REPUBLIC OF TURKEY
YILDIZ TECHNICAL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

SMART DISTRIBUTION PROTECTION WITHOUT VOLTAGE TRANSFORMER

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MSc. THESIS
DEPARTMENT OF ELECTRICAL ENGINEERING
PROGRAM OF ELECTRICAL POWER SYSTEMS

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İSTANBUL, 2019

REPUBLIC OF TURKEY

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SMART DISTRIBUTION NETWORK PROTECTION WITHOUT VOLTAGE TRANSFORMER

A thesis submitted by Fazlı ALPASLAN in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE** is approved by the committee on 22.07.2019 in Department of Electrical Engineering, Electrical Power Systems Program.

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ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my advisor Dr. Mustafa BAYSAL for his support and guidance throughout graduate study and research.

July, 2019

Fazlı ALPASLAN

TABLE OF CONTENTS

LIST OF SYMBOLS

I_{pre}	Pre-fault current
I_{fwd}	Fault current in forward direction
I_{rev}	Fault current in reverse direction
I_F	Total post-fault current in forward direction
I_R	Total post-fault current in reverse direction
O/C	Overcurrent
R	Relay
S	Transient energy
T	Period
V	Line peak voltage
w	Radial frequency
Z	Line impedance
ΔV	Superimposed voltage
ΔI	Superimposed current
$\Delta \emptyset$	Phase angle shift
Δt	Time offset

LIST OF ABBREVIATIONS

CB	Circuit Breaker
DG	Distributed Generation
DFT	Discrete Fourier Transform
DCE	Directional Current Element
DC	Direct Current
EHV	Extra High Voltage
MV	Medium Voltage
SIC	Superimposed Components
UHV	Ultra High Voltage
ZCT	Zero-crossing time

LIST OF FIGURES

Page

LIST OF TABLES

Page

ABSTRACT

SMART DISTRIBUTION PROTECTION WITHOUT VOLTAGE TRANSFORMER

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Department of Electrical Engineering

MSc. Thesis

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In electrical distribution networks, overcurrent relays are frequently used to protect the system from excessive currents due to ground faults, short circuits, etc. As the conventional radial distribution networks have unidirectional power flow, nondirectional overcurrent relays are typically used. However, due to the conversion of distribution networks from typical radial structure to meshed type and increasing integration of distributed generation(DG) systems into the grids, the power flow direction is no longer unidirectional and these conditions require utilization of directional overcurrent relays to enhance the selectivity in distribution protection systems.

The operation of conventional directional overcurrent relays are based on estimation of the phase angle difference between the current phasor and a reference voltage phasor which requires additional voltage transformers. This makes the cost for directional protection systems higher compared to nondirectional types. In order to reduce the cost, a new approach must be adapted to avoid the installation of voltage transformers in distribution netwoks having bidirectional power flow. By this way, directional protection systems without utilizing voltage transformers will gain a considerable role in future smart grid initiatives.

In this thesis, so far proposed current-only directional overcurrent relaying methods are examined and a new time-domain approach is suggested. The method relies on comparing the polarities of instantaneous current and initial superimposed components after the fault. The fault generated superimposed components are obtained by extracting the pre-fault current signals from the post-fault current signals. The proposed method is simulated for a ring network model in MATLAB/Simulink environment and it is shown that the method succeeds to detect faultly lines under various conditions such as different fault types, fault locations and load switchings.

Keywords: Distribution network, overcurrent protection, directional relaying, superimposed components, smart grid.

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ÖZET

GERİLİM TRAFOSUZ AKILLI DAĞITIM KORUMASI

Fazlı ALPASLAN

Elektrik Mühendisliği Anabilim Dalı
Yüksek Lisans Tezi

Tez Danışmanı: Dr. Mustafa BAYSAL

Elektrik dağıtım şebekelerinde, aşırı akım röleleri, sistemi toprak arızalarına ve kısa devrelere bağlı aşırı akımlardan korumak için sıklıkla kullanılır. Geleneksel radyal dağıtım şebekelerinin tek yönlü güç akışına sahip olması nedeniyle, tipik olarak yönlü olmayan aşırı akım röleleri kullanılır. Bununla birlikte, dağıtım şebekelerinin tipik radyal yapıdan ring tipine dönüştürülmesi ve dağıtık üretim (DÜ) sistemlerinin şebekelere artan entegrasyonu nedeniyle, güç akış yönü artık tek yönlü değildir ve bu koşullar dağıtım koruma sistemlerinde seçiciliği arttırmak için yönlü aşırı akım rölelerinin kullanılmasını gerektirir.

