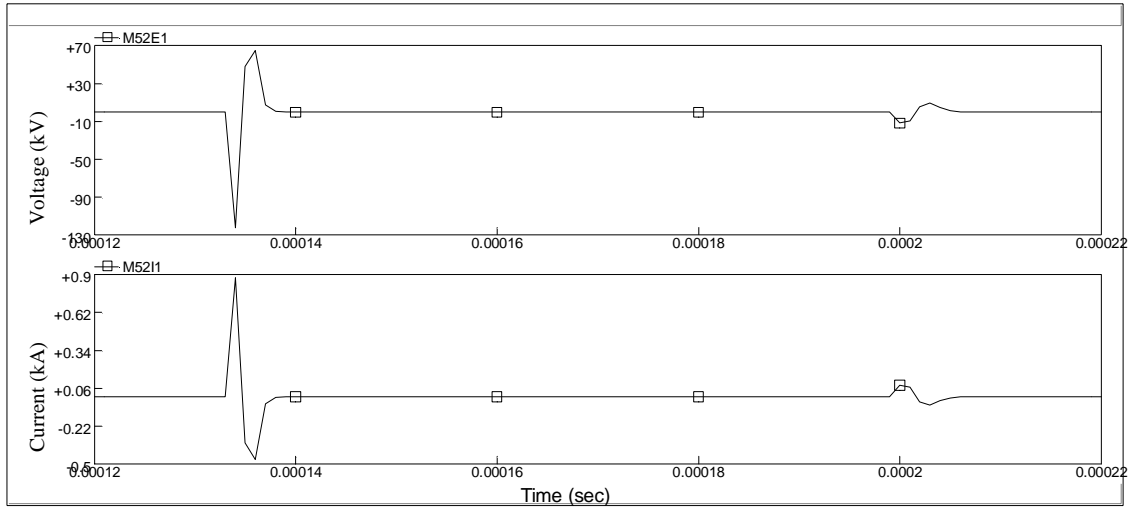
Figure 5.40: Output of mode 1 voltage and current sequence filters at bus B4 for phase 'c' to 'a' fault at 90 km on T5
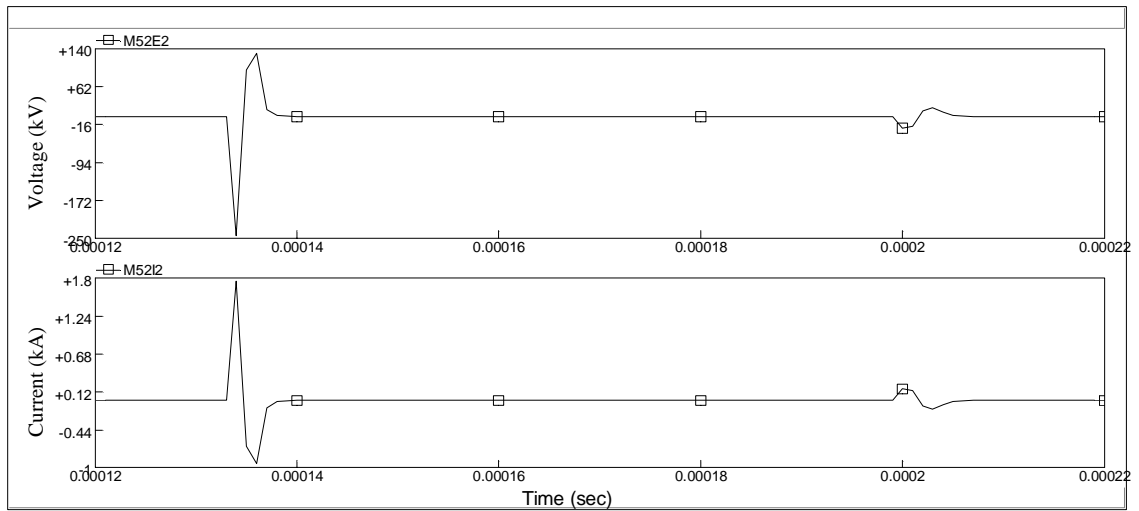
Figure 5.41: Output of mode 2 voltage and current sequence filters at bus B4 for phase 'c' to 'a' fault at 90 km on T5

Chapter 6

Summary and Conclusions

The objective of this thesis was to propose a digital technique, based on traveling waves, for protecting EHV transmission lines and to test the performance of the technique.

A fault on an EHV transmission line, if not detected and eliminated quickly, has potential to destroy the power system equipment permanently. The replacement of the equipment costs large amount of money, time and labor. The faults and the protection relays were discussed in the first chapter. The protection techniques, which are used commercially for protecting transmission lines, were also described. The traveling waves were introduced in the second chapter. The properties and behavior of the traveling waves on a transmission lines were also discussed.

Most of the transmission line protection relays, in the industry, use the fundamental frequency components of the voltages and currents as inputs. These relays take at least one frequency cycle, i.e. 16 ms, to detect a fault. This time is quite long, if, the fault level is very high.

Earlier studies have concluded that the protection techniques, based on the traveling waves, have high potential for detecting and locating faults on the transmission lines. The analog techniques, based on the traveling waves, for protecting transmission lines have been proposed in the past. The techniques implemented with analog technology have several limitations, which make them slow. The techniques, proposed in this thesis and implemented with digital electronics technology, can identify a fault on a transmission line in less than 3 ms. The development of a single-ended as well as a double-ended digital technique has been presented in the third chapter.

The techniques were tested on data generated by running various cases in EMTDC. The code for the protection techniques was written in the linear assembly language and C language. The logic for detecting and locating a fault on the transmission line was coded in the linear assembly program. The C program was coded to fetch data from the files saved on the personal computer and provide the results to the real time operating system, Diamond. The DSP module used and the software developed to implement the proposed techniques are discussed in Chapter 4.

The cases were simulated by applying faults on two transmission lines in a selected power system. Various types of faults were applied at various locations on the transmission lines. The cases were also run by varying the fault resistance and the fault inception angle. Chapter 5 described the test power system, which was simulated in EMTDC. The single-ended technique and double-ended technique were tested for their performance by executing the programs on the microprocessor. The fault data, saved on a personal computer, was used by the programs; they implemented the proposed traveling wave techniques for the presence of faults and calculated the distances of the faults. Some results from the programs are also discussed in Chapter 5.

