Chapter One

Introduction

1.1 Background

Electric power systems are most often divided into three main units: the generating unit, transmission unit and distribution unit. In such a system the transmission units have the main responsibility of supplying the generated electric energy to distribution units, where the major electric consumers are located. Since delivery of electric energy to consumers is the aim of electric systems there is a great importance for operation of transmission unit [1].

The rapid growth of electric power systems over the past few decades has resulted in a large increase of the number of lines in operation and their total length. These lines are exposed to faults as a result of lightning, short circuits, faulty equipment, human errors, overload, and aging.

Faults are 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 [2].

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. 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.

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 [3].

1.2 Technological Developments for the Relays

The relays play the most important role in protection scheme because they detect the fault, determines fault location and also by closing trip coils send tripping command to circuit breakers. Design of such relays undertakes considerable technological developments from the first immerged relays and can be classified as:

1.2.1 Electromechanical Relays

In the earliest design of protection relays moving mechanical parts are utilized. Working principal of electromechanical relays is based on the electromagnetic interactions. In these relays by inception of fault the current flow in one or more windings on a magnetic core or cores results in mechanical forces required to move the mechanical parts [4].

1.2.2 Solid-State Relays

These relays perform the same functions as electromagnetic relays using analogue electronic devices instead of coils and magnets. Therefore, they can be considered as an analogue electronic replacing the electromechanical relays. The protection functions are acquired by an analogue process of measured signals. Electronic devices such as transistors and diodes in combination with resistors, capacitors, inductors, etc., enable the signal processing and implementation of protection algorithms in such relay design.

1.2.3Numerical relays

In numerical relays microprocessors are used for implementation of the same protection logics as in case of the static relays. Processing of signals is carried out by conversion of input analogue signals into a digital representation and processing according to the appropriate protection algorithms implemented in the processors.

Nowadays, numerical relays utilizing digital techniques are used to protect almost all components of power systems. Furthermore a large number of functions previously implemented in separate protection relays can now be integrated in a single numerical relay unit.

1.3 Problem Statement

The continuity of electrical power supply to consumers is the most important role of the system. It is very crucial to equip the transmission lines with effective protection system in order to eliminate the faults as soon as possible to prevent fault from propagation to healthy sections.

The operational algorithm implemented inside the microprocessor in order to decide the line condition before signaling the circuit breaker represent the heart of the numeric relay.

It is very important to equip the numeric relay with effective, fast and accurate algorithm to protect the transmission line from faults

1.4 Objective

The objective of this dissertation is to develop new concept of transmission line protection scheme based on traveling waves. Distance protection algorithm based on travelling waves is to be developed in order to decide the condition of the system either it is normal or faulty.

The algorithm will be implemented in the MATLAB software used for transient study of power systems to verify the performance of newly developed scheme.

1.5 Outline of the Thesis

The organization of the thesis is includes five chapters summarized as follow:

Chapter two is about the concept of travelling waves in power system

Chapter three presents the design of numeric travelling waves relay and associated algorithms

Chapter four investigate the simulation results of the relay used with the transmission line

Chapter five is about conclusion and recommendations

Chapter Two

Traveling Waves in Transmission Lines

2.1 Introduction

Traveling wave phenomenon in high voltage lines constitutes one of the shortest system transients. It occurs from microseconds to milliseconds. Traveling waves are associated with the propagation of electromagnetic waves which result from the short circuits in transmission lines and the lightning or switching operations in power system. A sudden and significant change in voltage in at least one place within the high voltage line (Figure 2.1) leads to the initiation of an electromagnetic wave which propagates from that point in opposite directions.

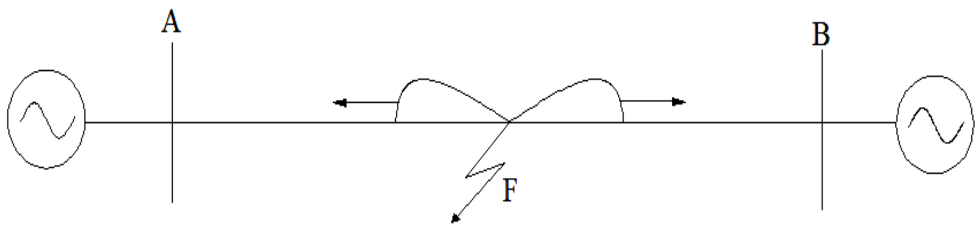

Figure 2.1: Propagation of electromagnetic wave as a result of fault

Electromagnetic wave can be divided into a voltage wave associated with phenomena occurring in the electric field and a current wave associated with the magnetic field. An important feature of such wave is moving the specific values of voltage and current along the lines with finite speed [5].

2-2 Propagation Theory of the Traveling Waves

The disturbance of the transmission line at any point is appears as a change in steady state power equation and propagate travelling wave in both directions of line terminals.

Consider a small section of length dx of transmission line as shown in Figure 2.2 travelling wave of the voltage (V) and current (I) are generated when a fault occurs on the transmission line.

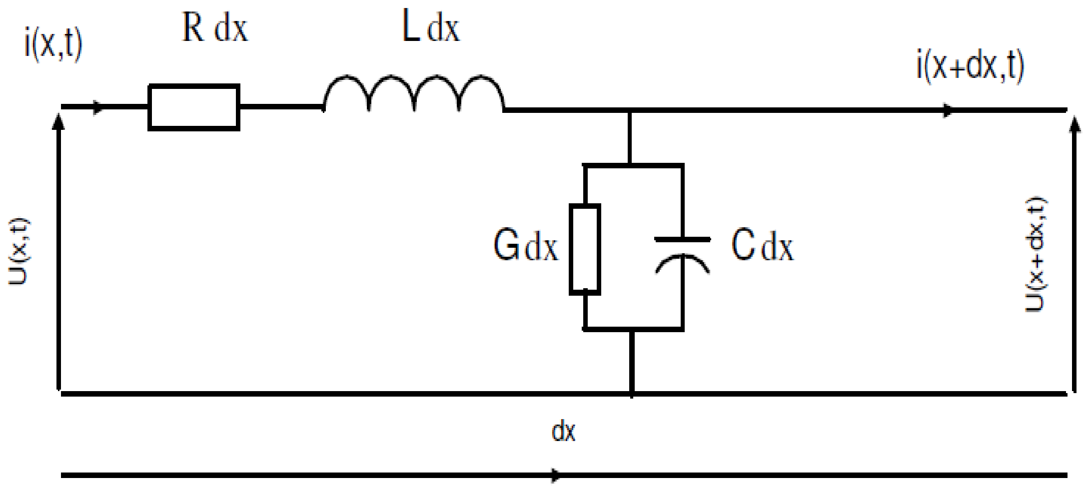

Figure 2.2: Single-phase transmission line model

The travelling waves of voltage drop in the positive x direction in the magnetic flux crated by the electromagnetic wave.

$$dV = Ridx + \frac{\delta\psi}{\delta t} \tag{2.1}$$

The change of flux linkages is equal $Lidx$,thus,

$$dV = Ridx + L\frac{\delta(idx)}{\delta t} + i\frac{\delta(Ldx)}{\delta t} \tag{2.2}$$

$$i\frac{\delta(Ldx)}{\delta t} = \text{Zero}$$

$$\frac{dV}{dx} = Ri + L\frac{di}{dt} \tag{2.3}$$

The travelling wave of the current through the leakage conductance (G) and capacitance(C)

$$di = GVdx + \frac{\delta\varphi}{\delta t} \tag{2.4}$$

φ is the change in the electric flux and equal CVdx ,thus,

$$di = VGdx + C\,\frac{\delta(Vdx)}{\delta t} + V\,\frac{\delta(Cdx)}{\delta t} \qquad (2.5)$$

$$V\,\frac{\delta(Cdx)}{\delta t} = \text{Zero}$$

$$\frac{di}{dx} = VG + C\,\frac{dV}{dt} \qquad (2.6)$$

Taking Laplace transform with respect to time variable t for equation (2.3) and (2.6)

$$\frac{dV_x}{dx} = (R + Ls).I_x = ZI_x \qquad (2.7)$$

$$\frac{dI_x}{dx} = (G + Cs).Vx = YV_x \qquad (2.8)$$

Assumed for the elemental section does not affect these first order differential relations.

Differentiating equation (2.7)

$$\frac{d^2V_x}{dx^2} = Z\,\frac{dI_x}{dx} \qquad (2.9)$$

And substituting the value of $\frac{dIx}{dx}$ from equation (2.9)

$$\frac{d^2V_x}{dx^2} = ZYVx \qquad (2.10)$$

Let $\gamma = \sqrt{ZY}$

$$\frac{d^2V_x}{dx^2} - \gamma^2 Vx = 0 \qquad (5.11)$$

The general solution of this equation

$V_x = A_1\ e^{\gamma x} + A_2\ e^{-\gamma x}$ (2.12)

The current equation can be obtained from the

$\frac{dV_x}{dx} = ZI_x$

$I_x = \frac{1}{Z} \cdot \frac{dV_x}{dx}$

$I_x = \frac{\gamma}{Z} (A_1\ e^{\gamma x} - A_2\ e^{-\gamma x})$

Where

$\gamma = \sqrt{ZY}$ it is called propagation constant

A_1 and A_2 are arbitrary constants to be evolved.

$I_x = \frac{\sqrt{ZY}}{Z} (A_1\ e^{\gamma x} - A_2\ e^{-\gamma x})$

$I_x = \sqrt{\frac{Y}{Z}} (A_1\ e^{\gamma x} - A_2\ e^{-\gamma x})$

$I_x = \frac{A_1}{Z_c} e^{\gamma x} - \frac{A_2}{Z_c} e^{-\gamma x}$ (2.13)

$Z_c = \sqrt{Z/Y}$ the characteristic impedance of the line.

The constant A_1 and A_2 may be evaluated using the end condition when x=0, $V_x = V_F$ and $I_x = I_F$ substituting in equation (2.12) an(2.13)

$V_F = A_1 + A_2$

$I_F = (A_1 - A_2)/\ Z_c$

By solving this equation can be obtained A_1 and A_2.

$A_1 = (V_F + Z_c I_F)/2$ (2.14)

$A_2 = (V_F - Z_c I_F)/2$ (2.15)

Where

V_F and I_F are post fault voltage and current

By substituting the value of A_1 and A_2 in equation (2.12) and (2.13).

$$V_x = ((V_F + Z_c I_F)/2)\, e^{\gamma x} + ((V_F - Z_c I_F)/2) e^{-\gamma x} \tag{2.16}$$

$$I_x = ((V_F/Z_c + I_F)/2)\, e^{\gamma x} - ((V_F/Z_c - I_F)/2) e^{-\gamma x} \tag{2.17}$$

When the propagation constant it is complex number

$\gamma = \alpha + J\beta$

Where

α = attenuation constant

β = phase constant

The value of V_x and I_x can be written

$$V_x = ((V_F + Z_c I_F)/2)\, e^{\alpha x} e^{j\beta x} + ((V_F - Z_c I_F)/2) e^{-\alpha x} e^{-j\beta x} \tag{2.18}$$

$$I_x = ((V_F/Z_c + I_F)/2)\, e^{\alpha x} e^{j\beta x} - ((V_F/Z_c - I_F)/2) e^{-\alpha x} e^{-j\beta x} \tag{2.19}$$

Transforming from phase domain to time domain, the instantaneous voltage as a function of $V_x(t)$ becomes.

$$V_x = ((V_F + Z_c I_F)/2) e^{\alpha x} e^{j(wt+\beta x)} + ((V_F - Z_c I_F)/2) e^{-\alpha x} e^{-j(wt+\beta x)} \tag{2.20}$$

And the instantaneous current as a function $I_x(t)$ can be written as

$$I_x = ((V_F/Z_c + I_F)/2)\, e^{\alpha x} e^{j(wt+\beta x)} - ((V_F/Z_c - I_F)/2) e^{-\alpha x} e^{-j(wt+\beta x)} \tag{2.21}$$

Equations (2.20) and (2.21) are used to obtain travelling wave at any point on the line at distance x from the fault point.

2.3 Forward and Backward of the Travelling Waves

The travelling wave equation consists as two terms:

The first term in equation (18) and (19) the progress along the line represent the forward part of the travelling wave. And the second term diminishes in magnitude represent the backward part of the travelling wave [6].

The two terms as function of two variables time (t) and distance (x)

$$V_x = V^f + V^r \tag{2.22}$$

Where

$$V^f = ((V_F + Z_c I_F)/2)\, e^{\alpha x} e^{j(wt+\beta x)} \tag{2.23}$$

Is called forward travelling voltage wave.

$$V^r = ((V_F - Z_c I_F)/2) e^{-\alpha x} e^{-j(wt+\beta x)} \tag{2.24}$$

Is called reflected voltage or reverse travelling voltage wave.

And it is similarly the current travelling wave equation.

$$I_x = I^f - I^r \tag{2.25}$$

Where

$$I^f = ((V_F/Z_c + I_F)/2)\, e^{\alpha x} e^{j(wt+\beta x)} \tag{2.26}$$

is called forward travelling current wave.

$$I^r = ((V_F/Z_c - I_F)/2) e^{-\alpha x} e^{-j(wt+\beta x)} \tag{2.27}$$

Is called reflected current or reverse travelling current wave.

2.4 Interpretation

Equation 2.9 indicates that there are two components of the voltage at any location on the transmission line. Components represent traveling waves.

The component $Ae^{\gamma x}$ represents the wave travelling in the forward direction and $Be^{-\gamma x}$ represents the wave travelling in the backward direction. The voltage and current can also be expressed as

$$V = V^{+} + V^{-} \quad (2.28)$$

$$I = I^{+} + I^{-} \quad (2.29)$$

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

$$V^{+} = Z_0 I^{+} \quad (2.30)$$

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

$$V^{-} = -Z_0 I^{-} \quad (2.31)$$

A typical positive traveling wave, as shown in Figure 2.3, has the following properties [7].

• 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.