Geleneksel yönlü aşırı akım rölelerinin çalışması, akım fazörü ile referans olarak alınan bir gerilim fazörü arasındaki faz açısı farkının tahminine dayanır ve bu da ek olarak gerilim trafolarının kullanılmasını gerektirir. Bu, yönlü koruma sistemleri için maliyeti, yönsüz türlere göre daha yüksek yapar. Maliyeti düşürmek için, iki yönlü güç akışına sahip olan dağıtım ağlarında gerilim trafolarının tesis edilmesini önleyerek yeni bir yaklaşım benimsenmelidir. Böylece, gerilim trafosuz yönlü koruma sistemleri gelecekteki akıllı şebeke girişimlerinde önemli bir rol oynayacaktır.

Bu tez çalışmasında, bugüne kadar önerilen sadece akım bilgisi kullanılarak yapılan yönlü aşırı akım koruma yöntemleri ele alınmış ve zaman bazında yeni bir yaklaşım önerilmiştir. Bu yöntem, arıza sonrası anlık akım ve fark bileşeninin polaritelerinin karşılaştırılmasına dayanır. Arıza ile meydana gelen fark bileşenleri, arıza öncesi akım sinyallerinin arıza sonrası akım sinyallerinden çıkarılmasıyla elde edilir. Önerilen yöntem bir ring şebekesi için MATLAB/Simulink ortamında simüle edilmiştir ve yöntemin farklı arıza tipleri, arıza konumları ve yük anahtarlamaları gibi çeşitli koşullar altında arızalı hatları tespit ettiği gösterilmiştir.

Anahtar Kelimeler: Dağıtım şebekesi, aşırı akım koruması, yönlü koruma rölesi, fark bileşenleri, akılı şebeke.

CHAPTER 1

INTRODUCTION

1.1 Literature Review

In electrical power systems, a continuous and normal operation to meet the load demand has a crucial role. These systems have faults and abnormalities which poses a threat to facilities and labor force. Therefore, a protection system is designed and installed in order to detect and isolate the faults from the rest of the electrical network.

Protections systems of distribution grids are equipped with protection relays having various protection schemes and requirements. Relays are operated by currents, voltages, frequencies or other quantities to distinguish any abnormal condition in a grid.

Overcurrent relays are the most widely used relays in distribution networks to protect the system from excessive currents caused by short circuits, ground faults and overloads. In order to detect an excessive current, a fault or an overload, separate current sensors with protective relays are required by circuit breakers to interrupt the circuit. Overcurrent relays may be utilized as directional or non-directional type depending on the distribution network topology [1].

In radial distribution systems, current flows in only one direction from source to the loads which requires no detection of direction of the fault current. Therefore, the protection schemes of radial systems are designed and operated irrespective of the direction of current flow. However, if there is a source at more than one of the line terminals, fault and load currents can flow in either direction. For this reason, selectivity is required to isolate only the faulty line from rest of the system in distribution networks having bidirectional power flow [2].

In distribution systems having meshed networks or distributed energy sources, power flow can be in either direction which requires a directional sensing unit. In order to make such a determination, directional overcurrent relays, a type of overcurrent relay, are used to distinguish the direction of the fault current. Directional overcurrent relays are made up of two units, a directional unit and an overcurrent unit [3].

Directional relay units need a polarizing quantity, which is reasonably fixed reference value, to compare the measured current in the protected line. During a fault, the phase angles of the voltages remain almost fixed, while the angles of the current phases can change significantly depending on the direction of the fault current [4]. Accordingly, the mainstream method for directional relaying is applied by utilizing voltage phasor as a polarizing quantity in numeric relays. The bus voltage is compared to the current flow by measuring the phase angles between the line currents and bus voltages [5].

There are two cases that the conventional voltage polarized relays are unreliable. The first is a short-circuit fault occurrence in a close distance to the voltage measurement point, named as closed-in faults, and the second one is absence of voltage signal because of blown fuses isolating the voltage transformer from the main circuit, known as voltage transformer failure. In both cases, the relay logic cannot draw the distinction between the two cases [6]. Furthermore, utilizing voltage sensors as a reference quantity in distribution lines requires a considerably high number of voltage transformers that increases the cost of the protection system.

By the increasing integration of distributed generation units to distribution grids and the conversion of radial networks to meshed networks with expansion of medium voltage networks, the fault current is no longer in a fixed direction which requires directional relaying. On account of that the voltage measurement information is not always available and installation of high number of voltage transformers in an existing non-directional protection system is costly and not feasible, a new directional protection logic is necessary without using any voltage sensor in distribution networks. Moreover, it can be used as a backup protection feature to enhance the reliability of traditional voltage polarized directional protection systems.

1.2 Objective of the Thesis

In this work, a directional overcurrent protection algorithm based on only current measurements is proposed. The proposed method is simulated for a ring network by using MATLAB/Simulink environment. The results are analyzed in terms of various cases such as fault types, power swings, fault locations.

1.3 Hypothesis

Several approaches have been suggested for directional overcurrent relaying without voltage sensors so far. Each method has its certain drawbacks depending on grid conditions, measurement sensitivity and various distribution schemes. However, these methods are not able to detect the faulty line for most cases; namely, they all require pre-fault power flow supervision or an additional status information from other relays in the network if the power flow direction prior to fault is not permanent for all load flow cases.