The results, obtained from implementing the single-ended technique and the double-ended technique in hardware, are satisfactory. The techniques provide correct results for different types of faults and for different values of the fault resistance. However, both techniques do not detect faults on a transmission line when the fault inception angle is close to zero degree. This behavior of the techniques is expected because traveling waves are not generated at fault, when fault occurs at zero fault inception angle. Also, the techniques do not detect when a fault occurs within 1 km of the relay location. Therefore, backup protection relays are needed for protecting the transmission lines during such occurrences.

The contributions made by this thesis are as follows

1. Single-ended and double-ended techniques for protecting EHV transmission lines using traveling waves are proposed. The techniques can detect and locate faults with high speed. The techniques are capable of protecting single circuit as well as double circuit transmission lines.

2. The performance of the techniques by implementing them in a microprocessor and testing on data generated from EMTDC simulations was found satisfactory.

3. The relays based on these techniques can be installed in a power system along with the backup relays for protecting the EHV transmission lines.

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Appendix A

Modal Analysis

The modal transformation decouples the power system equations [19]. This transformation is used to model electric systems in steady-state, under balanced and unbalanced operation, to analyze transients, dynamics and harmonics. The equation, which represents the phase currents in terms of the modal components, I_0, I_1 and I_2, is

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & -2 & 1 \\ 1 & 1 & -2 \end{bmatrix} \begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix}$$

The modal components of the currents can be expressed in terms of the phase components as

$$\begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} = \frac{1}{3} \times \begin{bmatrix} 1 & 1 & 1 \\ 1 & -1 & 0 \\ 1 & 0 & -1 \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$$

Similar equations are also applicable for the voltages. The modal currents during different types of faults are expressed in terms of the phase currents in Table A.1.

Fault	I_0	I_1	I_2
AG	$+I_a$	$+I_a$	$+I_a$
BG	$+I_b$	$-I_b$	0
CG	$+I_c$	0	$-I_c$
AB	0	$+2I_a$	$+I_a$
BC	0	$-I_b$	$+I_b$
CA	0	$+I_c$	$+2I_c$
ABG	I_a+I_b	I_a-I_b	$+I_a$
BCG	I_b+I_c	$-I_b$	$-I_c$
CAG	I_c+I_a	$+I_a$	I_a-I_c
ABC	0	I_a-I_b	I_a-I_c

Table A.1 Modal current analysis during faults

Appendix B

Test Power System
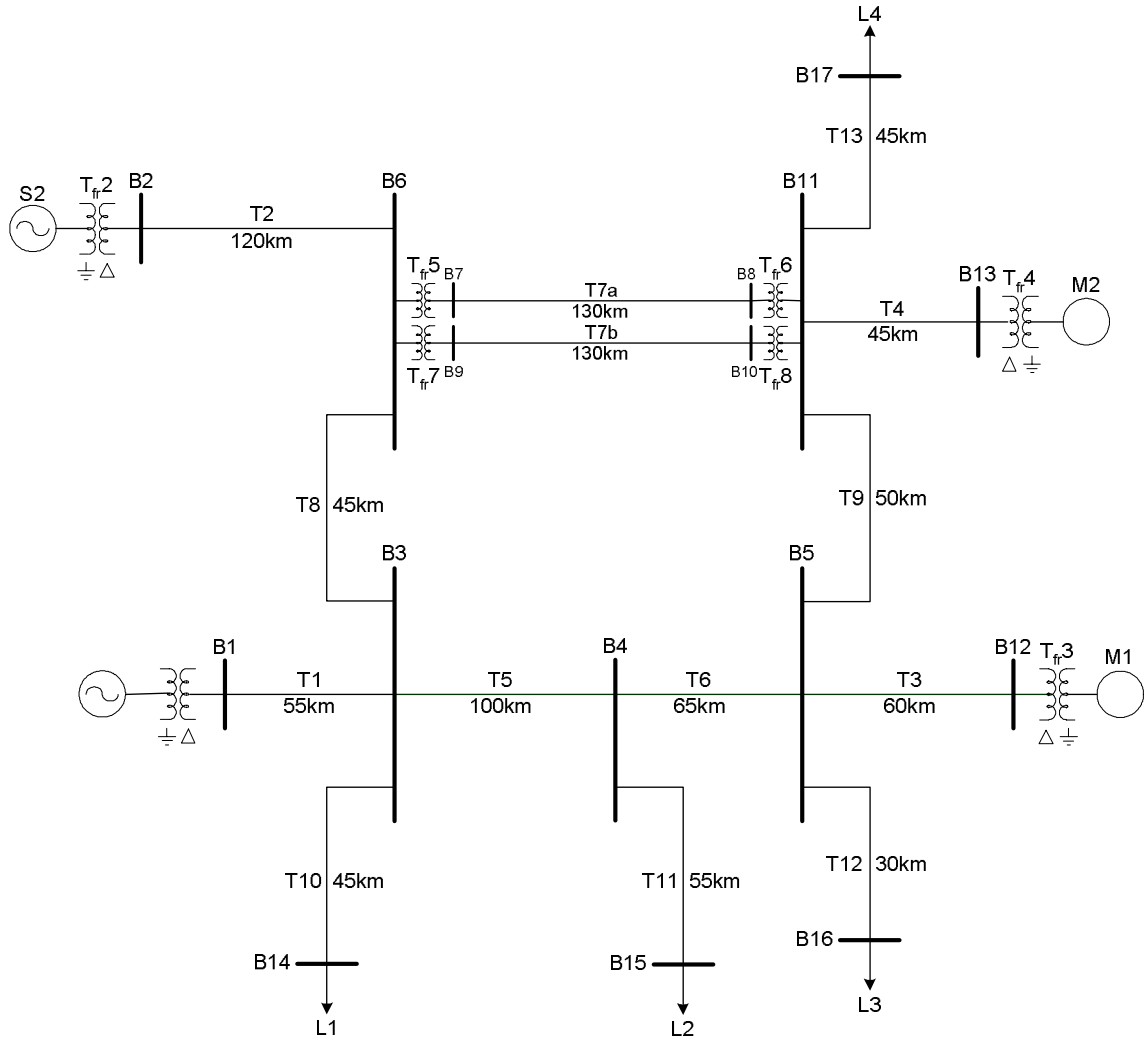
Figure B.2: Test power system for simulation studies

B.1 System Parameters

B.1.1 Source

Name	S1	S2
Rated Power (MW)	2000	1500
Rated rms L-L Voltage (kV)	15	15
X_d (p.u.)	0.866 lagging	0.866 lagging
Base Angular Frequency (rad/s)	376.992	376.992
Inertia Constant (s)	1.7	1.7
Mechanical Friction and Windage (p.u.)	0.0	0.0
Neutral Series Resistance (p.u.)	1.0E5	1.0E5
Neutral Series Reactance (p.u.)	0	0
Iron Loss Resistance (p.u.)	300	300
Armature Resistance (p.u.)	0.002	0.002