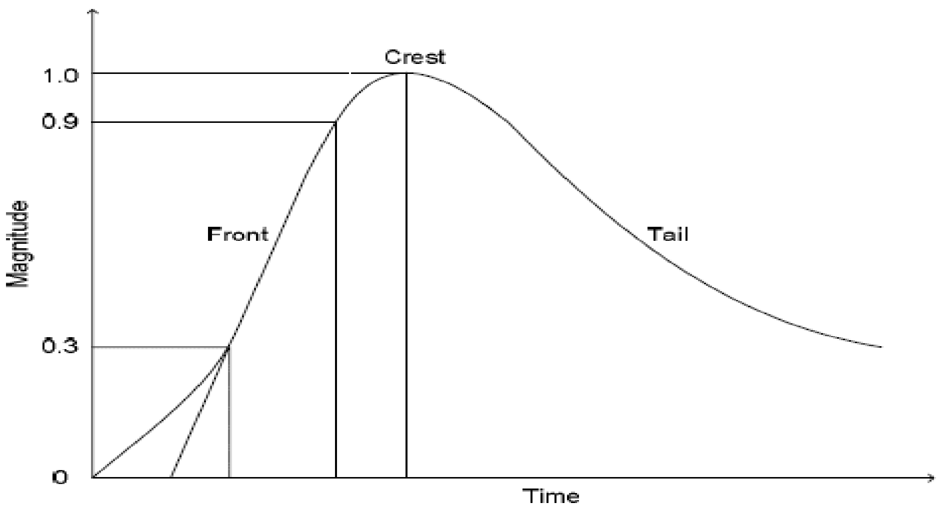

Figure 2.3 A positive traveling wave

2-5 Propagation Constant

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

$$\gamma = \alpha + J\beta \qquad (2.32)$$

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?

2-6 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, which is reproduced in Figure 2.4 This diagram shows the propagation of traveling waves that originates at a fault location that is 80 km from bus A, on a transmission line of 100 km length.

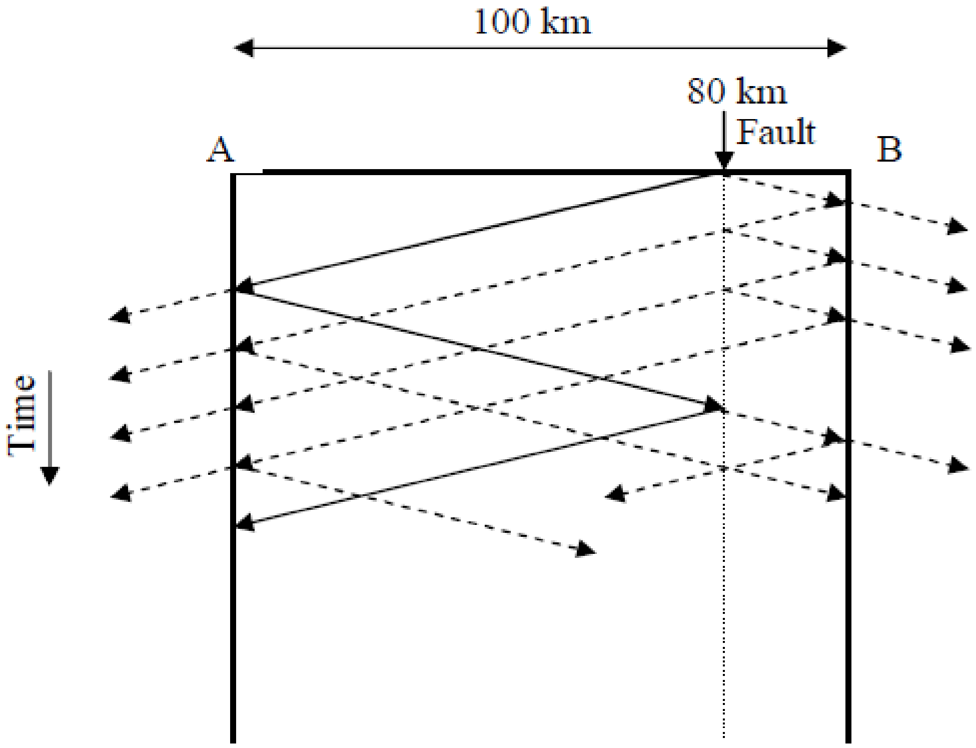

Figure 2.4 Bewley's Lattice diagram

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_0 From Equations 2.30 and 2.31,

$$Z_0 = \frac{V^+}{I^+} \tag{2.33}$$

$$-Z_0 = \frac{V^-}{I^-} \tag{2.34}$$

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

$$Z_t = \frac{V^t}{I^t} \tag{2.35}$$

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

$$V^t = V^+ + V^- \tag{2.36}$$

$$I^t = I^+ + I^- \tag{2.37}$$

Substituting Equations 2.36 and 2.37 in Equation 2.35 provides,

$$Z_t = \frac{V^+ + V^-}{I^+ + I^-} \tag{2.38}$$

Substituting for I^+ and I^- from Equations 2.30 and 2.31 in this equation gives

$$\frac{Z_t}{Z_0} = \frac{V^+ + V^-}{V^+ - V^-}$$

Rearranging this equation provides,

$$\frac{V^-}{V^+} = \frac{Z_t - Z_0}{Z_t + Z_0} \tag{2.39}$$

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

$$\rho_V = \frac{Z_t - Z_0}{Z_t + Z_0} \tag{2.40}$$

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

$$\rho_i = \frac{Z_0 - Z_t}{Z_0 + Z_t} \tag{2.41}$$

2.7 Line Termination

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

2.7.1 Line Terminated in a Short Circuit

When a transmission line is terminated in a short circuit, the voltage at the termination is zero. Equation 2.36 now becomes

$$V^{+} + V^{-} = 0$$

Rearranging the equation provides,

$$V^{-} = -V^{+} \qquad (2.42)$$

Substituting for V^{+} and V^{-} from Equations 2.30 and 2.31 in this equation, and rearranging provides,

$$I^{+} = I^{-} \qquad (2.43)$$

Substituting Equations 2.42 and 2.43 in Equation 2.38 provides,

$$Z_t = 0 \qquad (2.44)$$

Substituting Z_t in Equations 2.40 and 2.41 provides,

$$\rho_V = -1 \qquad (2.45)$$

$$\rho_i = +1 \qquad (2.46)$$

2.7.2 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 2.37, in this case, becomes.

$$I^{+} + I^{-} = 0$$

Rearranging this equation provides,

$$I^{+} = -I^{-} \qquad (2.47)$$

Substituting for $I^{+}$and I^{-} from Equations 2.30 and 2.31, and rearranging provides,

$$V^{-} = V^{+} \tag{2.48}$$

Substituting Equations 2.47 and 2.48 in Equation 2.38 provides,

$$Z_t = \infty \tag{2.49}$$

Substituting Z_t in Equations 2.40 and 2.41 provides,

$$\rho_V = +1 \tag{2.50}$$

$$\rho_i = -1 \tag{2.51}$$

2.8 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 [8].

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 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 [9 , 10].

$$V_f(x,t) = f^{+}\left[t - \frac{x}{v}\right] + f^{-}\left[t + \frac{x}{v}\right] \tag{2.52}$$

$$i_f(x,t) = \frac{1}{Z_0}\left[f^{+}\left[t - \frac{x}{v}\right] - f^{-}\left[t + \frac{x}{v}\right]\right] \tag{2.53}$$

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_0 is surge impedance of the transmission line, and

x is the distance traveled by the traveling waves.

Rearranging Equations 2.52 and 2.53 provides,

$$2f^+\left[t - \frac{x}{v}\right] = V_f(x,t) + Z_0 i_f(x,t) \quad (2.54)$$

$$2f^-\left[t + \frac{x}{v}\right] = V_f(x,t) - Z_0 i_f(x,t) \quad (2.55)$$

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

2.8.1 Chamia and Liberman Technique

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

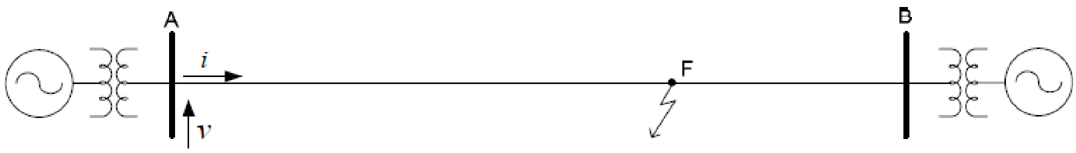

Figure 2.5 Voltage and current at fault inception

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.

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

$$V_f = V - V' \tag{2.56}$$

$$i_f = i - i' \tag{2.57}$$

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.

2.8.2 Crossley and McLaren Technique

Crossley and McLaren proposed a traveling waves technique [11] 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 $\emptyset_{ir}$ is the discrete correlation function establishing a correlation between incident signal, i and reflected signal, r.

$$\emptyset_{ir}(\tau) = \frac{1}{N} \sum_{k=1}^{N} i(k\Delta t + \tau) \, .r(k\Delta t) \tag{2.58}$$

Where,

i is the incident signal,

r is the reflected 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 time's velocity of propagation of traveling waves.

$$D = \frac{T * V}{2} \tag{2.59}$$

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 Three

Design of Numeric Travelling Waves Relay

3.1 Introduction

Numerical protection relays operate on the basis of sampling inputs and controlling outputs to protect or control the monitored system. System currents and/or voltages, for example, are not monitored on a continuous basis but, like all other quantities, are sampled one at a time. After acquiring samples of the input waveforms, calculations are performed to convert the incremental sampled values into a final value that represents the associated input quantity based on a defined algorithm. Once the final value of an input quantity can be established, the appropriate comparison to a setting, or reference value, or some other action, can be taken as necessary by the protection relay. Depending upon the algorithm used, and other system design or protection requirements, the final value may be calculated many times within a single sampling cycle, or only once over many cycles [12].

3.2 Protective Relays

The Protective Relay is used to give an alarm or to cause prompt removal of any element of power system from service when that element behaves abnormally. Fault current is the expression given to the current that flow in the circuit when load is shorted That is, flow in a path other than the load. This current is usually very high and may exceed ten times the rated current of a piece of plant. Faults on power system are inevitable due to external or internal causes, lightning may struck the overhead lines causes insulation damage. Internal overvoltage due switching or other power system phenomenon may also cause an over voltage leads to deterioration of the insulation and faults. Power networks are usually protected by means of two main components, relays that sense the abnormal current or voltage and a circuit breaker that put a piece of plant out of tension. Power System Protection is the art and science of the application of devices that monitor the power line currents and voltages (relays) and generate signals to de energize faulted sections of the power network by circuit breakers. The Goal is to minimize damage to equipment and property that would be caused by system faults, if residues, and maintain the delivery of electrical energy to the consumers. Many types of protective relays are used to protect power system equipment, they are classified according to their operating principles; over current relay senses the extra (more than set) current considered dangerous to a given equipment, differential relays compare in and out currents of a protected equipment, while impedance relays measure the impedance of the protected piece of planet. For a good performance of a relay in a power system it must have the following characteristics; dependability, security, selectivity, sensitivity and speed [13].

3.3 Numeric Relay Hardware

Figure 3.1.shows the general hardware outline of a numeric protection relay. Relaying voltages at 110 V or 50 V and currents, at 5 A or 1 A, are first passed through isolation transformers. Since analogue to digital conversion is usually performed on voltages, the current signals are converted to representative voltage signals by, for example, passing the current through a known resistance value. All the signals are then filtered using very simple. Since A/D are expensive it is common to find only one used in a digital relay, thus an analogue multiplexer, under microprocessor control, is used sequentially to select the required signal into the A/D. Because the A/D takes a finite conversion time, typically 25 μs, it is necessary to hold the incoming signal for the duration of the conversion; this is achieved with the sample and hold amplifier. Having been converted by the A/D, the signals can now be manipulated by the microprocessor. It is common to find more than one microprocessor in used. The relaying program will be located in the read only

memory (ROM), and the random access memory (RAM) will be used for storing sampled quantities and intermediate products in the relaying algorithm. Relay settings are stored in the electrically erasable programmable read only memory (E-PROM) [14].

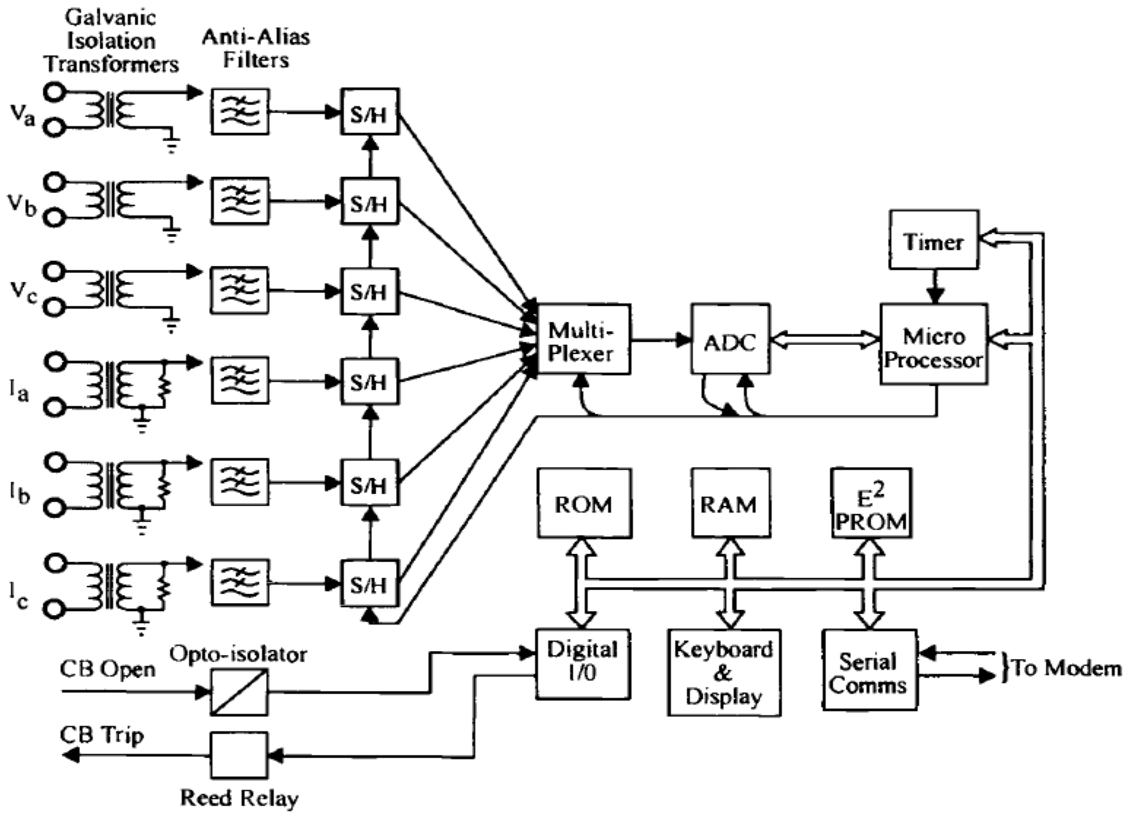

Figure 3.1 Typical numeric relay hardware

3.4 Software Considerations

Much emphasis has been placed within these pages on the hardware of numeric relays. However, an increasingly large part of a numeric relay development project is spent on software development and so it is appropriate to describe the stages involved in this process. On reception of a software specification for inclusion in the design of a relay, the software designer carries out a detailed analysis of what is required in the specification. There must be full understanding of the specification's intent and the designer must have the foresight to ensure that the requirements can be met physically before starting on the software design.