In the proposed scheme, a directional element is modelled without utilizing voltage measurement. For this purpose, a fault direction parameter which is estimated by a comparison between the superimposed current component polarity and the half- cycle current polarity is proposed. A conventional overcurrent element is considered in order to distinguish the line faults and load disturbances. Furthermore, a relay to relay communication, which receives and transmits the fault direction parameters between both line ends. By this way, directional parameters obtained from utilizing the current information at the local and remote ends are compared, and thus the faulty lines are detected without using any voltage sensor.

CHAPTER 2

CONVENTIONAL DIRECTIONAL OVERCURRENT PROTECTION

Directional overcurrent relays are necessary to provide sensitive tripping of circuit breakers for only one certain direction, which is forward or reverse. In multiple source networks, the fault current could be bidirectional at the relay location. Accordingly, it is essential to a have selective tripping to isolate only the faulty line from the rest of the system.

2.1 Directional Relaying Logic

In a meshed distribution network shown in Figure 2.1, in case switch X is open, the system is no longer meshed and becomes a typical radial network. When a fault occurs at F1, there is no current flow in circuit breakers 4 and 5 and tripping of circuit breaker 3 is adequate to isolate the fault. However, in case switch X is closed, the system becomes meshed type. Therefore, directional selectivity is provided by tripping of circuit breakers 3 and 4, which have opposite fault current directions [7].

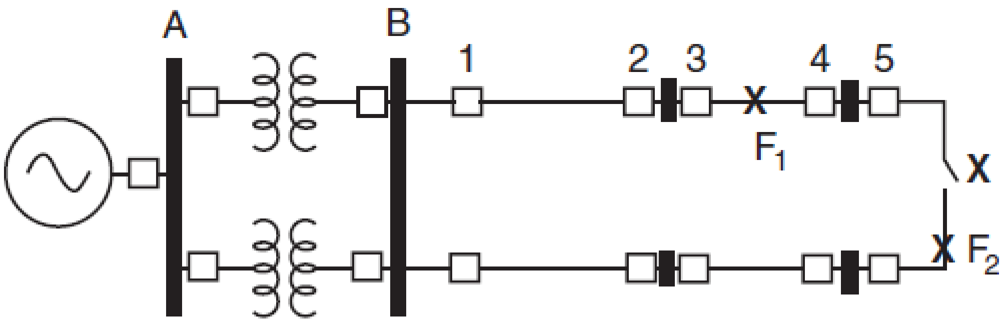

Figure 2.1 Radial and loop circuits [7]

There are two types of directional relaying logic as shown in Figure 2.2:

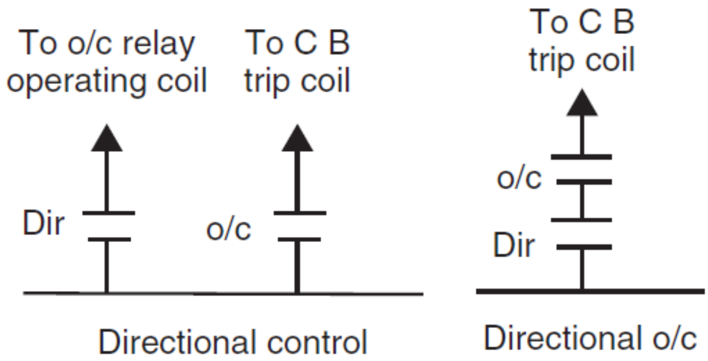

Figure 2.2 Directional overcurrent relaying logics [7]

- **Directional Overcurrent:** Directional overcurrent logic has two independent contacts in series. In order to energize the trip coil, both relay contacts must be closed. This configuration may cause false tripping in case of current reversal after the fault occurs.

- **Directional Control:** In directional control technique, the overcurrent element is controlled by the directional element in such a way that the directional element contact is connected in series with the overcurrent coil in electromechanical relay types. Thus, no torque is generated unless the overcurrent contact is closed. In static or digital relays, this is done by electronic logic circuitry.

2.2 Polarizing Method for Directional Element

The conventional type of the directional element is operated based on the phase difference between the voltage and current phasors at the measurement location. Since the voltage phasor remains almost constant in case of a fault occurrence, it is called polarizing quantity while the current phasor is called operating quantity. In Figure 2.3, since the power lines are mostly very close to be purely inductive, the current lags the voltage by the fault loop impedance, approximately 90 degrees, for forward faults; inversely, the current leads the voltage by 180 degrees minus the fault loop impedance which approximately equals to 90 degrees, for reverse faults. Hence, the sign of the torque product of the voltage and the current indicates the direction of the current flow; namely, positive sign for forward fault, negative sign for reverse fault [8].