B.1.2 Motors

Name	M1	M2
Power (MW)	600	500
Rated Voltage (kV)	15	15
Power Factor	0.866 lagging	0.866 lagging
Base Angular Frequency (rad/s)	376.99	376.99
Stator to Rotor Turns Ratio	1	1
Angular Moment of Inertia	0.3	0.3
Mechanical Damping (p.u.)	0.05	0.05
Stator Resistance (p.u.)	0.043	0.043
Wound Rotor Resistance (p.u.)	0.0	0.0
Mutual Inductance (p.u.)	1.0	1.0
Stator Leakage Inductance (p.u.)	0.0613	0.0613
Wound Rotor Leakage Reactance (p.u.)	0.0613	0.0613

B.1.3 Transformers

Name	Tfr1	Tfr2	Tfr3	Tfr4
3-Phase Transformer MVA	3000	1500	800	800
Voltage Ratio (kV)	15/500	15/500	500/15	500/15
Positive Sequence Leakage Reactance (p.u.)	0.1	0.1	0.1	0.1
No Load Loss (p.u.)	0.0	0.0	0.0	0.0

Name	Tfr5	Tfr6	Tfr7	Tfr8
3-Phase Transformer MVA	1000	1000	1000	1000
Voltage Ratio (kV)	500/735	735/500	500/735	735/500
Positive Sequence Leakage Reactance (p.u.)	0.1	0.1	0.1	0.1
No Load Loss (p.u.)	0.0	0.0	0.0	0.0

B.1.4 Transmission Lines

Name	T1	T2	T3	T4	T5
Length of Line (km)	55	120	60	45	100
Number of Conductors	3	3	3	3	3
Sub 'c'onductors in a Bundle	1	1	1	1	1
Shunt Conductance	1.0 e-10	1.0 e-10	1.0 e-10	1.0 e-10	1.0 e-10
Number of Ground Wires	1	1	1	1	1

Name	T6	T7a	T7b	T8	T9
Length of Line (km)	65	130	130	45	50
Number of Conductors	3	3	3	3	3
Sub 'c'onductors in a Bundle	1	1	1	1	1
Shunt Conductance	1.0 e-10	1.0 e-10	1.1 e-10	1.0 e-10	1.0 e-10
Number of Ground Wires	1	1	1	1	1

Name	T10	T11	T12	T13
Length of Line (km)	45	55	30	45
Number of Conductors	3	3	3	3
Sub-conductors in a Bundle	1	1	1	1
Shunt Conductance	1.0 e-10	1.0 e-10	1.0 e-10	1.0 e-10
Number of Ground Wires	1	1	1	1

B.1.5 Loads

Name	L1	L2	L3	L4
Rated Real Power (MW)	200	150	150	250
Rated Reactive Power (MVAR)	75	50	50	50
Rated L-L Voltage (kV)	500	230	500	500

Appendix C

Linear Assembly Language Programs

The linear assembly programs for single-ended technique and double-ended technique are given in the following sections.

C.1 Linear Assembly Program: Single-Ended Technique

```
                        .text
                        .global _algologic

        _algologic:     .cproc  Easamp_arr, Iasamp_arr, Ebsamp_arr, Ibsamp_arr, Ecsamp_arr,
Icsamp_arr, EMAX, IMAX, cntr1, Array
                        .reg    Easamp1, Easamp2, Easamp3, Ebsamp1, Ebsamp2, Ebsamp3,
Ecsamp1, Ecsamp2, Ecsamp3
                        .reg    Iasamp1, Iasamp2, Iasamp3, Ibsamp1, Ibsamp2, Ibsamp3, Icsamp1,
Icsamp2, Icsamp3
                        .reg    i, i1, n, n4, T, il3, ff, gg, nl5, q1, x, d2, d3, d4, one, Time, yset, PkSet1
                        .reg    Emod11, Emod21, Emod31, Emod12, Emod22, Emod32
                        .reg    Imod11, Imod21, Imod31, Imod12, Imod22, Imod32
                        .reg    Emod1, Imod1, Ires1, Eres1, AIres1, AEres1, Ires2, Eres2, AIres2,
AEres2
                        .reg    E1pos, I1pos, M1Fault, wait, pset1, pset2, T3, T4, ATcnt
                        .reg    I2, I1, Ipost2, Ipost1, set1pol, Gtr, Gtr1, Gtr2, count, sampT, T1, T2,
c1, c2, AbsI1, AbsGtr, cnt4, nzero, PkTrue , pol
                        .reg    n1, neq1, hang, hangh, nlx2
                        .reg    p, px, ff2, Tskip, Yskip, TFT, TD, T11, T22, PolDiff, ValSet1


                        MVK         5, x
                        MVK         1, i
                        SUB         cntr1, 1, cntr1
                        MVK         1,T

                        ZERO        T1
                        ZERO        T2
```

```
                    ZERO        Time


                    MVK         1, one
                    ZERO        count
                    ZERO        Ipost2
                    ZERO        I2
                    ZERO        Ipost1
                    ZERO        I1
                    ZERO        wait


                    MVK         1, ATcnt
                    MV          x, n
                    MVK         2, ff
                    ZERO        gg
                    ZERO        PkSet1
                    ZERO        yset
                    ZERO        p


                    ZERO        n1
                    ZERO        hang
                    ZERO        Tskip
                    ZERO        T11
                    ZERO        T22
                    ZERO        TFT
                    ZERO        ValSet1


Loop1:
                    CMPEQ       i, Tskip, Yskip
        [Yskip]     ADD         i, 6, i


                    ZERO        Yskip
                    ZERO        TD
                    ZERO        i1
                    ZERO        il3
                    ZERO        pol
                    ZERO        Emod1
                    ZERO        Imod1
                    ZERO        Eres1
```

```
              ZERO        Eres2
              ZERO        Ires1
              ZERO        Ires2
              ZERO        pset1
              ZERO        pset2
              ZERO        M1Fault
              ZERO        nzero
              ZERO        PkTrue
              ZERO        q1
              ZERO        nl5

              ZERO        neq1
              ZERO        d2
              ZERO        d3
              ZERO        d4
              ZERO        nlx2
              ZERO        hangh
              MVK         1, PolDiff
              ZERO        px

              CMPEQ       i, 1, i1
    [i1]      B           Loop11

              MV          Easamp2, Easamp1
              MV          Iasamp2, Iasamp1
              MV          Ebsamp2, Ebsamp1
              MV          Ibsamp2, Ibsamp1
              MV          Ecsamp2, Ecsamp1
              MV          Icsamp2, Icsamp1

              MV          Easamp3, Easamp2
              MV          Iasamp3, Iasamp2
              MV          Ebsamp3, Ebsamp2
              MV          Ibsamp3, Ibsamp2
              MV          Ecsamp3, Ecsamp2
              MV          Icsamp3, Icsamp2
```