3.5 Design of Travelling Wave relay

The numeric travelling wave relays include hardware and software components.

3.5.1 Hardware Components

The Hardware component used in travelling wave relay is consist from group of element voltage transformer (VT) and current transformer (CT) as isolated transformer, All the signals passed through filter , Sample and Hold (S&H), Analogue to digital convertor A/D, analogue multiplexer, algorithm implemented in travelling wave equation, and Decision.

3.5.1.1 Proposed Protection Scheme

The decision making process in proposed transient based protection scheme and overall functionality of the numerical relay model used in such scheme are explained. The model for a transient based numerical relay unit installed at each terminal of the transmission line is proposed in Figure 3.2.

In such relay unit the data processing of signals starts at analog information unit as shown in Figure 3.2. Since the protection scheme is based on forward and backward travelling waves for all phases of fault transients in voltage and current signals, the analog information unit accepts the analog measurements of three-phase current and voltage from secondary side of measurement instruments. Afterwards, signals pass through the digital transformation unit where an analog to digital conversion takes place. Thus, converted digital voltage and current signals will be available at the input of fault transient detection unit.

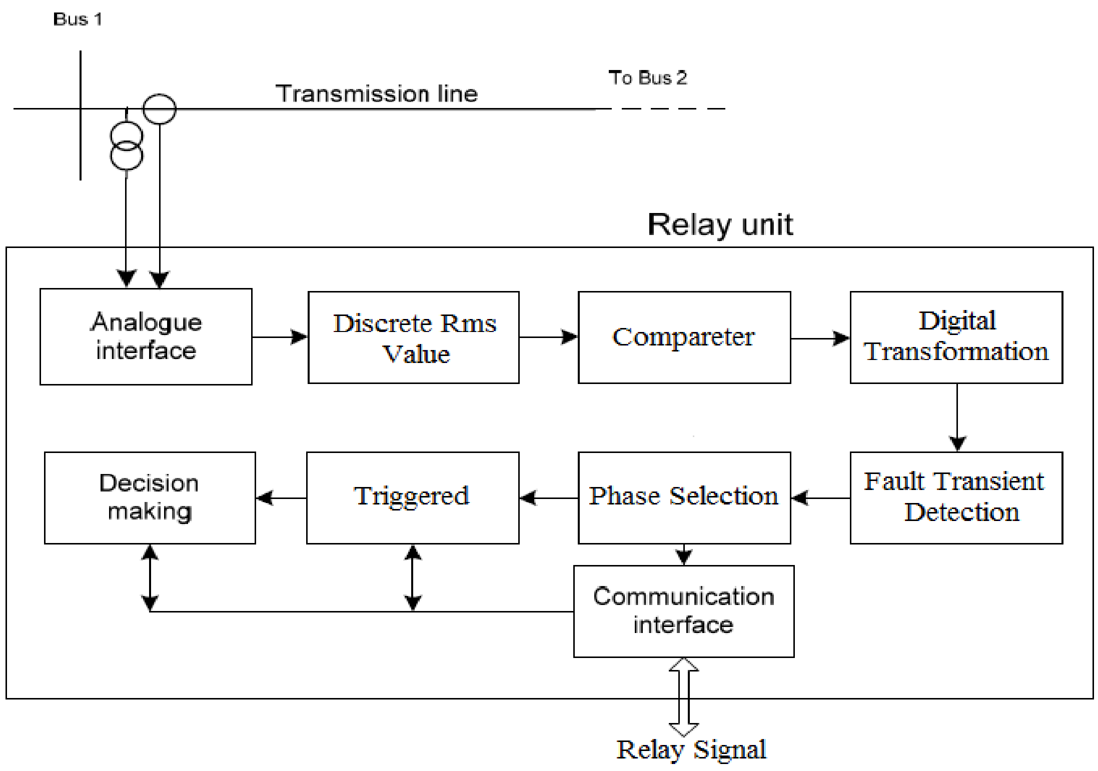

Figure 3.2 Transient based numerical relay unit

3.5.2 Software Program

The software program depend on calculating the forward and backward travelling waves in order to decide the system conditions based on setting specified value.

The code for the proposed techniques is written using MATLAB program in M-File. The inputs are system voltage, currents and parameters and the output is forward and backward waves as shown in Figure 3.3 to Figure 3.6. The code is equipped in microprocessor ROM and the input is entered through ADC converter as shown in Figure 3.1. The microprocessor calculated the traveling wave's component using the developed code to sent/not sent trip signals.

The developed code is written as follow:

```
% enter parameters of the system model
t = 0:1E-3:20E-2;
u=0.000023507;
```

```
q=0.00130044;
V=336000;
zc=270000+4.89*1i;
Z=1410.7;
W=2*pi*60;
I=V/Z;
x=200;
x1=exp(u*x)*(cos(+q*x)+1i*sin(q*x));
x2=exp(-u*x)*(cos(-q*x)+1i*sin(-q*x));
vr = V*cos(W*t);
vy = V*cos(W*t-2*pi/3);
vb = V*cos(W*t-4*pi/3);
a_deg = (30); % angle in degree
ir = I*cos(W*t + a_deg);
iy = I*cos(W*t + a_deg-2*pi/3);
ib = I*cos(W*t + a_deg-4*pi/3);
%find forward and backward voltage travelling wave
VFr=((vr+zc*ir)/2)*x1;
VFy=((vy+zc*iy)/2)*x1;
VFb=((vb+zc*ib)/2)*x1;
VRr=((vr-zc*ir)/2)*x2;
VRy=((vy-zc*iy)/2)*x2;
VRb=((vb-zc*ib)/2)*x2;
%find forward and backward current travelling wave
IFr=((vr/zc+ir)/2)*x1;
IFy=((vy/zc+iy)/2)*x1;
IFb=((vb/zc+ib)/2)*x1;
IRr=((vr/zc-ir)/2)*x2;
IRy=((vy/zc-iy)/2)*x2;
IRb=((vb/zc-ib)/2)*x2;
%find voltage and current at fault point travelling wave
VXr=VFr+VRr;
VXy=VFy+VRy;
VXb=VFb+VRb;
IXr=IFr-IRr;
IXy=IFy-IRy;
IXb=IFb-IRb;
figure(1),plot(t,VFr,'r',t,VFy,'y',t,VFb,'b')
xlabel('tim.sec')
ylabel('Voltage(V)')
title('forward voltge travelling wave')
figure(2),plot(t,VRr,'r',t,VRy,'y',t,VRb,'b')
xlabel('time.sec')
ylabel('Voltage(V)')
title('backward voltge travelling wave')
figure(3),plot(t,IFr,'r',t,IFy,'y',t,IFb,'b')
```

```
xlabel('time.sec')
ylabel('Current(A)')
title('forward current travelling wave')
figure(4),plot(t,IRr,'r',t,IRy,'y',t,IRb,'b')
xlabel('Sec')
ylabel('Current(A)')
title('backward current travelling wave')
```

The calculated travelling wave's components are shown in Figure 3.3 to Figure 3.6. Figure 3.3 is the forward voltage travelling wave, Figure 3.4 is the backward voltage travelling wave, Figure 3.5 is the forward current travelling wave, and Figure 3.6 is the backward current travelling wave

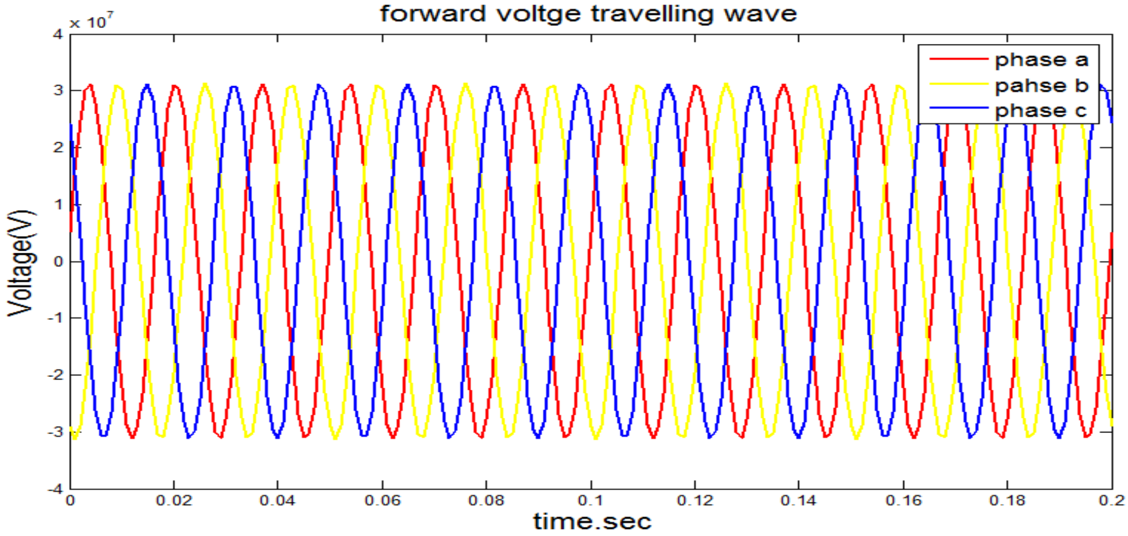

Figure 3.3 output of forward voltage travelling wave by MATLAB code

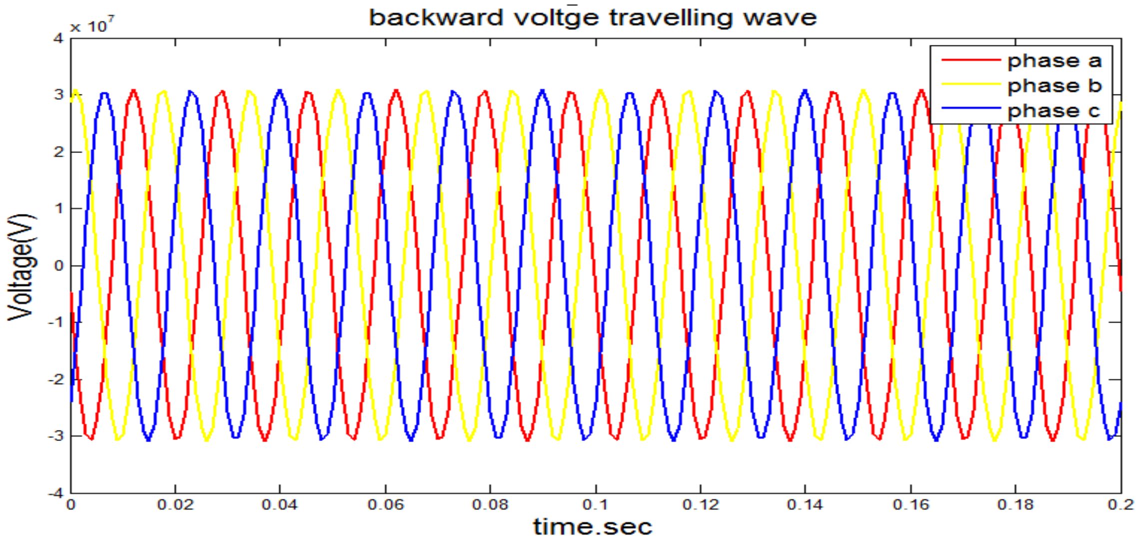

Figure 3.4 output of backward voltage travelling wave by MATLAB code

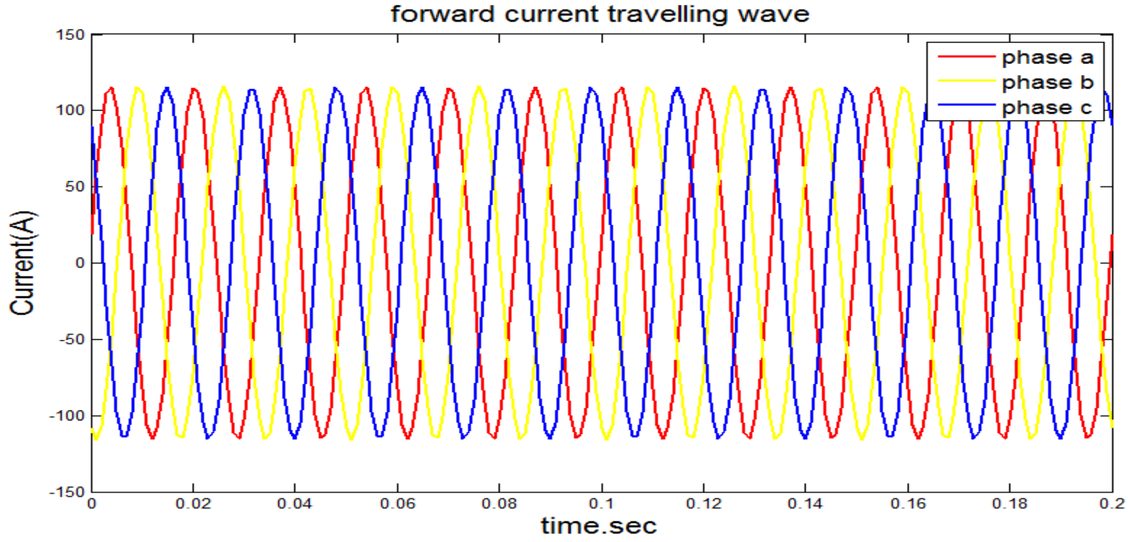

Figure 3.5 output of forward current travelling wave by MATLAB code

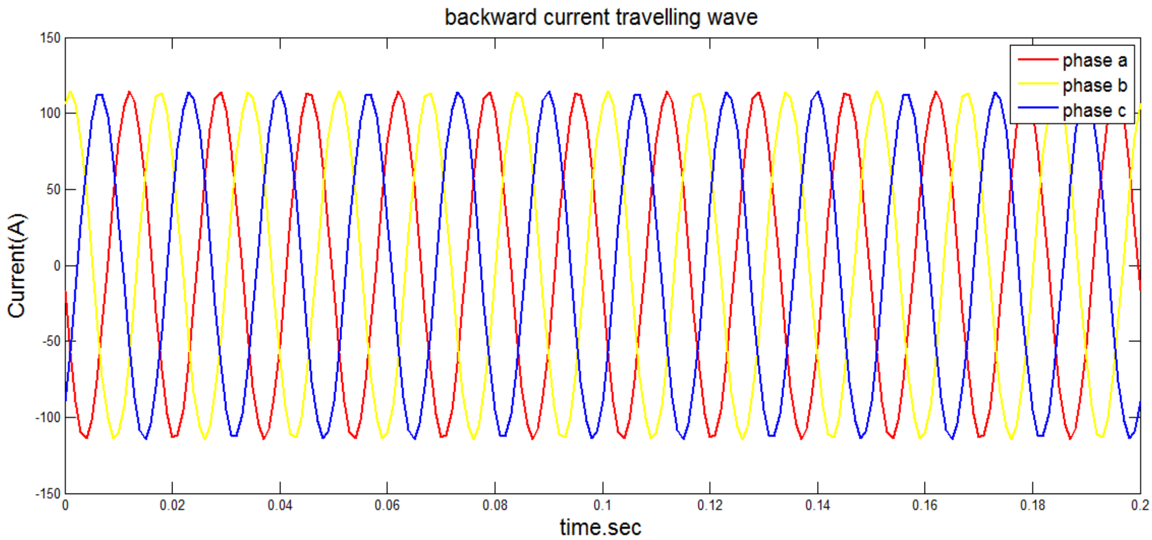

Figure 3.6 output of backward current travelling wave by MATLAB code

3.6 Developed algorithm and Simulink diagram of the relay

The traveling wave based protection algorithms are usually based on analysis of measured transients in voltage and current quantities at transmission line terminals. The traveling waves propagated in the system due to presence of abnormal conditions due to any reasons. The flow chart used to design the relay is shown in Figure 3.7