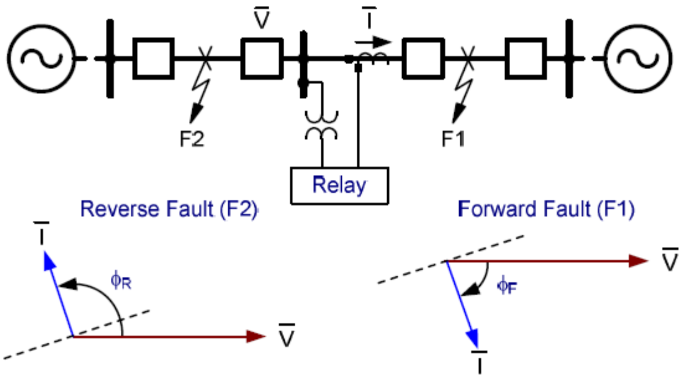

Figure 2.3 Voltage polarizing for conventional directional element [8]

2.3 Relay Types for Directional Overcurrent Protection

There are two types of directional overcurrent relaying designs; which are electromechanical and static designs [9]. Both methods rely on that the overcurrent element is controlled by the directional element. If the fault current flows in tripping direction, the directional element allows the overcurrent element to trip the circuit breaker when the current exceeds the predetermined current limit. However, if the fault current flows in non-tripping direction, the directional element prevents the overcurrent element to trip the circuit breaker [9].

2.3.1 Electromechanical Design

The electromechanical design is based the torque generated by the conventional induction disk time-delay overcurrent element and an instantaneous power directional element as shown in Figure 2.4. The directional element is operated by the operating coil and the polarizing coil. Once the angle between the operating coil current and the polarizing coil voltage reaches the maximum torque angle of the relay, the over current element is activated [9].

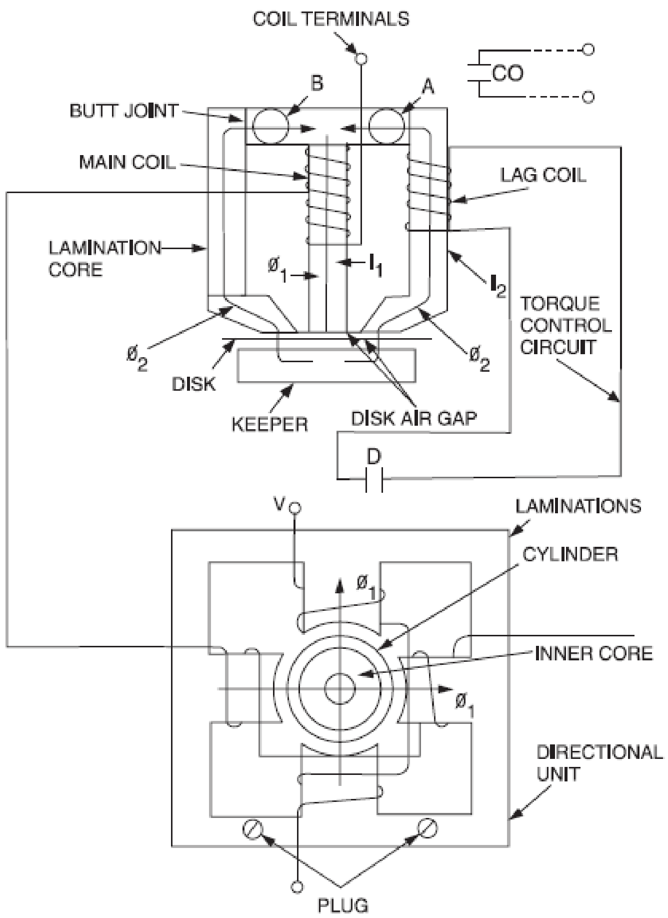

Figure 2.4 Electromechanical relay design for directional overcurrent protection [9]

2.3.2 Static Design

The operating principle of the static design is very similar to electromechanical design. The input quantities, polarizing voltage and operating current, are transmitted to a microprocessor that decides if the fault current exceeds the threshold value and it is in the tripping direction. If both conditions are fulfilled, a tripping output signal is sent to the circuit breaker [9]. Unlike the electromechanical design, the torque product is estimated by utilizing numerical logic. Moreover, microprocessor technology has enabled it very flexible and easy to adjust the relay settings over a wide range to accommodate various system conditions