Loop11:

	LDW	*Easamp_arr[i], Easamp3
	LDW	*Iasamp_arr[i], Iasamp3
	LDW	*Ebsamp_arr[i], Ebsamp3
	LDW	*Ibsamp_arr[i], Ibsamp3
	LDW	*Ecsamp_arr[i], Ecsamp3
	LDW	*Icsamp_arr[i], Icsamp3
[i1]	B	J1
	MV	Emod21, Emod11
	MV	Emod22, Emod12
	MV	Emod31, Emod21
	MV	Emod32, Emod22
	MV	Imod21, Imod11
	MV	Imod22, Imod12
	MV	Imod31, Imod21
	MV	Imod32, Imod22

J1:

	SUB	Easamp3, Ebsamp3, Emod31
	SUB	Easamp3, Ecsamp3, Emod32
	SUB	Iasamp3, Ibsamp3, Imod31
	SUB	Iasamp3, Icsamp3, Imod32
	MPY	2, Emod21, Emod1
	MPY	2, Imod21, Imod1
	SUB	Emod31, Emod21, Eres1
	SUB	Imod31, Imod21, Ires1
	SUB	Eres1, Emod21, Eres1
	SUB	Ires1, Imod21, Ires1
	ADD	Eres1, Emod11, Eres1
	ADD	Ires1, Imod11, Ires1
	ABS	Eres1, AEres1

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		ABS	Ires1, AIres1
		SUB	Emod32, Emod22, Eres2
		SUB	Imod32, Imod22, Ires2
		SUB	Eres2, Emod22, Eres2
		SUB	Ires2, Imod22, Ires2
		ADD	Eres2, Emod12, Eres2
		ADD	Ires2, Imod12, Ires2
		ABS	Eres2, AEres2
		ABS	Ires2, AIres2
		SUB	cntr1, 1, cntr1
		ADD	i, 1, i
		MV	i, T
		MV	T, sampT
		ADD	T, 1, T
		CMPEQ	n, x, n4
	[wait]	SUB	wait, 1, wait
	[wait]	MV	x, n
	[wait]	ZERO	count
	[wait]	ZERO	hang
	[wait]	B	Out_Fault2
		CMPLT	i, 15, il3
	[il3]	B	Out_Fault2

Mode1:

| | | CMPEQ | PkSet1, 1, q1 |

TEST1:

		CMPGT	AIres1, IMAX, d2
	[!d2]	MV	AIres2, AIres1
	[!d2]	MV	Ires2, Ires1
	[!d2]	CMPGT	AIres2, IMAX, d2

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	CMPGT	AEres1, EMAX, d3
[!d3]	MV	AEres2, AEres1
[!d3]	MV	Eres2, Eres1
[!d3]	CMPGT	AEres1, EMAX, d3
[d2]	CMPEQ	d3, 1, d4
[q1]	B	Loop80
[d4]	B	TEST2
[d2]	B	TEST2
	B	Out_Fault2

TEST2:

	CMPGT	Eres1, 0, E1pos
	CMPLT	Ires1, 0, I1pos
	CMPEQ	E1pos, I1pos, PolDiff
[!PolDiff]	MVK	1, M1Fault
[M1Fault]	B	Loop85

Loop80:

	MVK	0, PolDiff
[d4]	CMPGT	Eres1, 0, E1pos
[d4]	CMPLT	Ires1, 0, I1pos
[d4]	CMPEQ	E1pos, I1pos, PolDiff
[PolDiff]	MVK	1, M1Fault
[d4]	B	Loop85
[hang]	CMPGT	hang, 0, hangh
[hangh]	CMPLT	n, x, nlx2
[nlx2]	SUB	hang, 1, hang
[nlx2]	B	Out_Fault3

Loop85:

[p]	B	Loop2D
[M1Fault]	B	Loop2
	B	Out_Fault2

Out_Fault1:

| | MVK | 2, wait |

	MV	x, n
	ZERO	count
	ZERO	hang
	CMPEQ	ATcnt, 1, pset1
	CMPEQ	ATcnt, 2, pset2
[pset1]	STW	T1, *+Array[1]
[pset1]	STW	T2, *+Array[2]
[pset1]	MV	T1, T3
[pset1]	B	Decide
	STW	T1, *+Array[3]
	STW	T2, *+Array[4]
	MV	T1, T4

Decide:

| | ADD | ATcnt, 1, ATcnt |
| [pset2] | B | End_Prog1 |

Out_Fault2:

	CMPLT	n, x, nl5
[nl5]	ADD	n1, 1, n1
[nl5]	CMPGT	n1, 3, neq1
[neq1]	MV	x, n
	ZERO	hang
[cntr1]	B	Loop1
[!cntr1]	B	End_Prog2

Out_Fault5:

	ADD	i, 5, i
	ZERO	p
	B	Out_Fault3

Out_Fault4:

| | LDW | *Array[1], TFT |

```
                    SUB         T11, TFT, TD
                    MVK         364, gg
                    ADD         TD, gg, Tskip
                    ADD         Tskip, TFT, Tskip

                    STW         T11, *+Array[5]
                    STW         T22, *+Array[6]
                    STW         one, *+Array[0]

                    MVK         2, wait
                    ZERO        p
                    ZERO        count
                    ZERO        hang

Out_Fault3:
        [cntr1]     B           Loop1
        [!cntr1]    B           End_Prog2

Loop2D:
                    CMPEQ       ff, 2, ff2
        [!ff2]      B           Out_Fault5

                    CMPEQ       p, x, px
        [!px]       B           Loop3D

                    MV          Ires1, I2
                    CMPGT       I2, 0, Ipost2

Loop50D:
                    MV          I2, Gtr
                    MV          Gtr, Gtr1
                    MVK         1, count
                    MV          sampT, T11
                    SUB         p, 1, p
                    B           EndCheckD

Loop3D:
                    SUB         p, 1, p
```

```
                        CMPEQ        count, 1, c1
                        CMPEQ        count, 2, c2


                        MV           Ires1, I1
                        CMPGT        I1, 0, Ipost1
                        CMPEQ        Ipost1, Ipost2, pol


        [pol]           B            Loop4D


                        MV           Ires1, Gtr
                        MV           Ipost1, Ipost2
                        MV           I1, I2
                        ADD          count, 1, count


                        CMPEQ        count, 2, c2
        [c2]            MV           sampT, T22
        [c2]            MV           Gtr, Gtr2


                        B            EndCheckD


Loop4D:
                        ABS          I1, AbsI1
                        ABS          Gtr, AbsGtr


                        CMPGT        AbsI1, AbsGtr, cnt4
        [!cnt4]         B            EndCheckD


                        MV           I1, Gtr


        [c1]            MV           sampT, T11
        [c2]            MV           sampT, T22
        [c1]            MV           Gtr, Gtr1
        [c2]            MV           Gtr, Gtr2


EndCheckD:
                        MVK          1, hang
                        CMPLT        p, 2, nzero
        [nzero]         CMPEQ        count, 2, PkTrue
```