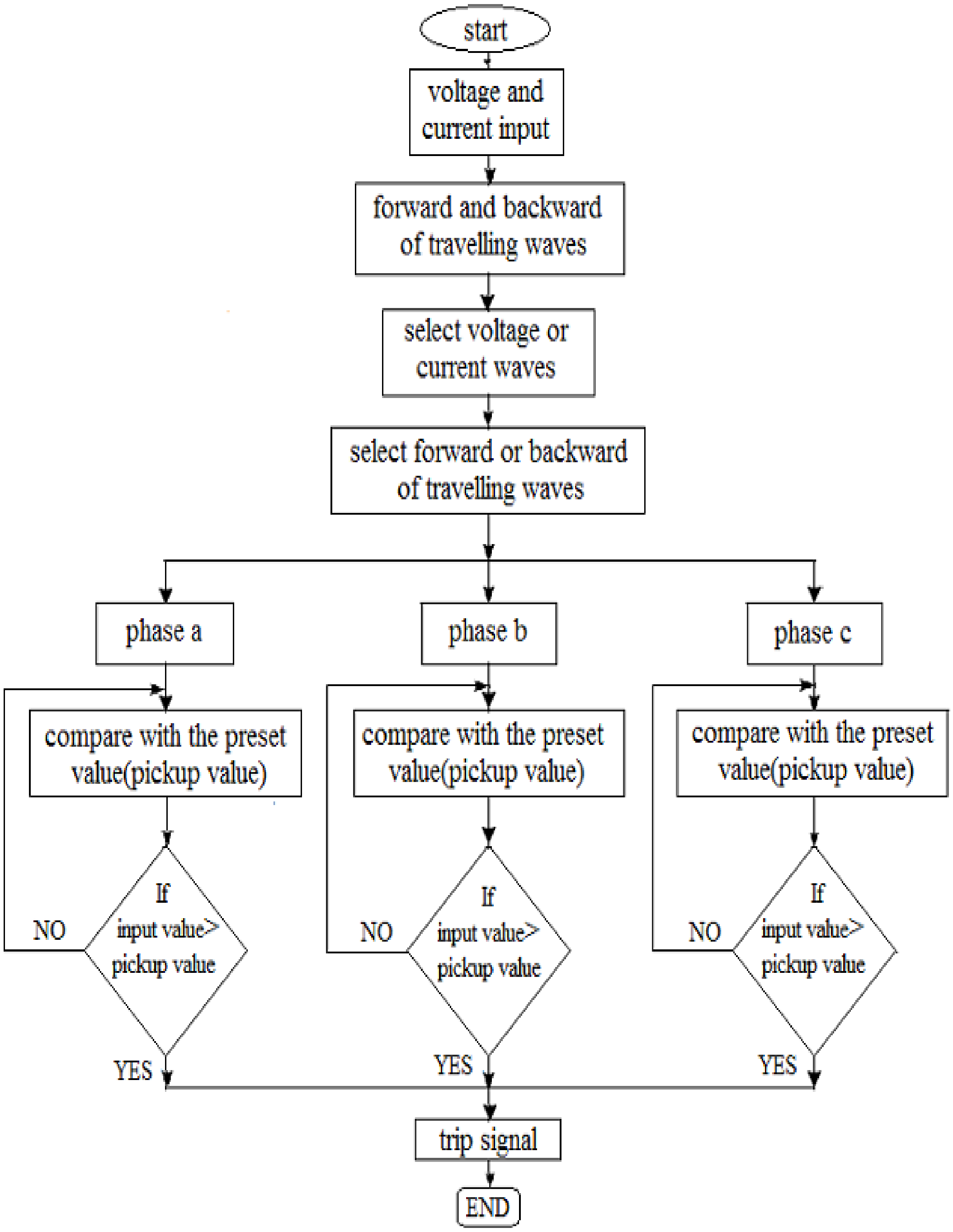

Figure 3.7 Travelling Wave Algorithm

The flow chart in Figure 3.7 is converted to Simulink blocks to simulate the operation of travelling wave relay. The Simulink blocks used to represent travelling wave relay is shown in Figure 3.8. The voltages and currents entre travelling wave calculating block which is built using equations (2.20) to (2.27). The output of travelling wave block is forward current (i_f) which is passed to RMS calculator. Each of 3-phase forward currents is compared to specified setting value. The AND gate is used to generate trip signal and sent it to triggered circuit. The triggered circuit finally signaled the circuit breaker to trip the circuit if there is an abnormal case.

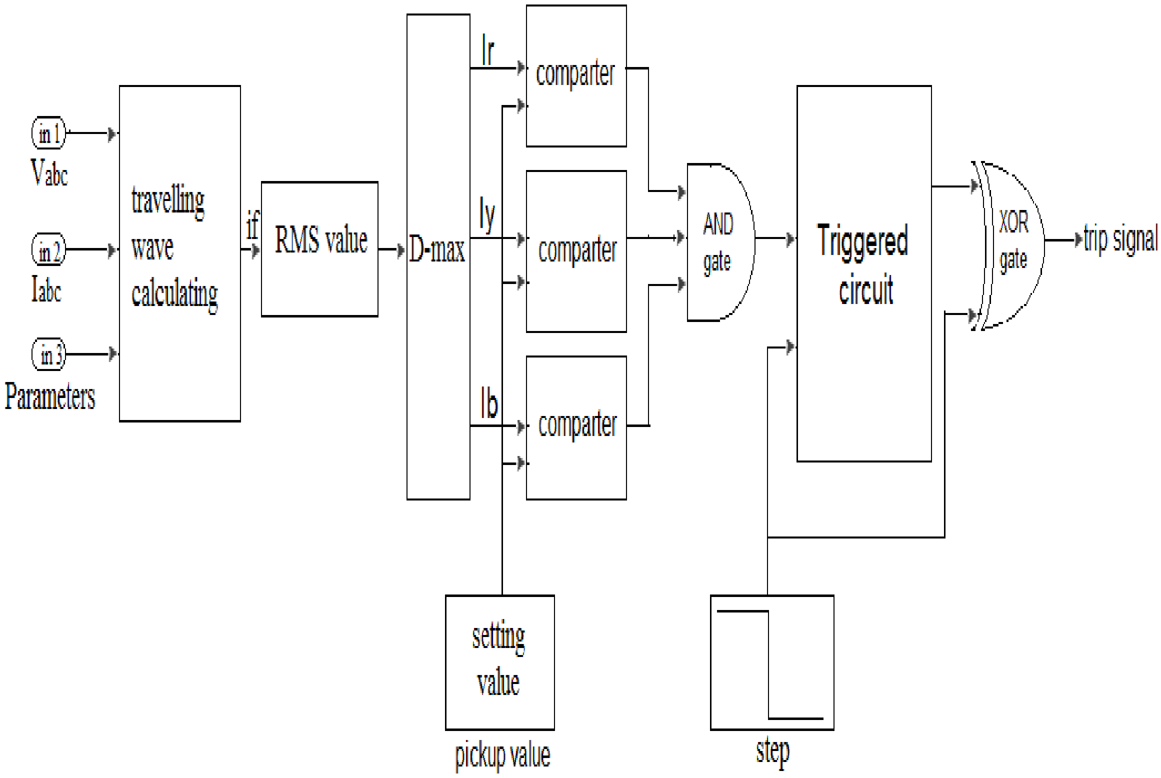

Figure 3.8 travelling wave relay Implemented in MATLAB/Simulink

3.7 Relay Communication

The relay discussed uses a 64 kbps channel that exchanges currents for differential protection purposes. The relay takes advantage of this bandwidth and includes travelling wave information within the data packet without affecting the performance of the differential element. The relays exchange the times of arrival of the travelling wave (see Figure 3.9) and use this information to estimate the fault location, make the results available at the relay location, and send the results to the control center within a couple of seconds after the occurrence of the fault [15].

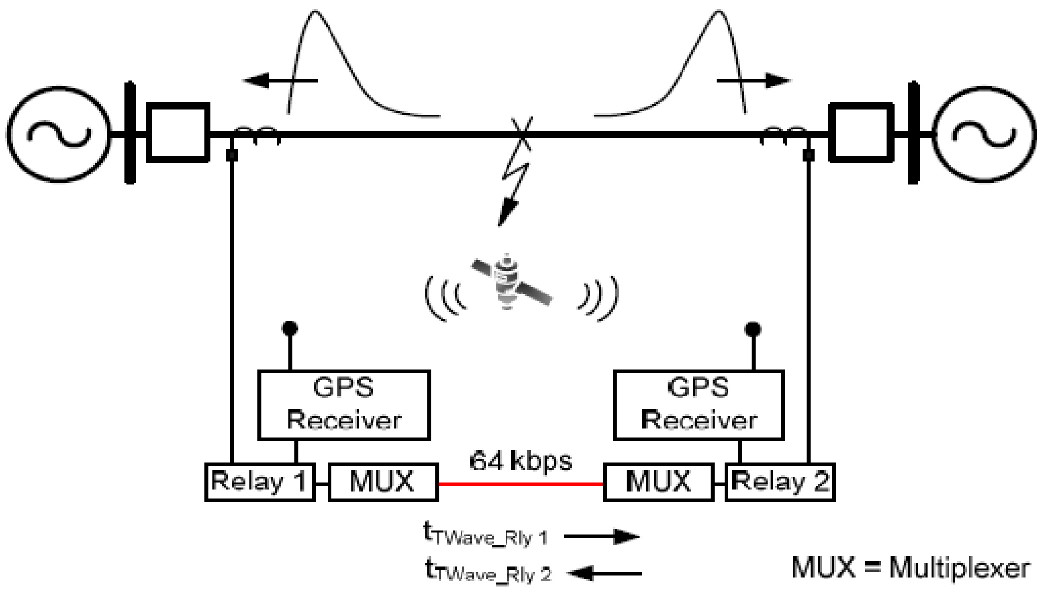

Figure 3.9 Relays communication

3.8 Fault Location

Fault location using traveling wave can be recognized with the help of Bewley lattice diagram. Consider voltage and current at any point x on transmission line. Forward (e_f and i_f) and reverse (e_r and i_r) waves leave the disturbed area "*x*" traveling in different directions. The velocity of the wave approaches the speed of light, this is not precisely (300 km/millisecond). In transmission lines the speed can be calculated by:

$$v = \sqrt{LC} \qquad (3.1)$$

Where:

L is the line inductance.

C is the line shunt capacitance.

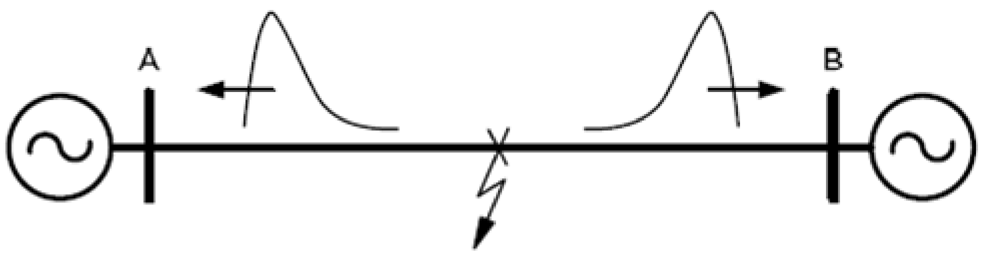

Figure.3.10 travelling waves in transmission line

Transmission line ends represent a discontinuity or impedance change where some of the wave's energy will reflect back to the disturbance. The remaining energy will travel to other power system elements or transmission lines as described by Bewley lattice diagram in chapter two.

If τ_a and τ_b represent the travel time from the fault to the discontinuity at begining and the end of the line, The traveling wave method relies on calculation of time (τ_a and τ_b) for the line disturbance to reach both ends of the line (total length of the line *l*).

Since the wave moves at near-light speed(c), by comparing the time difference of the arrival of the wave at each of the ends, the distance to the source of the disturbance can be determined. Either voltage or current wave data can be used.

$$x = \frac{(t_a - t_b).v}{2} \tag{3.2}$$

3.9 Summary

Traveling wave relay is designed based on travelling wave components generated when fault occur. Microprocessor is used to calculate the components using software code and then signaled the breaker to trip the circuit if fault exist.

The relay is designed in Simulink environment using travelling wave calculation block, AND gate and trigger circuit. Also fault location method can be used with the relay to determine the location of the fault.

Chapter Four

Simulation Results

4.1 Introduction

This chapter presents the simulation results to evaluate the operation of developed travelling wave relay. The developed travelling wave relay is implemented in MATLAB SIMULINK environment. The model has been created with a toolbox of MATLAB / SIMULINK called SimPowerSystems. It is a collection of blocks that allow the modeling of different elements that usually are present on power systems.

4.2 System Lay-Out

To study the operation of traveling waves relay, the system in Figure 4.1 is built in Simulink environment. The proposed system is composes of three-phase voltage source supplies a static load via π-section transmission line. Travelling waves relay is located at beginning of the line to protect the line against abnormal conditions.

The transmission line under study is operating at 400 kV, 1200MVA short-circuit level. A load of 400kV, 100MW and 100MVAr rating is connected at the sending end B_2 through transmission line of 200km long connected between B_1 and B_2.