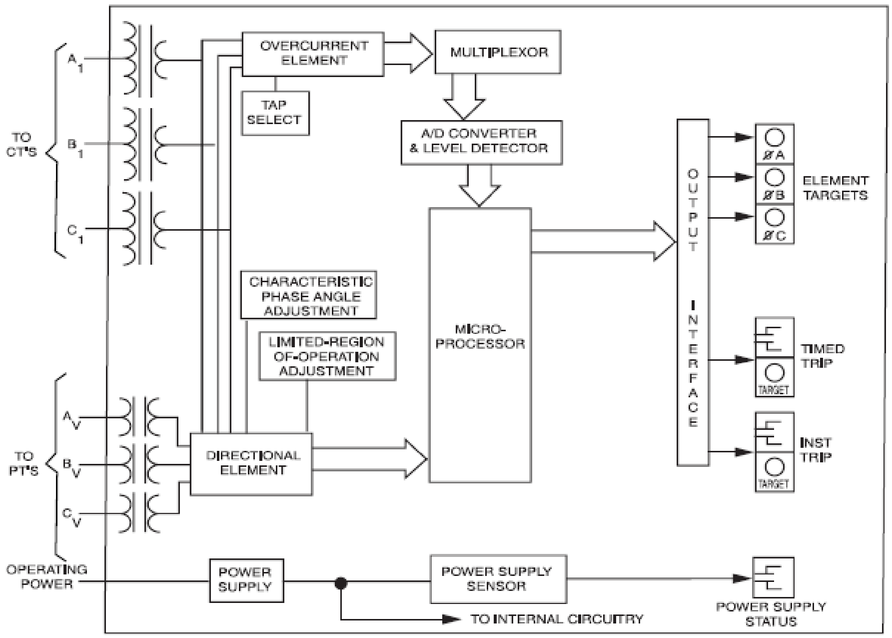

Figure 2.5 Static relay design for directional overcurrent protection [9]

CHAPTER 3

CURRENT ONLY DIRECTIONAL PROTECTION METHODS

There have been different methods studied for directional overcurrent relaying. All of these methods relies on microprocessor based relaying technology which made it possible to compute various logical and mathematical algorithms in a flexible and reliable way.

3.1 Theoretical Analysis

Current-only directional relaying techniques rely on analyzing the transient characteristics of the fault current based on phase change. These characteristics are used to distinguish between forward and reverse types of faults.

A simplified distribution system comprising a normal power I_{pre} from source(S) to grid(G) is shown in Figure 3.1. When a fault F occurs between the substation and the grid, the fault current I_{fwd} is towards to the grid as same as I_{pre}; while a fault R occurs between the source and the substation, I_{rev} becomes in opposite direction with I_{pre}.

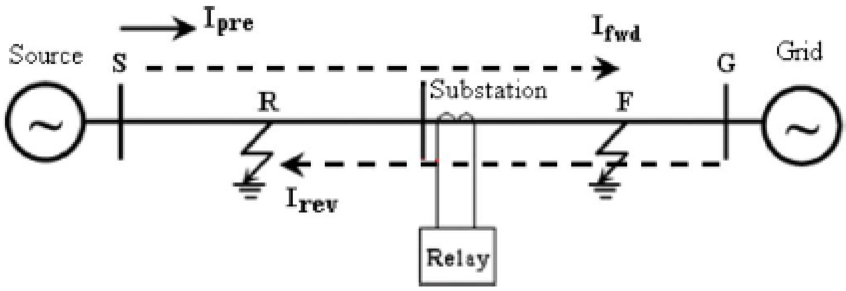

Figure 3.1 Forward and reverse fault representation [10]

Referring to Fig 3.1, I_{pre} is given by the following equation where Z_{SG} is the total impedance between the source and the grid side and V_S, V_G are voltages at the busbars S and G.

$$I_{pre} = (V_S - V_G)/Z_{SG} \tag{3.1}$$

For a forward fault between the substation and the grid, I_{fwd} is given by:

$$I_{fwd} = V_S/Z_{SF} \tag{3.2}$$

Where V_S is the source voltage and Z_{SF} is the impedance between the source and the fault point F.

Likewise, for a reverse fault between the substation and the grid, I_{rev} is given by:

$$I_{rev} = V_G/Z_{GR} \tag{3.3}$$

Where V_G is the grid voltage and Z_{GR} is the impedance between the grid and the fault point.

The total post-fault current I_F, which is composed of the pre-fault and the forward fault current, is calculated as:

$$I_F = I_{pre} + I_{fwd} = I_{pre} + V_S/Z_{SF} \tag{3.4}$$

Similarly, the total post-fault current I_R, which is composed of the pre-fault and the reverse fault current, is calculated as:

$$I_R = I_{pre} - I_{rev} = I_{pre} - V_G/Z_{GR} \tag{3.5}$$

Even though the impedances Z_{SF} and Z_{GR} is not exactly known; but assuming that the impedances are almost purely inductive, the phasor diagram in Figure 3.2 illustrates I_{pre}, I_{fwd}, I_{rev}, I_F, I_R derived from the equations (3.1, 3.2, 3.3, 3.4, 3.5).