[PkTrue]	SUB	ff, 1, ff
[PkTrue]	B	Out_Fault4
	B	Out_Fault3

Loop2:

[!n4]	B	Loop3
	MV	Ires1, I2
	CMPGT	I2, 0, Ipost2
[!PkSet1]	MV	Ipost2, set1pol
[PkSet1]	CMPEQ	Ipost2, set1pol, yset
[PkSet1]	B	YSET1
	B	Loop50

YSET1:

[!yset]	MV	x, p
[!yset]	ZERO	count
[!yset]	B	Loop2D

Loop50:

	MV	I2, Gtr
	MV	Gtr, Gtr1
	MVK	1, count
	MV	sampT, T1
	MV	Ires1, ValSet1
	SUB	n, 1, n
	B	EndCheck

Loop3:

	SUB	n, 1, n
	CMPEQ	count, 1, c1
	CMPEQ	count, 2, c2
	MV	Ires1, I1
	CMPGT	I1, 0, Ipost1
	CMPEQ	Ipost1, Ipost2, pol

[pol]	B	Loop4
	MV	Ires1, Gtr
	MV	Ipost1, Ipost2
	MV	I1, I2
	ADD	count, 1, count
	CMPEQ	count, 2, c2
[c2]	MV	sampT, T2
[c2]	MV	Gtr, Gtr2
	B	EndCheck

Loop4:

	ABS	I1, AbsI1
	ABS	Gtr, AbsGtr
	CMPGT	AbsI1, AbsGtr, cnt4
[!cnt4]	B	EndCheck
	MV	I1, Gtr
[c1]	MV	sampT, T1
[c1]	MV	Ires1, ValSet1
[c2]	MV	sampT, T2
[c1]	MV	Gtr, Gtr1
[c2]	MV	Gtr, Gtr2

EndCheck:

	MVK	1, hang
	CMPLT	n, 2, nzero
[nzero]	CMPEQ	count, 2, PkTrue
[PkTrue]	MVK	1, PkSet1
[PkTrue]	B	Out_Fault1
	B	Out_Fault3

End_Prog1:

	SUB	T4, T3, Time

End_Prog2:

                    .return   Time

                    .endproc

C.2 Linear Assembly Program: Double-Ended Technique

                    .text

                    .global _algologic

_algologic: .cproc   Easamp_arr, Iasamp_arr, Ebsamp_arr, Ibsamp_arr, Ecsamp_arr, Icsamp_arr, EMAX, IMAX, cntr1, Array

                    .reg   Easamp1, Easamp2, Easamp3, Ebsamp1, Ebsamp2, Ebsamp3, Ecsamp1, Ecsamp2, Ecsamp3

                    .reg   Iasamp1, Iasamp2, Iasamp3, Ibsamp1, Ibsamp2, Ibsamp3, Icsamp1, Icsamp2, Icsamp3

                    .reg   i, i1, n, n4, T, il3, ff, gg, nl5, q1, x, d2, d3, d4, one, Time, yset, PkSet1

                    .reg   Emod11, Emod21, Emod31, Emod12, Emod22, Emod32

                    .reg   Imod11, Imod21, Imod31, Imod12, Imod22, Imod32

                    .reg   Emod1, Imod1, Ires1, Eres1, AIres1, AEres1, Ires2, Eres2, AIres2, AEres2

                    .reg   E1pos, I1pos, M1Fault, wait, pset1, T3, T4, ATcnt

                    .reg   I2, I1, Ipost2, Ipost1, set1pol, Gtr, Gtr1, Gtr2, count, sampT, T1, T2, c1, c2, AbsI1, AbsGtr, cnt4, nzero, PkTrue , pol

                    .reg   n1, neq1, hang, hangh, nlx2

                    .reg   p, px, ff2, Tskip, Yskip, TFT, TD, T11, T22, PolDiff, ValSet1

                    MVK   5, x

                    MVK   1, i

                    SUB   cntr1, 1, cntr1

                    MVK   1,T

                    ZERO   T1

                    ZERO   T2

                    ZERO   Time

                    MVK   1, one

                    ZERO   count

                    ZERO   Ipost2

                    ZERO   I2

```
            ZERO        Ipost1
            ZERO        I1
            ZERO        wait

            MVK         1, ATcnt
            MV          x, n
            MVK         2, ff
            ZERO        gg
            ZERO        PkSet1
            ZERO        yset
            ZERO        p

            ZERO        n1
            ZERO        hang
            ZERO        Tskip
            ZERO        T11
            ZERO        T22
            ZERO        TFT
            ZERO        ValSet1

Loop1:
            CMPEQ       i, Tskip, Yskip
   [Yskip]  ADD         i, 6, i

            ZERO        Yskip
            ZERO        TD
            ZERO        i1
            ZERO        il3
            ZERO        pol
            ZERO        Emod1
            ZERO        Imod1
            ZERO        Eres1
            ZERO        Eres2
            ZERO        Ires1
            ZERO        Ires2
            ZERO        pset1
            ZERO        M1Fault
            ZERO        nzero
```

```
                     ZERO         PkTrue
                     ZERO         q1
                     ZERO         nl5

                     ZERO         neq1
                     ZERO         d2
                     ZERO         d3
                     ZERO         d4
                     ZERO         nlx2
                     ZERO         hangh
                     MVK          1, PolDiff
                     ZERO         px

                     CMPEQ        i, 1, i1
          [i1]       B            Loop11

                     MV           Easamp2, Easamp1
                     MV           Iasamp2, Iasamp1
                     MV           Ebsamp2, Ebsamp1
                     MV           Ibsamp2, Ibsamp1
                     MV           Ecsamp2, Ecsamp1
                     MV           Icsamp2, Icsamp1

                     MV           Easamp3, Easamp2
                     MV           Iasamp3, Iasamp2
                     MV           Ebsamp3, Ebsamp2
                     MV           Ibsamp3, Ibsamp2
                     MV           Ecsamp3, Ecsamp2
                     MV           Icsamp3, Icsamp2

Loop11:

                     LDW          *Easamp_arr[i], Easamp3
                     LDW          *Iasamp_arr[i], Iasamp3
                     LDW          *Ebsamp_arr[i], Ebsamp3
                     LDW          *Ibsamp_arr[i], Ibsamp3
                     LDW          *Ecsamp_arr[i], Ecsamp3
                     LDW          *Icsamp_arr[i], Icsamp3
```