Table 4.1. Simulation model software with following parameters

Component	Parameters
Voltage source	400KV, 60Hz, 1200MVA, X/R=8
Transmission Line	200 km, 400KV, R_1 =0.01273Ω/Km, L_1 =0.9337e-3H/Km, C_1=12.74e-9 F/Km, R_0 =0.3864Ω/Km, L_0 =4.126e-3H/Km, C_0=7.751e-9 F/Km
Fault resistance	100 ohm

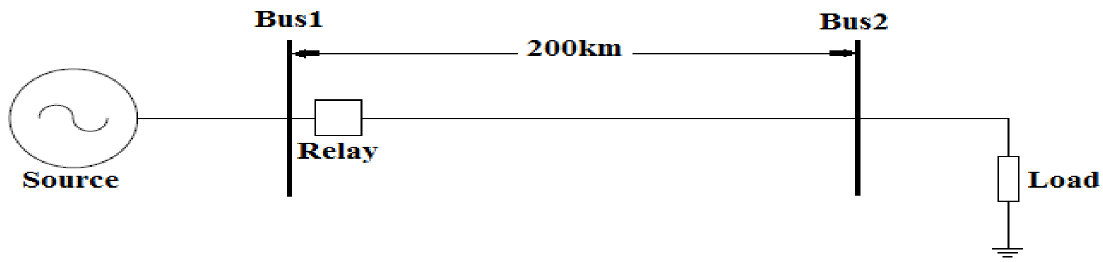

Figure 4.1 Single line diagram of Power System under Study

4.3 Simulation Cases Results

The investigation of the travelling waves relay is carried out using MATLAB Simulink environment. The system in Figure 4.1 is modeled and simulated in the MATLAB software with the parameters given in table 4.1.

The operational scenarios for traveling wave relay investigation include:

a) Operational during normal condition

b) Operational when symmetrical fault occur in the mid of transmission line

c) Operational when unsymmetrical fault occur in the mid of transmission line

4.4 Investigations During Normal Operation

The system in Figure 4.1 is operated in normal operation condition without any disturbance for period of 0.2s. The results obtained simulation is shown in Figure 4.2.

As shown in Figure 4.2a and Figure 4.2b the waveforms of the voltages and current are uniform during simulation period without any disturbances. Also, the travelling wave components (forward and backward currents) calculated by the travelling wave relay are uniform during simulation period as shown in Figure 4.2c and Figure 4.2d.

The relay signal sent to circuit breaker in this case is 1 which means the breakers should close its contacts to allow the current to flow in the system and supplies the static load.

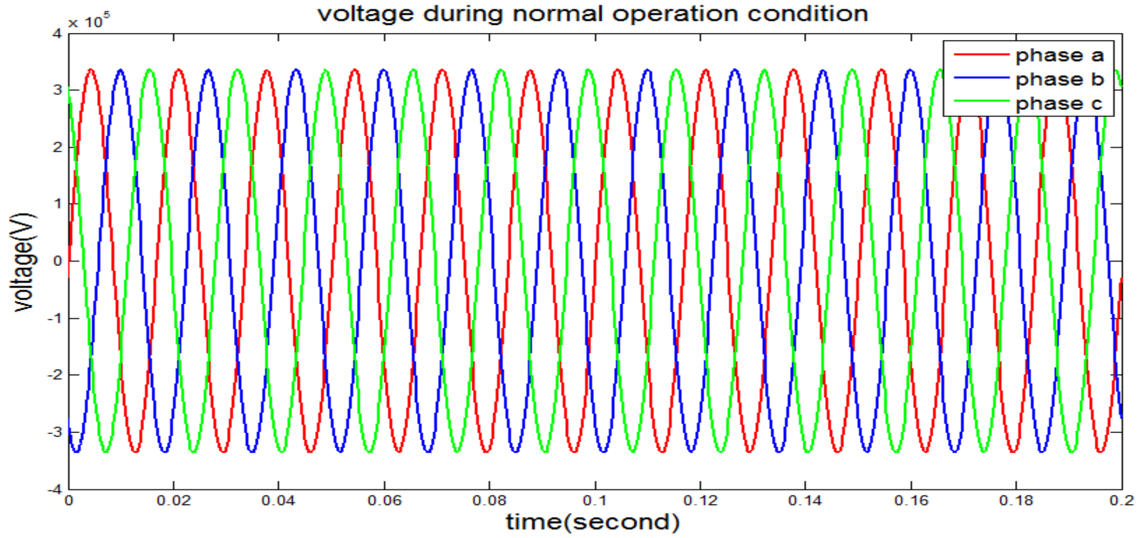

Figure 4.2a system voltage wave during normal operation

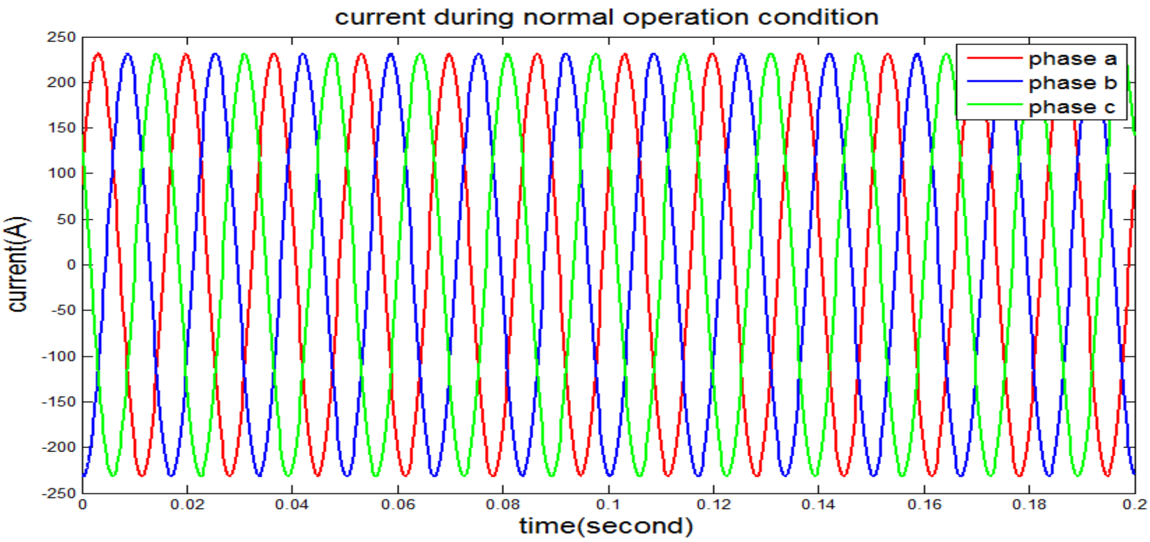

Figure 4.2b system current wave during normal operation

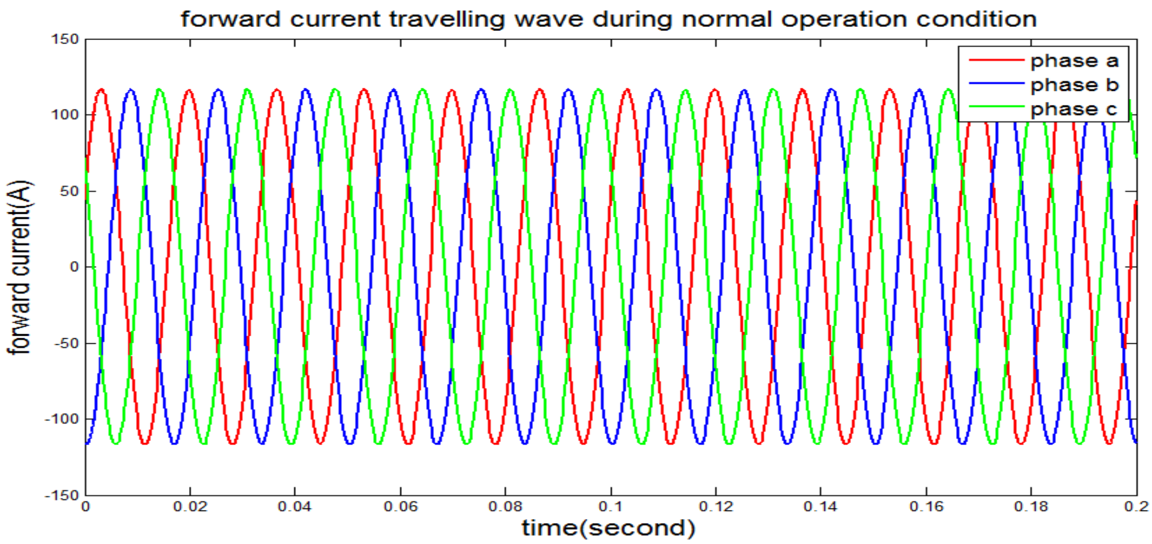

Figure 4.2c forward travelling wave during normal operation

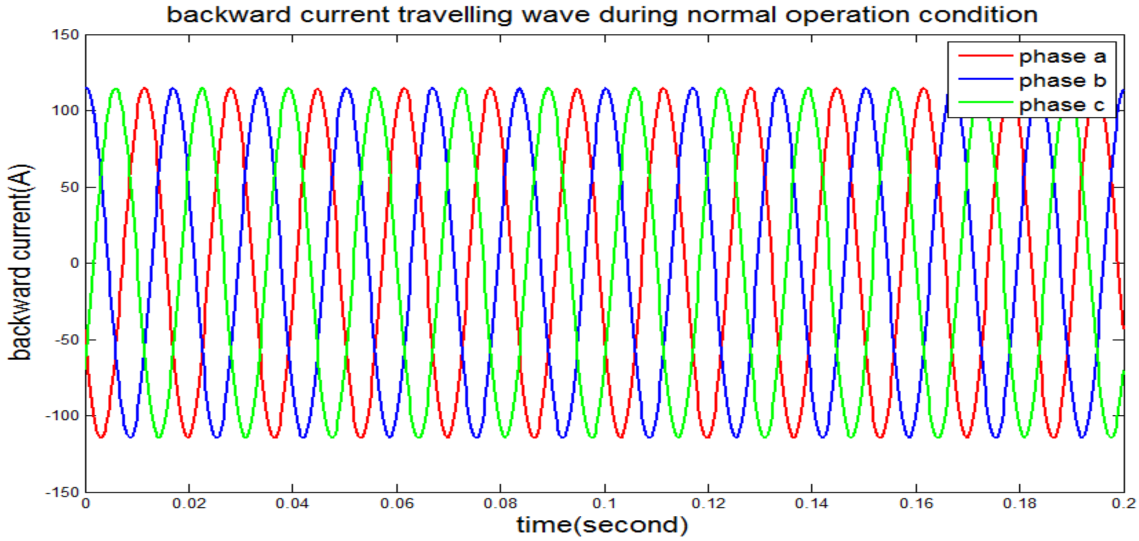

Figure 4.2d backward travelling wave during normal operation

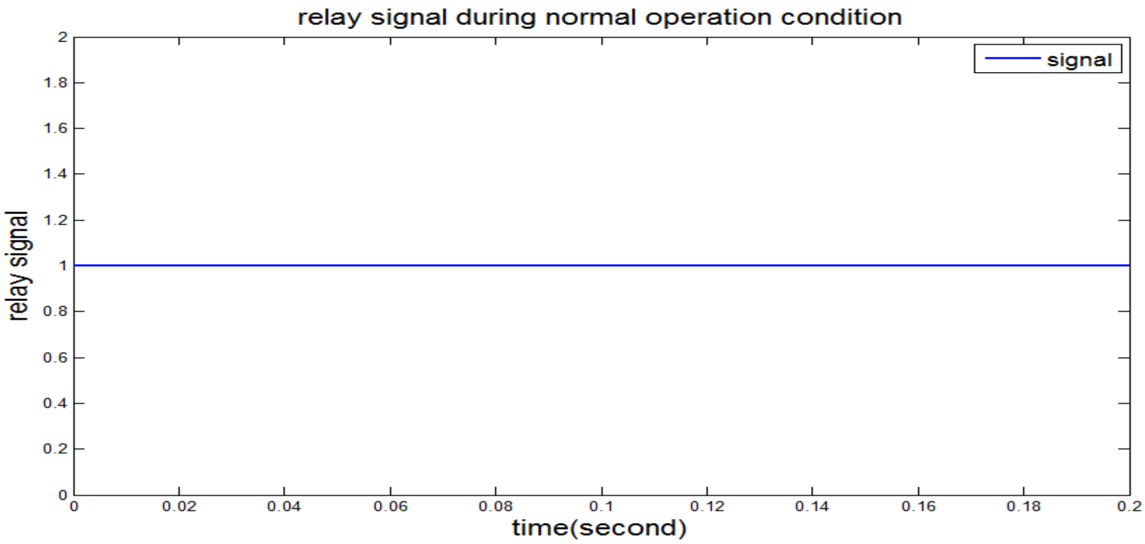

Figure 4.2e Relay signal during normal operation

Figure 4.2simulation result demonstrate operation during normal operation

4.5 Investigations During Symmetrical Fault

To demonstrate the ability of travelling wave relay during abnormal conditions, the system in Figure 4.1is subjected to three phase symmetrical fault in the middle of transmission line for duration of 0.1sec.

The results obtained during the simulation are shown in Figure 4.3. As shown in Figure 4.3a and Figure 4.3b the waveforms of the voltages and current observe increases in current and decrease in voltage when the fault occur and recover again when fault is cleared. The system is subjected to 6 times the rated current for duration of 0.1s and this may destroy the entire system.

If travelling wave relay is used for protection of the line the system is subjected to high current for duration of just 0.01 s until the breaker eliminate the fault as shown in Figure 4.3d.

The travelling wave components (forward and backward currents) calculated by the relay are not uniformed during simulation period as shown in Figure 4.3c and Figure 4.3d which indicate occurring of abnormal condition and initiate the relay to send trip signal to the breaker just after appearance of the fault as shown in Figure 4.3e. The relay signal to circuit break in this case is change from 1 to 0 at 0.05s which mean the breakers should open its contact and clear the fault.

Figure 4.3f and Figure 4.3g show the voltage and current waveform after operation of breaker. The voltage is subjected to transient decrease but recover to nominal values while the current is fall to zero because the breakers are open.