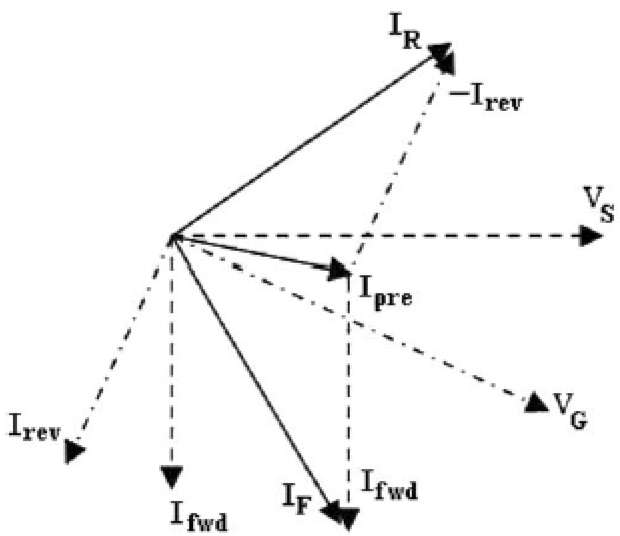

Figure 3.2 Phasor diagram for forward and reverse faults [10]

The phase jump between the pre-fault current I_{pre} and the total post-fault currents I_F, I_R discriminates the type of the fault, forward or reverse. Therefore, instead of utilizing bus voltage as a polarizing quantity, it is possible to design a directional element by comparing pre-fault and post-fault current characteristics.

3.2 Detection Methods

Transient characteristics of the current resulting from phase shift during a fault can be detected by three basic approaches involving phase angle estimation, extraction of high frequency components and time domain methods.

3.2.1 Phase Angle Estimation

In this approach, the principle of directional element design is based on the phase angle difference between the pre-fault and the post-fault currents by using phasor estimation methods. Various phasor estimation methods such as Discrete Fourier Transform(DFT), Kalman Filtering, Recursive Least Square algorithms can be used. The current phasor to be estimated can be either the positive sequence component of three phase current or the phase current of each phase. The pre-fault current data is obtained from one cycle of data (20ms for 50hz system) previous to the last sample of the current data [11].

Considering the simplified single phase system having a power flow from a distributed generation(DG) source to the grid in Figure 3.3, at the fault point F1, the pre-fault current and the fault current measured at the relay location are in opposite direction; at the fault point F2, the pre-fault current and the fault current are in the same direction.

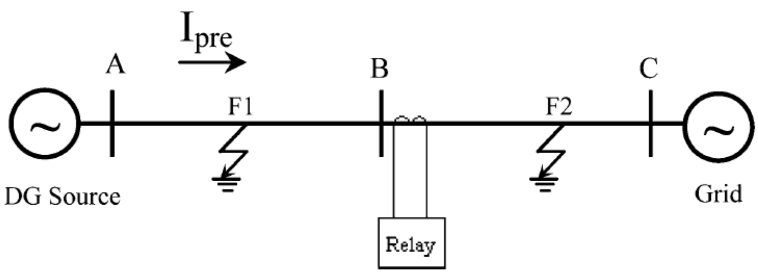

Figure 3.3 Simplified DG system with two fault cases [11]

In Figure 3.4, the pre-fault and the fault currents (including pre-fault current) measured by the relay are shown in phasor diagram for two different fault points, F1 and F2.

For the reverse fault F1, the phase angle difference $\Delta\emptyset_1$ between I_{pre} and I_1 is positive. Conversely, for the forward fault F2, the phase angle difference $\Delta\emptyset_2$ between I_{pre} and I_2 is positive.

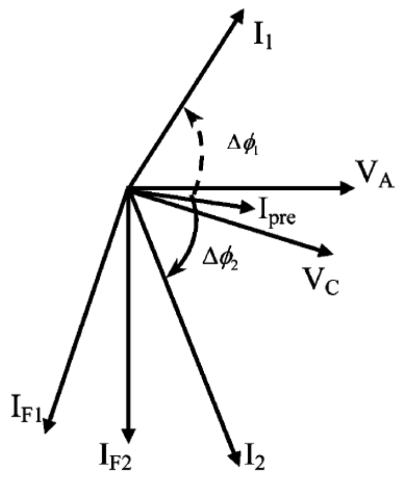

Figure 3.4 Phasor Diagram for F1 and F2 [11]

3.2.2 Time Domain Methods

In time domain methods, variations of phase angle difference between the pre-fault and post-fault currents are directly determined from the current signal samples without using any phasor estimation technique.

3.2.2.1 Zero-Crossing Time Detection

Zero-crossing time(ZCT) elapsed between two consecutive zero-crossing points can be used as an indicative parameter for directional fault detection [12]. During a healthy operation in a distribution network having 50hz frequency, ZCT would be 10ms for a half-cycle. However, the phase angle shift $\Delta\emptyset$ resulting from a fault leads to a time offset Δt which equals to:

$$\Delta t = \Delta\emptyset/\omega \tag{3.6}$$

Where;

$$\omega = 2\pi/T \tag{3.7}$$

By combining equations (3.6) and (3.7) which yields to:

$$\Delta t = (\Delta\emptyset/2\pi) \cdot T \tag{3.8}$$

Where $\Delta\emptyset$ is the phase shift in radians, w is the angular frequency and T = 20ms for 50hz system.