[i1]	B	J1
	MV	Emod21, Emod11
	MV	Emod22, Emod12
	MV	Emod31, Emod21
	MV	Emod32, Emod22
	MV	Imod21, Imod11
	MV	Imod22, Imod12
	MV	Imod31, Imod21
	MV	Imod32, Imod22

J1:

	SUB	Easamp3, Ebsamp3, Emod31
	SUB	Easamp3, Ecsamp3, Emod32
	SUB	Iasamp3, Ibsamp3, Imod31
	SUB	Iasamp3, Icsamp3, Imod32
	MPY	2, Emod21, Emod1
	MPY	2, Imod21, Imod1
	SUB	Emod31, Emod21, Eres1
	SUB	Imod31, Imod21, Ires1
	SUB	Eres1, Emod21, Eres1
	SUB	Ires1, Imod21, Ires1
	ADD	Eres1, Emod11, Eres1
	ADD	Ires1, Imod11, Ires1
	ABS	Eres1, AEres1
	ABS	Ires1, AIres1
	SUB	Emod32, Emod22, Eres2
	SUB	Imod32, Imod22, Ires2
	SUB	Eres2, Emod22, Eres2
	SUB	Ires2, Imod22, Ires2
	ADD	Eres2, Emod12, Eres2

		ADD	Ires2, Imod12, Ires2
		ABS	Eres2, AEres2
		ABS	Ires2, AIres2
		SUB	cntr1, 1, cntr1
		ADD	i, 1, i
		MV	i, T
		MV	T, sampT
		ADD	T, 1, T
		CMPEQ	n, x, n4
	[wait]	SUB	wait, 1, wait
	[wait]	MV	x, n
	[wait]	ZERO	count
	[wait]	ZERO	hang
	[wait]	B	Out_Fault2
		CMPLT	i, 15, il3
	[il3]	B	Out_Fault2

Mode1:

		CMPEQ	PkSet1, 1, q1

TEST1:

		CMPGT	AIres1, IMAX, d2
	[!d2]	MV	AIres2, AIres1
	[!d2]	MV	Ires2, Ires1
	[!d2]	CMPGT	AIres2, IMAX, d2
		CMPGT	AEres1, EMAX, d3
	[!d3]	MV	AEres2, AEres1
	[!d3]	MV	Eres2, Eres1
	[!d3]	CMPGT	AEres1, EMAX, d3
	[d2]	CMPEQ	d3, 1, d4
	[q1]	B	Loop80
	[d4]	B	TEST2

```
        [d2]            B              TEST2
                        B              Out_Fault2


TEST2:
                        CMPGT          Eres1, 0, E1pos
                        CMPLT          Ires1, 0, I1pos
                        CMPEQ          E1pos, I1pos, PolDiff
        [!PolDiff]      MVK            1, M1Fault
        [M1Fault]       B              Loop85


Loop80:
                        MVK            0, PolDiff
        [d4]            CMPGT          Eres1, 0, E1pos
        [d4]            CMPLT          Ires1, 0, I1pos
        [d4]            CMPEQ          E1pos, I1pos, PolDiff
        [PolDiff]       MVK            1, M1Fault
        [d4]            B              Loop85


        [hang]          CMPGT          hang, 0, hangh
        [hangh]         CMPLT          n, x, nlx2
        [nlx2]          SUB            hang, 1, hang
        [nlx2]          B              Out_Fault3


Loop85:
        [p]             B              Loop2D
        [M1Fault]       B              Loop2
                        B              Out_Fault2


Out_Fault1:
                        MVK            2, wait
                        MV             x, n

                        ZERO           count
                        ZERO           hang

                        CMPEQ          ATcnt, 1, pset1

        [pset1]         STW            T1, *+Array[1]
```

```
         [pset1]        STW         T2, *+Array[2]
         [pset1]        MV          T1, T3
         [pset1]        B           Decide
                        B           Out_Fault3


Decide:
                        ADD         ATcnt, 1, ATcnt
         [pset1]        B           End_Prog1


Out_Fault2:
                        CMPLT       n, x, nl5
         [nl5]          ADD         n1, 1, n1
         [nl5]          CMPGT       n1, 3, neq1
         [neq1]         MV          x, n
                        ZERO        hang


         [cntr1]        B           Loop1
         [!cntr1]       B           End_Prog2


Out_Fault3:
         [cntr1]        B           Loop1
         [!cntr1]       B           End_Prog2


Loop2:
         [!n4]          B           Loop3


                        MV          Ires1, I2
                        CMPGT       I2, 0, Ipost2


         [!PkSet1]      MV          Ipost2, set1pol


Loop50:
                        MV          I2, Gtr
                        MV          Gtr, Gtr1
                        MVK         1, count
                        MV          sampT, T1
                        MV          Ires1, ValSet1
                        SUB         n, 1, n
```

| | B | EndCheck |

Loop3:

	SUB	n, 1, n
	CMPEQ	count, 1, c1
	CMPEQ	count, 2, c2
	MV	Ires1, I1
	CMPGT	I1, 0, Ipost1
	CMPEQ	Ipost1, Ipost2, pol
[pol]	B	Loop4
	MV	Ires1, Gtr
	MV	Ipost1, Ipost2
	MV	I1, I2
	ADD	count, 1, count
	CMPEQ	count, 2, c2
[c2]	MV	sampT, T2
[c2]	MV	Gtr, Gtr2
	B	EndCheck

Loop4:

	ABS	I1, AbsI1
	ABS	Gtr, AbsGtr
	CMPGT	AbsI1, AbsGtr, cnt4
[!cnt4]	B	EndCheck
	MV	I1, Gtr
[c1]	MV	sampT, T1
[c1]	MV	Ires1, ValSet1
[c2]	MV	sampT, T2
[c1]	MV	Gtr, Gtr1
[c2]	MV	Gtr, Gtr2