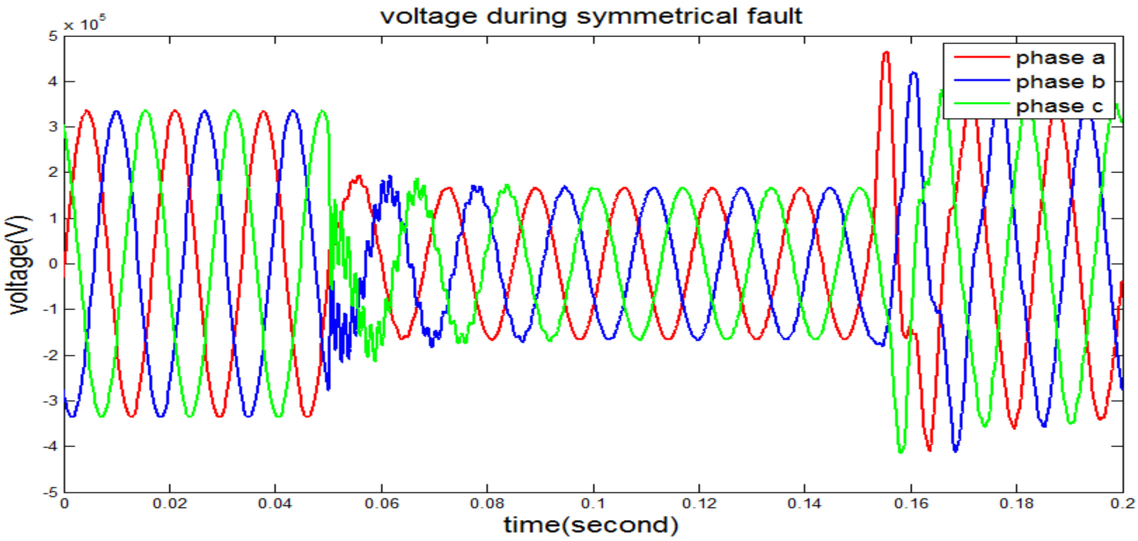

Figure 4.3a system voltage wave during symmetrical fault

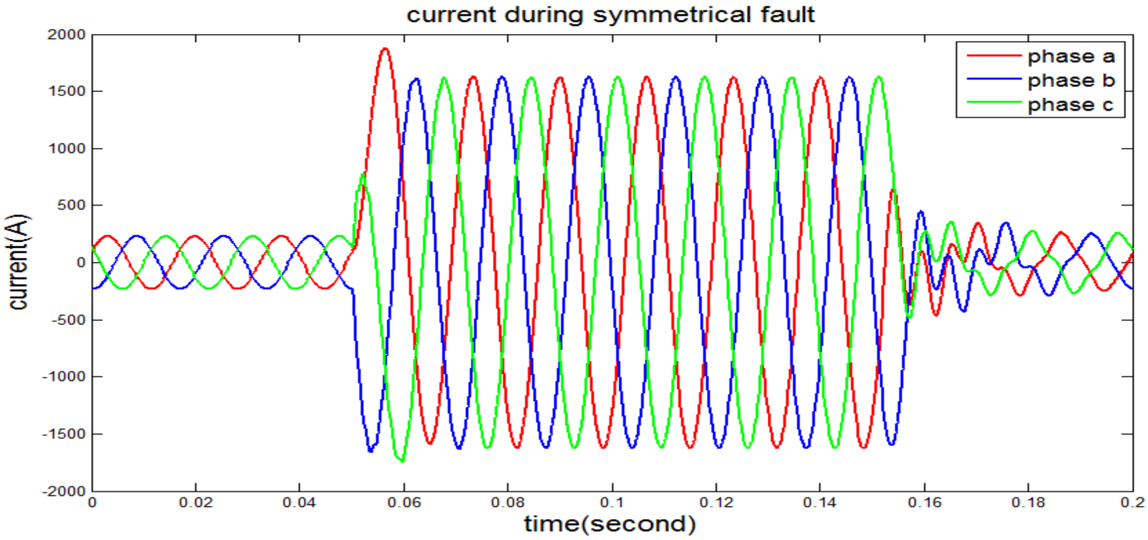

Figure 4.3b system current wave during symmetrical fault

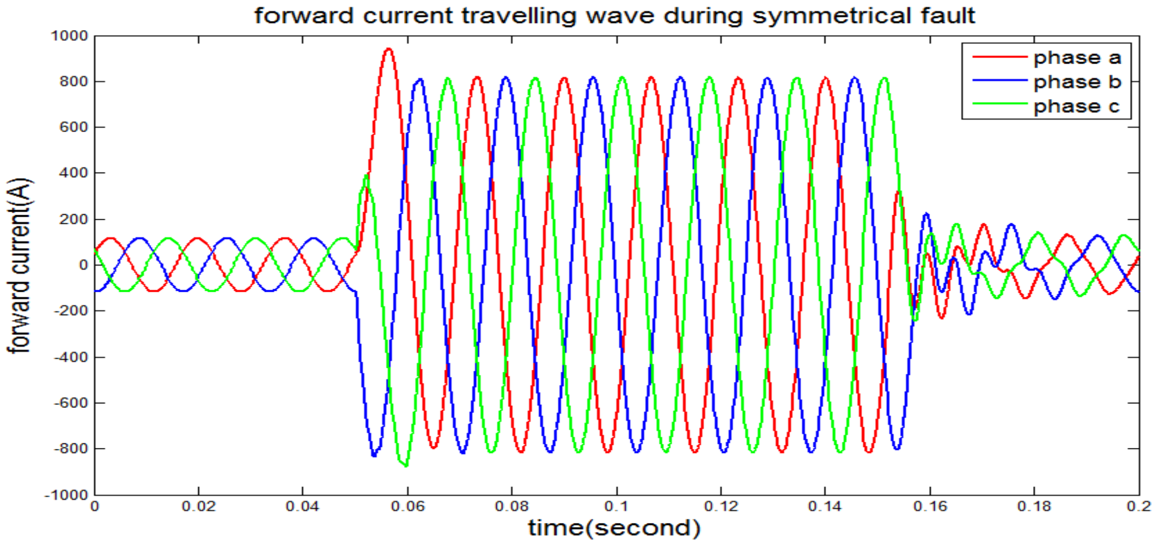

Figure 4.3c forward travelling wave during symmetrical fault

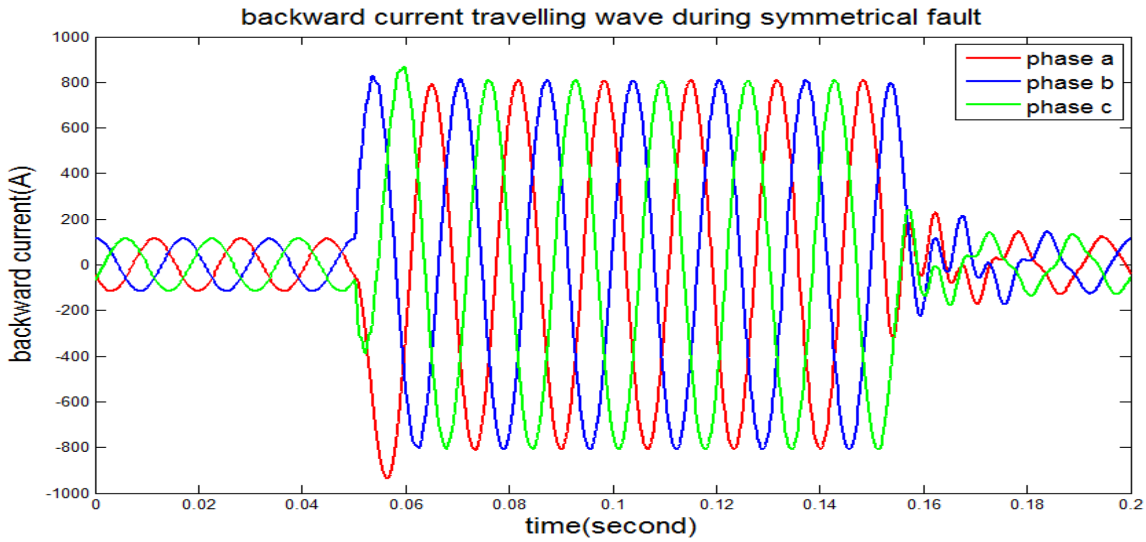

Figure 4.3d backward travelling wave during symmetrical fault

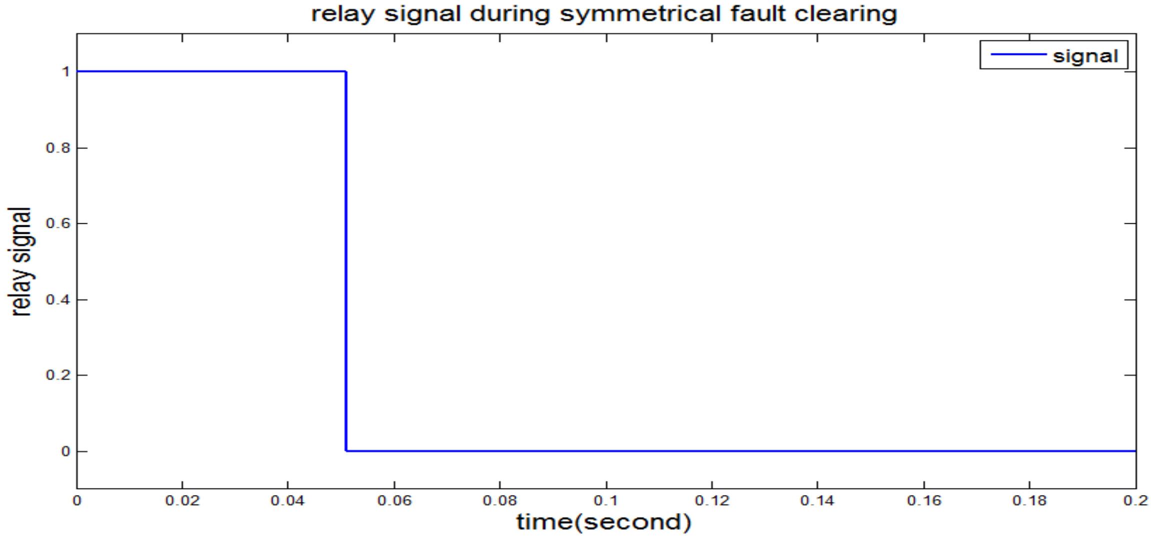

Figure 4.3e Relay signal during symmetrical fault clearing

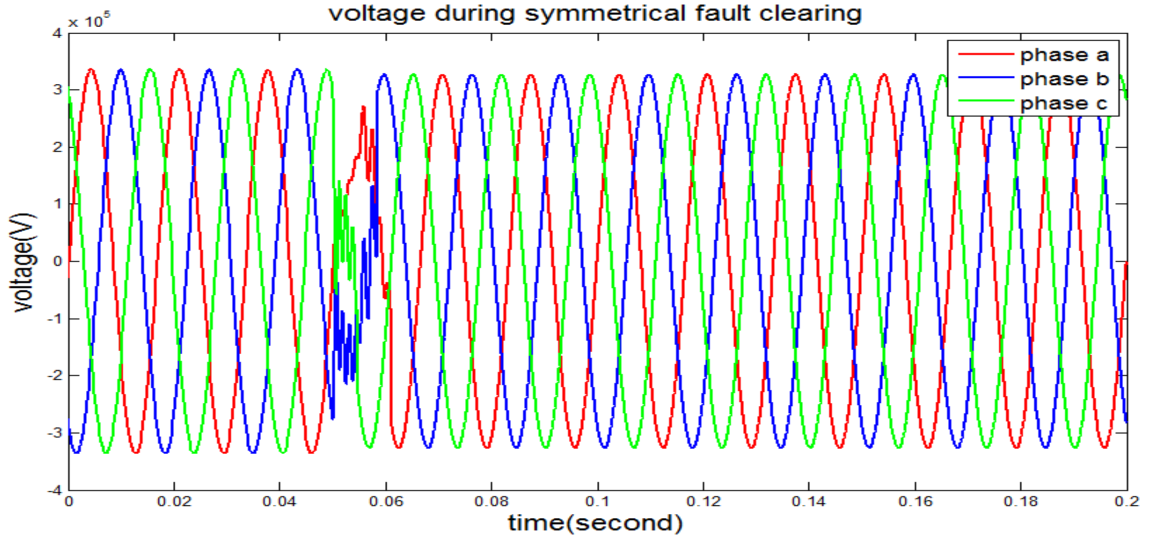

Figure 4.3f system voltage wave during symmetrical fault clearing

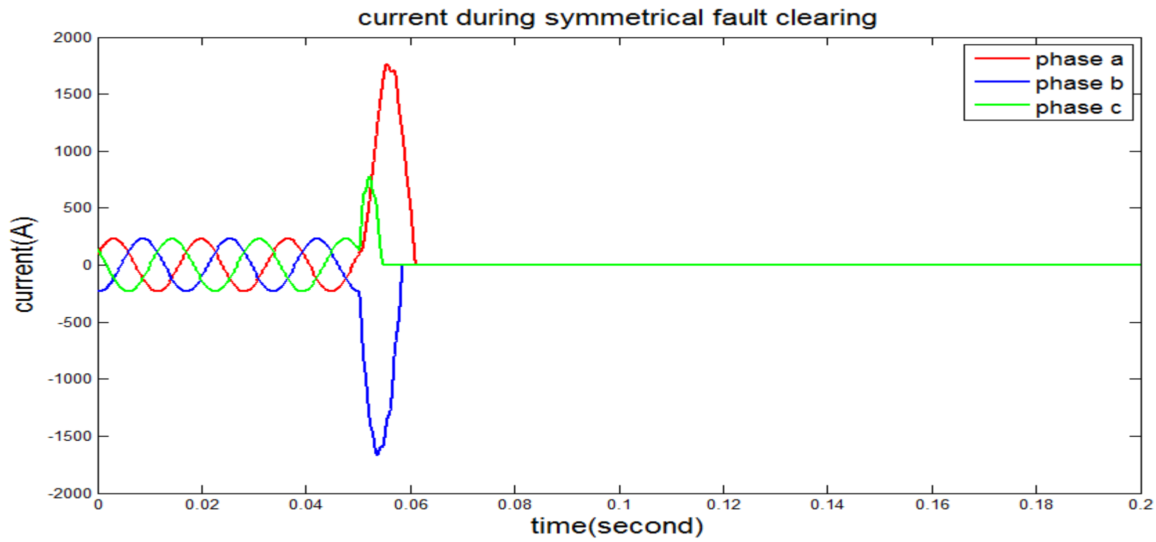

Figure 4.3g system current wave during symmetrical fault clearing

Figure 4.3 simulation result demonstrate operation during symmetrical fault

4.6 Investigations During Unsymmetrical Fault

The system in Figure 4.1is subjected to phase to ground unsymmetrical fault in the middle of transmission line for duration of 0.1s. Figure 4.4 show the simulation result during occurring of phase to ground fault.

As shown in Figure 4.4a the voltage of phase a is decrease during fault period and recover again when the fault is eliminated. Also phase a current is increase dramatically to about 6 times the rated value and this will destroy the system components if no proper protection is used as shown in Figure 4.4b.

Again if travelling wave relay is used for protection of the line than the system is subjected to high current for duration of just 0.01s until the breaker eliminating the fault as shown in Figure 4.4g.

The travelling wave components regarding phase a (forward and backward currents) calculated by the relay are not uniformed during simulation period as shown in Figure 4.4c and Figure 4.4d which indicate occurring of abnormal condition and initiate the relay to send trip signal to the breaker just after appearance of the fault as shown in Figure 4.4e. The relay signal to circuit break in this case is change from 1 to 0 at 0.05s which mean the breakers should open its contact and clear the fault.