The directional decision is made by comparing the number of the samples at the last ZCT with the number of the samples lying at the previous ZCT width.

It can be seen in Figure 3.5 that, the ZCT interval is increased with positive Δt in forward fault cases; similarly, ZCT interval is decreased with negative Δt in reverse fault cases.

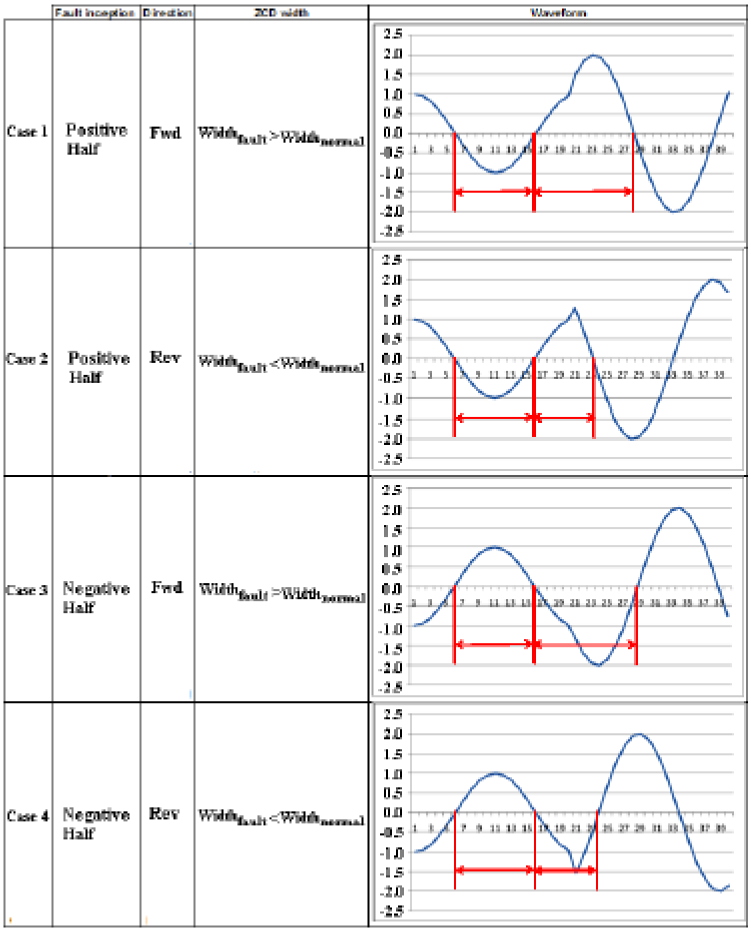

Figure 3.5 Directional analysis using ZCT deviations [12]

3.2.2.2 Cumulative Sum Method

In the proposed method, a directional current element DCE is defined by extracting the cumulative sum of the absolute current signal for each cycle from the cumulative sum of the absolute value obtained by adding the pre-fault current signal to the recent current signal for each cycle as described in the formula below [13].

$$\mathrm{DCE}(j) = \sum_{j=k}^{k+n} |i(j) + i(j-n)| - \sum_{j=k}^{k+n} |i(j)| \tag{3.9}$$

The sign of DCE is indicative of directional information such that, after the fault, if DCE becomes greater than a positive threshold value, the fault is identified in the forward direction. Inversely, if DCE becomes less than a negative threshold value, the fault is identified in the reverse direction. The positive and negative threshold values to be selected depend on nominal current magnitudes that could flow in either direction.

3.2.3 Extraction of High Frequency Components

Rapid developments in microprocessor technology has made it possible to utilize high frequency components in relaying schemes. Traditional protection relaying systems treats high frequency signal components as noise and filter them out. This method relies on extracting fault generated high frequency components from line current signals by filtering techniques. High frequency components due to fault currents contain information about the fault type, location, direction and sustain time than power frequency signals do [14]. Unlike the methods described in 3.2.1. and 3.2.2, this technique does not determine whether the fault is of forward or reverse type.