EndCheck:

	MVK	1, hang
	CMPLT	n, 2, nzero
[nzero]	CMPEQ	count, 2, PkTrue
[PkTrue]	MVK	1, PkSet1
[PkTrue]	B	Out_Fault1
	B	Out_Fault3

End_Prog1:

| | SUB | T4, T3, Time |

End_Prog2:

| | .return | Time |
| | .endproc | |

Appendix D

C Language Programs

D.1 C Program for Single-Ended Technique

```c
#include <stdio.h>
#define N 1500
#define  Emax 5
#define  Imax 5
int algologic(int*, int*, int*, int*, int*, int*, int, int, long, int*);
main()
{
        long    c = 299792.458;
        float   Ia1[N], Ea1[N], Eb1[N], Ib1[N], Ec1[N], Ic1[N], Dist;
        int     Results[7], j, Ea[N], Ia[N], Eb[N], Ib[N], Ec[N], Ic[N];
        FILE    *Eaptr, *Iaptr, *Ebptr, *Ibptr, *Ecptr, *Icptr;
        Eaptr = fopen("T5\\01km\\ABCG\\T51\\P51EA.out", "r");
        Iaptr = fopen("T5\\01km\\ABCG\\T51\\P51IA.out", "r");
        Ebptr = fopen("T5\\01km\\ABCG\\T51\\P51EB.out", "r");
        Ibptr = fopen("T5\\01km\\ABCG\\T51\\P51IB.out", "r");
        Ecptr = fopen("T5\\01km\\ABCG\\T51\\P51EC.out", "r");
        Icptr = fopen("T5\\01km\\ABCG\\T51\\P51IC.out", "r");
        for(j=0; j<=(N-1); j++)
        {
                fscanf(Eaptr,"%f",&Ea1[j]);
                fscanf(Iaptr,"%f",&Ia1[j]);
                fscanf(Ebptr,"%f",&Eb1[j]);
                fscanf(Ibptr,"%f",&Ib1[j]);
                fscanf(Ecptr,"%f",&Ec1[j]);
                fscanf(Icptr,"%f",&Ic1[j]);
                Ia1[j] = (Ia1[j]*1000);
                Ea1[j] = (Ea1[j]*100);
                Ib1[j] = (Ib1[j]*1000);
```

```
                    Eb1[j] = (Eb1[j]*100);
                    Ic1[j] = (Ic1[j]*1000);
                    Ec1[j] = (Ec1[j]*100);
                    Ea[j] = (int)Ea1[j];
                    Ia[j] = (int)Ia1[j];
                    Eb[j] = (int)Eb1[j];
                    Ib[j] = (int)Ib1[j];
                    Ec[j] = (int)Ec1[j];
                    Ic[j] = (int)Ic1[j];
            }
        Dist = algologic(Ea, Ia, Eb, Ib, Ec, Ic, Emax, Imax, N, Results);
                printf("\nDistance of Fault from Bus : %f km\n", (c*Dist/2000000));
                printf("\nTime of 1st peak of 1st set  : %d usec", Results[1]);
                printf("\nTime of 2st peak of 1st set  : %d usec", Results[2]);
                printf("\nTime of 1st peak of 2st set  : %d usec", Results[3]);
                printf("\nTime of 2st peak of 2st set  : %d usec", Results[4]);
        if(Results[0]==1)
                {
                printf("\n\nTime of 1st peak from remote end  : %d usec", Results[5]);
                printf("\nTime of 2st peak from remote end  : %d usec", Results[6]);
                }
        printf("\n\n**************************************************");
        fclose(Eaptr);
        fclose(Iaptr);
        fclose(Ebptr);
        fclose(Ibptr);
        fclose(Ecptr);
        fclose(Icptr);
    }
```

D.2 C Programs for Double-Ended Technique

Three programs were developed for the double-ended technique. The relays at two ends of the transmission line are represented by two stand alone programs: Prog1 and Prog2. These programs, along with the linear assembly program, run simultaneously in multithreading mode [16]. When Prog1 and Prog2 detect the fault generated traveling waves, they send the time of arrival of the traveling waves to the main program, Mprog.

Mprog waits for the values of time from Prog1 and Prog2, which when received; Mprog calculates the distance of the fault.

D.2.1 C Program: Mprog

```
#include <chan.h>
#include <stdio.h>
main(int argc, char *argv[], char *envp[],
    CHAN * in_ports[], int ins,
    CHAN *out_ports[], int outs)
{
        int Tr1, Tr2, N;
        double c = 299792.458;
        int L =   100;
        double T,  DelT1, DelT2 ;
long double TR1, TR2;
        long double DR1, DR2;
T = (L/c)*1000000;
chan_in_word(&Tr1, in_ports[0]);
chan_in_word(&Tr2, in_ports[1]);
        DelT1 = Tr1 - Tr2 + T;
        DR1 = (DelT1/1000000)* c/2;
        DelT2 = T - (Tr1 - Tr2) ;
        DR2 = (DelT2/1000000)* c/2;
        TR1 = 1000000/Tr1;
        TR1 = 1/TR1 ;
        TR2 = 1000000/Tr2;
        TR2 = 1/TR2 ;
        printf("\n\n*************************************************");
        printf("\n\nTime of arrival of Traveling Waves at Relay1: %f s", TR1);
        printf("\nTime of arrival of Traveling Waves at Relay2: %f s", TR2);
        printf("\n\nDistance of fault from Relay1 : %f km", DR1);
        printf("\nDistance of fault from Relay2 : %f km", DR2);
        printf("\n\n*************************************************");
}
```