Figure 4.3f and Figure 4.3g showed the voltage and current waveform after operation of breaker. The voltage is subjected to transient decrease but recover to nominal values while the current is fall to zero because the breakers are open.

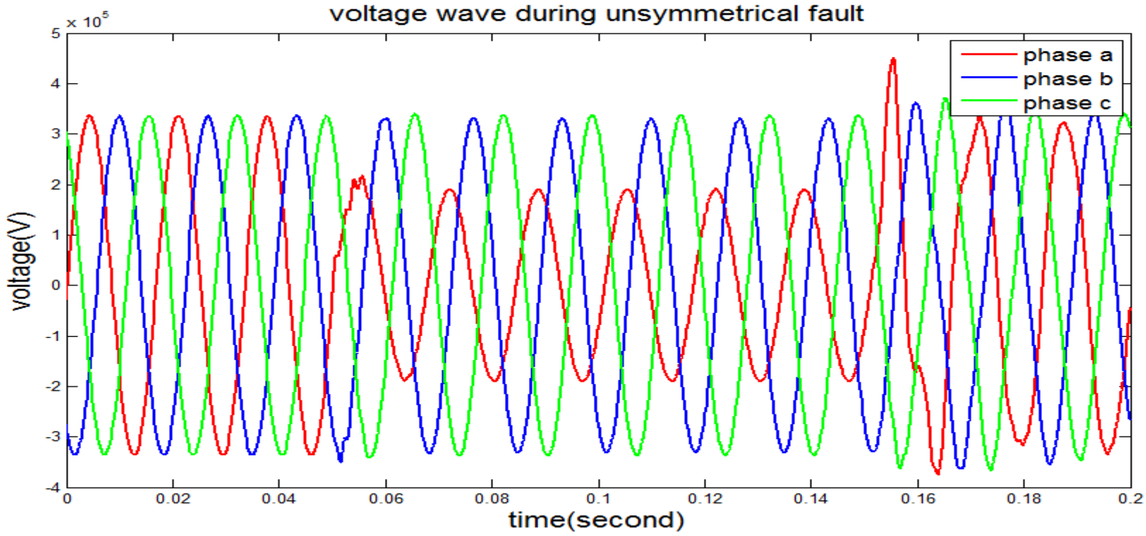

Figure 4.4.a system voltage wave during unsymmetrical fault

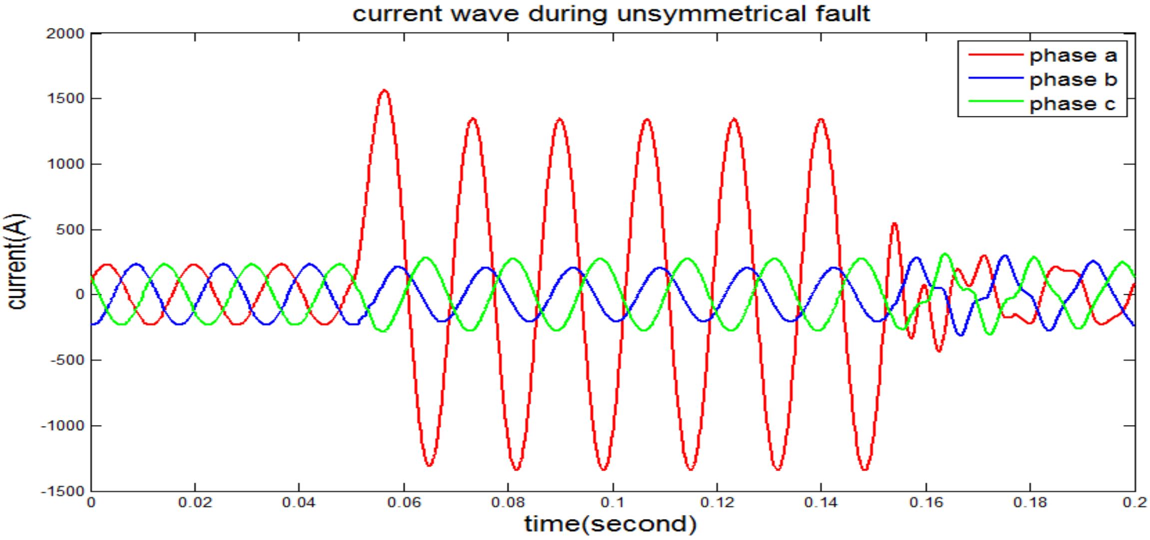

Figure 4.4.b system current wave during unsymmetrical fault

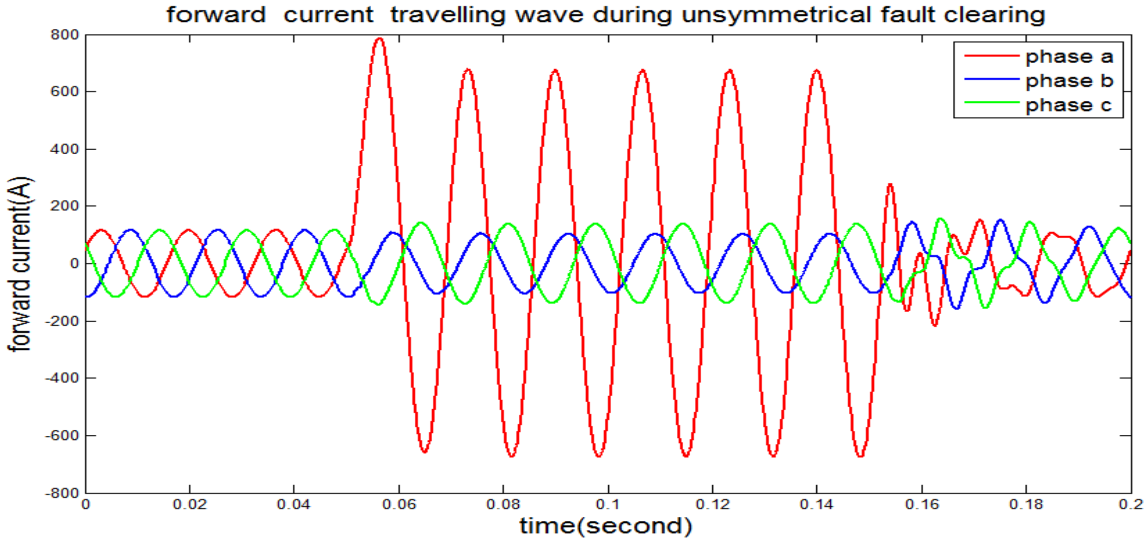

Figure 4.4.c forward travelling wave during unsymmetrical fault

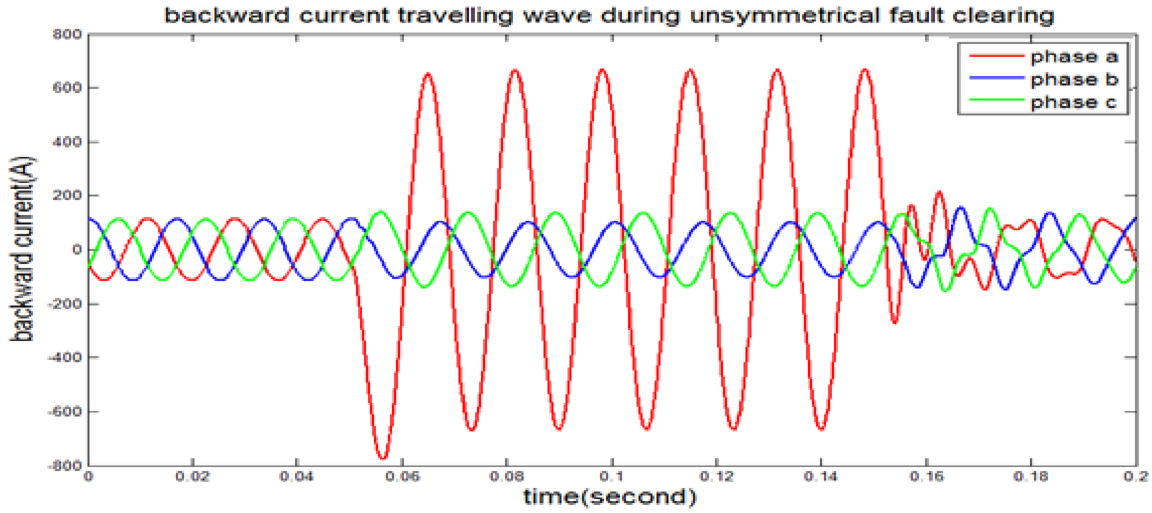

Figure 4.4.d backward travelling wave during unsymmetrical fault

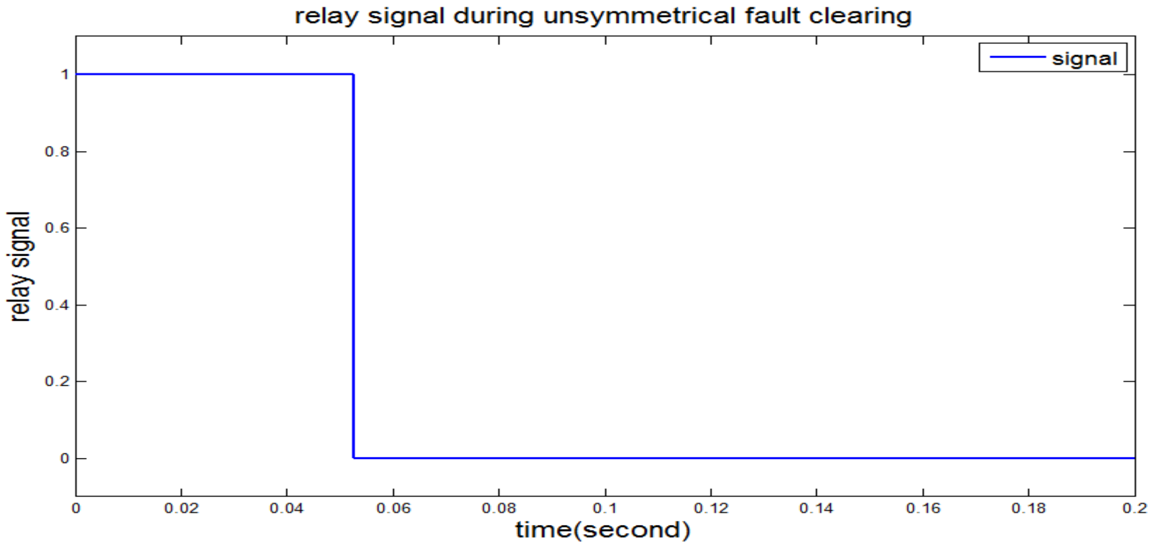

Figure 4.4.e Relay signal during unsymmetrical fault clearing

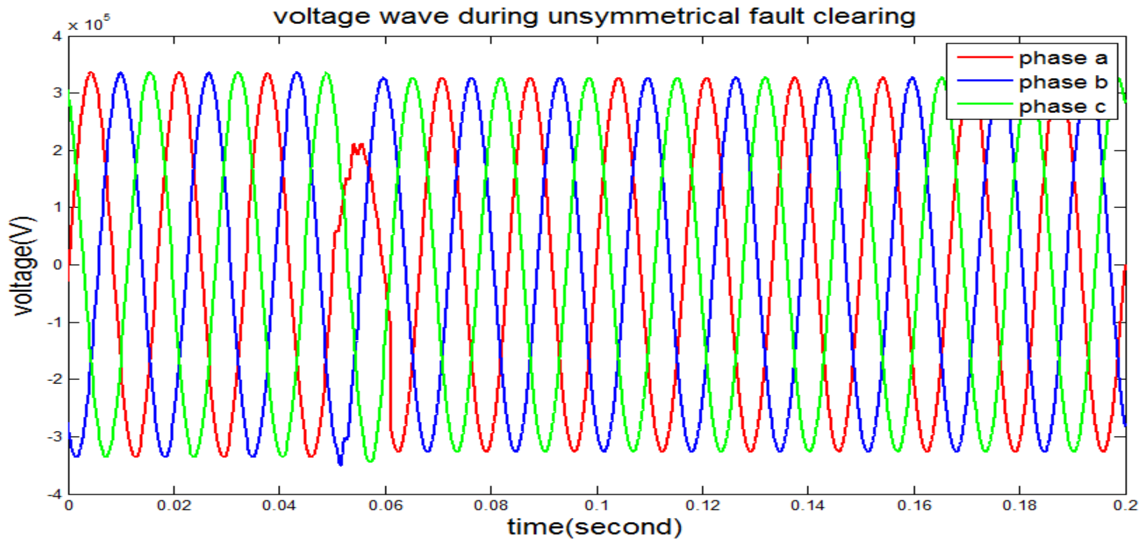

Figure 4.4.f system voltage wave during unsymmetrical fault clearing

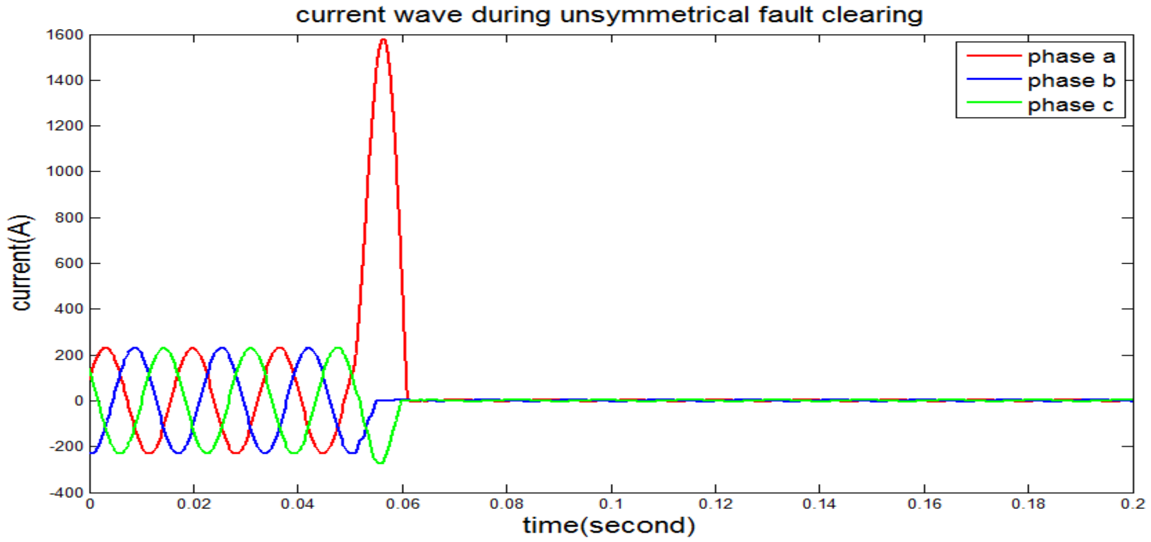

Figure 4.4.g system current wave during unsymmetrical fault clearing

Figure 4.4 simulation result demonstrate operation during unsymmetrical fault

4.7 Summary

The travelling wave relay is effective protection element which employee the forward and backward components to sense the abnormal conditions in the system. The relay is selective and operates only to eliminate the faulty part as soon as possible. The validation of the relay using Simulink shows the effectiveness of the relay during normal and abnormal conditions.