D.2.2 C Program: Prog1

```
/*
** prog1.c stand-alone processing task. Communicates with mprog.c.
*/
#include <chan.h>
#include <ctype.h>
#include <stdio.h>
#define LLength 100
#define N 1500
#define Emax 5
#define Imax 5
int algologic(int*, int*, int*, int*, int*, int*, int, int, long, int*);
main(int argc, char *argv[], char *envp[],
    CHAN * in_ports[], int ins,
    CHAN *out_ports[], int outs)
{
        int c, j, Results[5], Ea[N], Ia[N], Eb[N], Ib[N], Ec[N], Ic[N];
        float Ia1[N], Ea1[N], Eb1[N], Ib1[N], Ec1[N], Ic1[N], Dist;
FILE *Eaptr, *Iaptr, *Ebptr, *Ibptr, *Ecptr, *Icptr;
chan_in_word(&N1, in_ports[0]);
        Eaptr = fopen("T5\\10km\\A00G\\T51\\P51EA.out", "r");
        Iaptr = fopen("T5\\10km\\A00G\\T51\\P51IA.out", "r");
        Ebptr = fopen("T5\\10km\\A00G\\T51\\P51EB.out", "r");
        Ibptr = fopen("T5\\10km\\A00G\\T51\\P51IB.out", "r");
        Ecptr = fopen("T5\\10km\\A00G\\T51\\P51EC.out", "r");
        Icptr = fopen("T5\\10km\\A00G\\T51\\P51IC.out", "r");
        for(j=0; j<=N; j++)
        {
                fscanf(Eaptr,"%f",&Ea1[j]);
                fscanf(Iaptr,"%f",&Ia1[j]);
                fscanf(Ebptr,"%f",&Eb1[j]);
                fscanf(Ibptr,"%f",&Ib1[j]);
                fscanf(Ecptr,"%f",&Ec1[j]);
                fscanf(Icptr,"%f",&Ic1[j]);
        }
                for(j=0; j<=(N-1); j++)
        {
```

```
                    fscanf(Eaptr,"%f",&Ea1[j]);
                    fscanf(Iaptr,"%f",&Ia1[j]);
                    fscanf(Ebptr,"%f",&Eb1[j]);
                    fscanf(Ibptr,"%f",&Ib1[j]);
                    fscanf(Ecptr,"%f",&Ec1[j]);
                    fscanf(Icptr,"%f",&Ic1[j]);
                    Ia1[j] = (Ia1[j]*1000);
                    Ea1[j] = (Ea1[j]*100);
                    Ib1[j] = (Ib1[j]*1000);
                    Eb1[j] = (Eb1[j]*100);
                    Ic1[j] = (Ic1[j]*1000);
                    Ec1[j] = (Ec1[j]*100);
                    Ea[j] = (int)Ea1[j];
                    Ia[j] = (int)Ia1[j];
                    Eb[j] = (int)Eb1[j];
                    Ib[j] = (int)Ib1[j];
                    Ec[j] = (int)Ec1[j];
                    Ic[j] = (int)Ic1[j];
               }
               Dist = algologic(Ea, Ia, Eb, Ib, Ec, Ic, Emax, Imax, N, Results);
               c =  Results[1];
     chan_out_word(c, out_ports[0]);
               fclose(Eaptr);
               fclose(Iaptr);
               fclose(Ebptr);
               fclose(Ibptr);
               fclose(Ecptr);
               fclose(Icptr);
     }
```

D.2.3 C Program: Prog2

```
/*
** Prog1.c stand-alone processing task. Communicates with Mprog.c.
*/
#include <chan.h>
#include <ctype.h>
#include <stdio.h>
```

```c
#define LLength 100
#define N 1500
#define  Emax 5
#define  Imax 5
int algologic(int*, int*, int*, int*, int*, int*, int, int, long, int*);
main(int argc, char *argv[], char *envp[],
    CHAN * in_ports[], int ins,
    CHAN *out_ports[], int outs)
{
        int c, j, Results[5], Ea[N], Ia[N], Eb[N], Ib[N], Ec[N], Ic[N];
        float Ia1[N], Ea1[N], Eb1[N], Ib1[N], Ec1[N], Ic1[N], Dist;
        FILE *Eaptr, *Iaptr, *Ebptr, *Ibptr, *Ecptr, *Icptr;
chan_in_word(&N1, in_ports[0]);
        Eaptr = fopen("T5\\10km\\A00G\\T52\\P52EA.out", "r");
        Iaptr = fopen("T5\\10km\\A00G\\T52\\P52IA.out", "r");
        Ebptr = fopen("T5\\10km\\A00G\\T52\\P52EB.out", "r");
        Ibptr = fopen("T5\\10km\\A00G\\T52\\P52IB.out", "r");
        Ecptr = fopen("T5\\10km\\A00G\\T52\\P52EC.out", "r");
        Icptr = fopen("T5\\10km\\A00G\\T52\\P52IC.out", "r");
        for(j=0; j<=N; j++)
        {
                fscanf(Eaptr,"%f",&Ea1[j]);
                fscanf(Iaptr,"%f",&Ia1[j]);
                fscanf(Ebptr,"%f",&Eb1[j]);
                fscanf(Ibptr,"%f",&Ib1[j]);
                fscanf(Ecptr,"%f",&Ec1[j]);
                fscanf(Icptr,"%f",&Ic1[j]);
        }
                for(j=0; j<=(N-1); j++)
        {
                fscanf(Eaptr,"%f",&Ea1[j]);
                fscanf(Iaptr,"%f",&Ia1[j]);
                fscanf(Ebptr,"%f",&Eb1[j]);
                fscanf(Ibptr,"%f",&Ib1[j]);
                fscanf(Ecptr,"%f",&Ec1[j]);
                fscanf(Icptr,"%f",&Ic1[j]);
                Ia1[j] = (Ia1[j]*1000);
                Ea1[j] = (Ea1[j]*100);
```

```
                Ib1[j] = (Ib1[j]*1000);

                Eb1[j] = (Eb1[j]*100);

                Ic1[j] = (Ic1[j]*1000);

                Ec1[j] = (Ec1[j]*100);

                Ea[j] = (int)Ea1[j];

                Ia[j] = (int)Ia1[j];

                Eb[j] = (int)Eb1[j];

                Ib[j] = (int)Ib1[j];

                Ec[j] = (int)Ec1[j];

                Ic[j] = (int)Ic1[j];

        }

        Dist = algologic(Ea, Ia, Eb, Ib, Ec, Ic, Emax, Imax, N, Results);

        c =  Results[1];

        chan_out_word(c, out_ports[0]);

        fclose(Eaptr);

        fclose(Iaptr);

        fclose(Ebptr);

        fclose(Ibptr);

        fclose(Ecptr);

        fclose(Icptr);

}
```

Appendix E

EMTDC PSCAD

EMTDC is an electromagnetic transient program, which simulates the practical power systems for analysis. In EMTDC, the power system components are defined by using FORTRAN code. PSCAD stands for Power System Computer Aided Design, which provides a user interface to the EMTDC. PSCAD has a built-in library of models of power system components, which can be configured by adjusting their parameters. A used defined model can also be created in PSCAD. PSCAD also supports models written in C/C++ code.

All the power system simulations, described in this thesis, were done in EMTDC. The data generated from the simulation studies was used to test the performance of the proposed transmission line protection techniques.