Chapter five
Conclusion and Recommendation

5.1 Conclusions

The protection is needed to remove as speedily as possible any element of the power system in which a fault has developed so long as the fault remains connected. Fault on the transmission line needs to be restored as quickly as possible. The sooner it is restored, the less the risk of power outage, damage in equipment of grid.

The proposed relay is based on travelling waves generated when fault occur in the line. The travelled wave components in opposite sides can be used to determine the line states and the location of the fault if fault is happened.

The developed algorithm is equipped in the microprocessor of numeric relay with proper software and hardwiring.

The methodology is developed based on travelling wave and tested on 400 kV voltage level with length 200km transmission line system .Extensive simulation test results show the algorithm correctly detects faults in each line section. The algorithm has been tested for several fault types symmetrical and unsymmetrical. The relay signal output 1/0 of the simulator during normal operation condition the relay signal to circuit breaker is 1 the breakers is closed, during symmetrical or unsymmetrical fault the relay signal to circuit breaker is 0 the breakers is opened.

The developed algorithm is accurate and very fast in detecting abnormal conditions in the system and this improves the reliability and stability of overall system.

5.2 Recommendations

At the end of this dissertation the following recommendations

1. Designing of numeric relay (hardware and software) using developed algorithm.
2. Implementation of developed algorithm in realistic transmission line.
3. Using travelling wave for medium voltage distribution system protection
4. Test the relay with source impedance variations.

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[14] Michael Faraday House- Six Hills Way, Stevenage "Power System Protection" -Institution of Electrical Engineers-2005
[15] Stephen Marx -Brian K. Johnson, "Traveling Wave Fault Location in Protective Relays": Design, Testing, and Results, Presented at the 16th Annual Georgia Tech Fault and Disturbance Analysis Conference Atlanta, Georgia-May 6–7, 2013

Appendix

Generate code for subsystem of travelling wave in MATLAB SIMULINK

```
* File: modway100.exp *

* IEC 61131-3 Structured Text (ST) code generated for Simulink
mode l   "moday100.mdl" *

 * Model version                     : 1.230

 * Simulink PLC Coder version        : 1.0 (R2010a) 25-Jan-2010

 * ST code generated on              : Sun Sep 06 13:26:05 2015 *

 * Target IDE selection              : CoDeSys 2.3

 * Test Bench included               : No **)

FUNCTION_BLOCK Subsystem

VAR_INPUT

    ssMethodType: SINT;

    signal: ARRAY [0..2] OF LREAL;

    signal_g: ARRAY [0..2] OF LREAL;

END_VAR

VAR_OUTPUT

    vf: ARRAY [0..2] OF LREAL;

    vr: ARRAY [0..2] OF LREAL;

    vx: ARRAY [0..2] OF LREAL;

    ix: ARRAY [0..2] OF LREAL;

    if_k: ARRAY [0..2] OF LREAL;

    ir: ARRAY [0..2] OF LREAL;

END_VAR

VAR

END_VAR

VAR_TEMP

    rtb_backwardcurrent_0: LREAL;

    rtb_forwardcurrent_0: LREAL;

    ax: LREAL;

    Mathf: LREAL;

    bx: LREAL;

    ime1: LREAL;

    Mathf1: LREAL;
```

```
    wt: LREAL;
    ime2: LREAL;
    Mathf2: LREAL;
    product: LREAL;
    UnaryMinus: LREAL;
    Mathf3: LREAL;
    UnaryMinus1: LREAL;
    ime3: LREAL;
    Mathf4: LREAL;
    UnaryMinus2: LREAL;
    ime4: LREAL;
    Mathf5: LREAL;
    product1: LREAL;
    ime: LREAL;
    Zc: LREAL;
END_VAR
CASE ssMethodType OF
    SS_OUTPUT:
        (* ComplexToRealImag: '<S1>/ime'  *)
        ime := 0;
        (* Sum: '<S1>/Zc' incorporates:* Constant: '<S1>/R'*)
        Zc := 2.7E+05 + ime;
        (* Product: '<S1>/a*x' incorporates:*Constant:
'<S1>/X'*Constant: '<S1>/a'*)
        ax := 0.00470152188;
        (* Math: '<S1>/Math f'*
         * About '<S1>/Math f':
         *  Operator: exp *)
        Mathf := EXP(ax);
        (* Product: '<S1>/b*x' incorporates:
         *  Constant: '<S1>/B'
         *  Constant: '<S1>/X' *)
        bx := 0.260088096;
        (* ComplexToRealImag: '<S1>/ime1' *)
        ime1 := 0;
```

```
(* Math: '<S1>/Math f1'*
 * About '<S1>/Math f1':
 *  Operator: exp  *)
Mathf1 := EXP(ime1);
(* Product: '<S1>/w*t' incorporates:
 *  Constant: '<S1>/T'
 *  Constant: '<S1>/w' *)
wt := 6.29256;
(* ComplexToRealImag: '<S1>/ime2'  *)
ime2 := 0;
(* Math: '<S1>/Math f2'*
 * About '<S1>/Math f2':
 *  Operator: exp *)
Mathf2 := EXP(ime2);
(* Product: '<S1>/product'  *)
product := (Mathf * Mathf1) * Mathf2;
(* UnaryMinus: '<S1>/Unary Minus'  *)
UnaryMinus :=  -ax;
(* Math: '<S1>/Math f3'*
 * About '<S1>/Math f3':
 *  Operator: exp *)
Mathf3 := EXP(UnaryMinus);
(* UnaryMinus: '<S1>/Unary Minus1'  *)
UnaryMinus1 :=  -bx;
(* ComplexToRealImag: '<S1>/ime3'  *)
ime3 := 0;
(* Math: '<S1>/Math f4' *
 * About '<S1>/Math f4':
 *  Operator: exp *)
Mathf4 := EXP(ime3);


(* UnaryMinus: '<S1>/Unary Minus2'  *)
UnaryMinus2 :=  -wt;
(* ComplexToRealImag: '<S1>/ime4'  *)
```

```
        ime4 := 0;
        (* Math: '<S1>/Math f5'*
         * About '<S1>/Math f5':
         *  Operator: exp *)
        Mathf5 := EXP(ime4);
        (* Product: '<S1>/product1'  *)
        product1 := (Mathf3 * Mathf4) * Mathf5;
        (* Product: '<S1>/If*Zc' incorporates:
         *  Inport: '<Root>/Iryb' *)
        rtb_forwardcurrent_0 := signal_g[0] * Zc;
        (* Product: '<S1>/forward voltage' incorporates:
         *  Constant: '<S1>/c'
         *  Inport: '<Root>/Vryb'
         *  Product: '<S1>/multy'
         *  Sum: '<S1>/add' *)
        rtb_backwardcurrent_0 := ((signal[0] + rtb_forwardcurrent_0) /
2) * product;
        (* Outport: '<Root>/vf'  *)
        vf[0] := rtb_backwardcurrent_0;
        (* Product: '<S1>/backward voltage' incorporates:
         *  Constant: '<S1>/c1'
         *  Inport: '<Root>/Vryb'
         *  Product: '<S1>/multy1'
         *  Sum: '<S1>/Subtract' *)
        rtb_forwardcurrent_0 := ((signal[0] - rtb_forwardcurrent_0)    /
2) * product1;
        (* Outport: '<Root>/vr'  *)
        vr[0] := rtb_forwardcurrent_0;
        (* Outport: '<Root>/vx' incorporates:
         *  Sum: '<S1>/voltage at fault point'*)
        vx[0] := rtb_backwardcurrent_0 + rtb_forwardcurrent_0;


        (* Product: '<S1>/Vf// Zc' incorporates:
         *  Inport: '<Root>/Vryb'
          *)
```

```
        rtb_backwardcurrent_0 := signal[0] / Zc;


        (* Product: '<S1>/forward current' incorporates:
         *  Constant: '<S1>/c2'
         *  Inport: '<Root>/Iryb'
         *  Product: '<S1>/multy2'
         *  Sum: '<S1>/add1'
          *)
        rtb_forwardcurrent_0 := ((rtb_backwardcurrent_0 + signal_g[0]) /
2) * product;


        (* Product: '<S1>/backward current' incorporates:
         *  Constant: '<S1>/c3'
         *  Inport: '<Root>/Iryb'
         *  Product: '<S1>/multy3'
         *  Sum: '<S1>/Subtract1'
          *)
        rtb_backwardcurrent_0 := ((rtb_backwardcurrent_0 - signal_g[0])
/ 2) * product1;


        (* Outport: '<Root>/ix' incorporates:
         *  Sum: '<S1>/current at fault point'
          *)
        ix[0] := rtb_forwardcurrent_0 - rtb_backwardcurrent_0;


        (* Outport: '<Root>/if'  *)
        if_k[0] := rtb_forwardcurrent_0;


        (* Outport: '<Root>/ir'  *)
        ir[0] := rtb_backwardcurrent_0;


        (* Product: '<S1>/If*Zc' incorporates:
         *  Inport: '<Root>/Iryb'
          *)
        rtb_forwardcurrent_0 := signal_g[1] * Zc;
```

```
        (* Product: '<S1>/forward voltage' incorporates:
         *  Constant: '<S1>/c'
         *  Inport: '<Root>/Vryb'
         *  Product: '<S1>/multy'
         *  Sum: '<S1>/add'
          *)
        rtb_backwardcurrent_0 := ((signal[1] + rtb_forwardcurrent_0) /
2) * product;


        (* Outport: '<Root>/vf'  *)
        vf[1] := rtb_backwardcurrent_0;


        (* Product: '<S1>/backward voltage' incorporates:
         *  Constant: '<S1>/c1'
         *  Inport: '<Root>/Vryb'
         *  Product: '<S1>/multy1'
         *  Sum: '<S1>/Subtract'
          *)
        rtb_forwardcurrent_0 := ((signal[1] - rtb_forwardcurrent_0) / 2)
* product1;


        (* Outport: '<Root>/vr'  *)
        vr[1] := rtb_forwardcurrent_0;


        (* Outport: '<Root>/vx' incorporates:
         *  Sum: '<S1>/voltage at fault point'
          *)
        vx[1] := rtb_backwardcurrent_0 + rtb_forwardcurrent_0;


        (* Product: '<S1>/Vf// Zc' incorporates:
         *  Inport: '<Root>/Vryb'
          *)
        rtb_backwardcurrent_0 := signal[1] / Zc;
```

```
        (* Product: '<S1>/forward current' incorporates:
         *  Constant: '<S1>/c2'
         *  Inport: '<Root>/Iryb'
         *  Product: '<S1>/multy2'
         *  Sum: '<S1>/add1'
          *)
        rtb_forwardcurrent_0 := ((rtb_backwardcurrent_0 + signal_g[1]) /
2) * product;


        (* Product: '<S1>/backward current' incorporates:
         *  Constant: '<S1>/c3'
         *  Inport: '<Root>/Iryb'
         *  Product: '<S1>/multy3'
         *  Sum: '<S1>/Subtract1'
          *)
        rtb_backwardcurrent_0 := ((rtb_backwardcurrent_0 - signal_g[1])
/ 2) * product1;


        (* Outport: '<Root>/ix' incorporates:
         *  Sum: '<S1>/current at fault point'
          *)
        ix[1] := rtb_forwardcurrent_0 - rtb_backwardcurrent_0;


        (* Outport: '<Root>/if'  *)
        if_k[1] := rtb_forwardcurrent_0;


        (* Outport: '<Root>/ir'  *)
        ir[1] := rtb_backwardcurrent_0;


        (* Product: '<S1>/If*Zc' incorporates:
         *  Inport: '<Root>/Iryb'
          *)
        rtb_forwardcurrent_0 := signal_g[2] * Zc;


        (* Product: '<S1>/forward voltage' incorporates:
```

```
         *  Constant: '<S1>/c'
         *  Inport: '<Root>/Vryb'
         *  Product: '<S1>/multy'
         *  Sum: '<S1>/add'
          *)
        rtb_backwardcurrent_0 := ((signal[2] + rtb_forwardcurrent_0) /
2) * product;

        (* Outport: '<Root>/vf'  *)
        vf[2] := rtb_backwardcurrent_0;

        (* Product: '<S1>/backward voltage' incorporates:
         *  Constant: '<S1>/c1'
         *  Inport: '<Root>/Vryb'
         *  Product: '<S1>/multy1'
         *  Sum: '<S1>/Subtract'
          *)
        rtb_forwardcurrent_0 := ((signal[2] - rtb_forwardcurrent_0) / 2)
* product1;

        (* Outport: '<Root>/vr'  *)
        vr[2] := rtb_forwardcurrent_0;

        (* Outport: '<Root>/vx' incorporates:
         *  Sum: '<S1>/voltage at fault point'
          *)
        vx[2] := rtb_backwardcurrent_0 + rtb_forwardcurrent_0;

        (* Product: '<S1>/Vf// Zc' incorporates:
         *  Inport: '<Root>/Vryb'
          *)
        rtb_backwardcurrent_0 := signal[2] / Zc;

        (* Product: '<S1>/forward current' incorporates:
         *  Constant: '<S1>/c2'
```

```
         *  Inport: '<Root>/Iryb'
         *  Product: '<S1>/multy2'
         *  Sum: '<S1>/add1'
          *)
        rtb_forwardcurrent_0 := ((rtb_backwardcurrent_0 + signal_g[2]) /
2) * product;

        (* Product: '<S1>/backward current' incorporates:
         *  Constant: '<S1>/c3'
         *  Inport: '<Root>/Iryb'
         *  Product: '<S1>/multy3'
         *  Sum: '<S1>/Subtract1'
          *)
        rtb_backwardcurrent_0 := ((rtb_backwardcurrent_0 - signal_g[2])
/ 2) * product1;

        (* Outport: '<Root>/ix' incorporates:
         *  Sum: '<S1>/current at fault point'
          *)
        ix[2] := rtb_forwardcurrent_0 - rtb_backwardcurrent_0;

        (* Outport: '<Root>/if'  *)
        if_k[2] := rtb_forwardcurrent_0;

        (* Outport: '<Root>/ir'  *)
        ir[2] := rtb_backwardcurrent_0;

END_CASE;
END_FUNCTION_BLOCK
VAR_GLOBAL CONSTANT
    SS_OUTPUT: SINT := 3;
END_VAR
VAR_GLOBAL
END_VAR
```