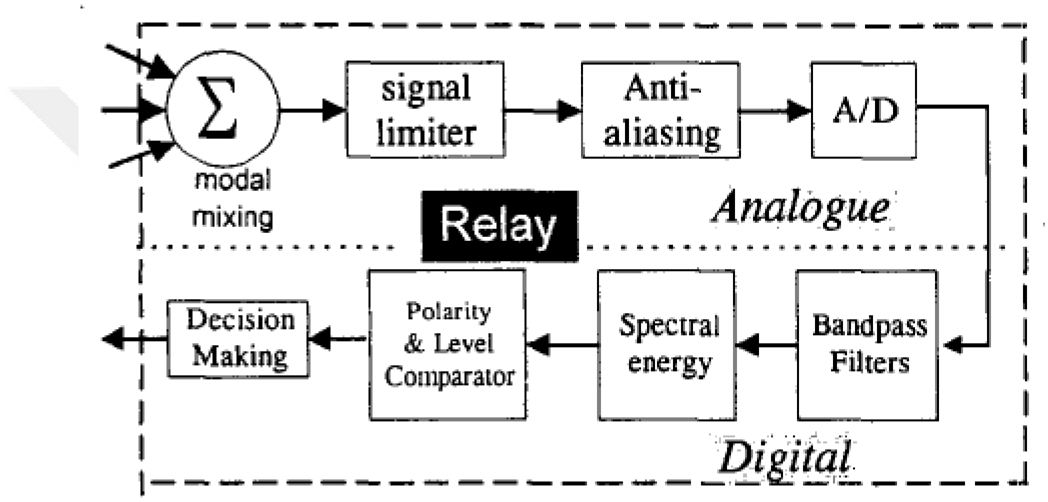

Figure 3.6 Relay design for extraction of high frequency components [14]

Initial fault generated high frequency signals are obtained by detecting the transient current signal at both ends of the distribution line. Referring to Figure 3.6, the relay design substantially depends on the band-pass filter which is used to extract the high frequency components from the current signals. The polarities of the spectral energies of the filtered signals at local and remote ends are compared to decide whether the fault is in the protected zone. If the relays have same polarity, the fault is external; if don't, it is an internal fault [15].

3.3 Limitations

There are various limitations with which current only directional relaying methods cope in terms of grid conditions and current measurement.

3.3.1 Reversal of pre-fault current

According to the methods stated in parts 3.2.1 and 3.2.2, the directional element decides the position of the fault with respect to the pre-fault power flow direction. However, if the assumed pre-fault current direction changes in healthy grid conditions, forward and reverse fault locations would also change accordingly.

Considering the simple distribution network in Figure 3.7 with normal power flow from source 1 to source 2; relays R1, R2 and R3 detects a forward fault, while R4 detects a reverse fault if a ground fault F occurs between Substation 2 and Substation 3.

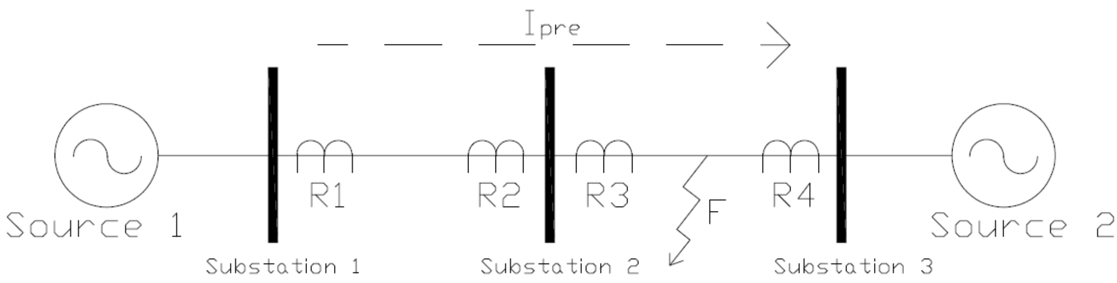

Figure 3.7 Simple distribution network

If the normal power flow I_{pre} reverses as from source 2 to source 1, R1, R2 and R3 detect the same fault F as reverse fault, while R4 detects it as forward. It is a considerable disadvantage of current-only directional relaying since the pre-fault power flow direction may change depending on the grid conditions, which the relay is not able to detect itself.

3.3.2 Harmonics

In phasor angle estimation method, the presence of harmonics due to the nonlinear loads have to be handled for an accurate phasor estimation. DFT algorithm is a suitable way to overcome harmonic problem compared to the other phasor estimation methods such as Kalman Filtering and Recursive Least Squares in terms of computation speed and accuracy [16].

Furthermore, in time domain methods, digital low-pass filtering techniques [17] should be applied to acquire more accurate ZCT and cumulative sum values.

3.3.3 Frequency Deviation

Due to the imbalances between generation and consumption in a power grid, the frequency deviates in a range of ±0.5hz which affects the accuracy of the DFT calculation [18]. Moreover, the time interval between two consecutive zero crossings changes as a result of the frequency deviation. Therefore, an adaptive real time frequency measurement can be used by estimating zero crossing intervals for an accurate phasor estimation and zero crossing detection.

3.3.4 Sampling Frequency

The detection of the phase angle shift is considerably affected by sampling rate such that the sensitivity of the measurement depends on the sampling frequency. Assuming a 50hz system with 1khz sampling rate, the minimum phase angle change sensitivity is 360x50/1000=18º. As depicted in Figure 3.8, during the fault, the phase shift occurred between two samples of N-1 and N cannot be detected reliably. Therefore, a higher rate of sampling is required for a dependable operation [19].

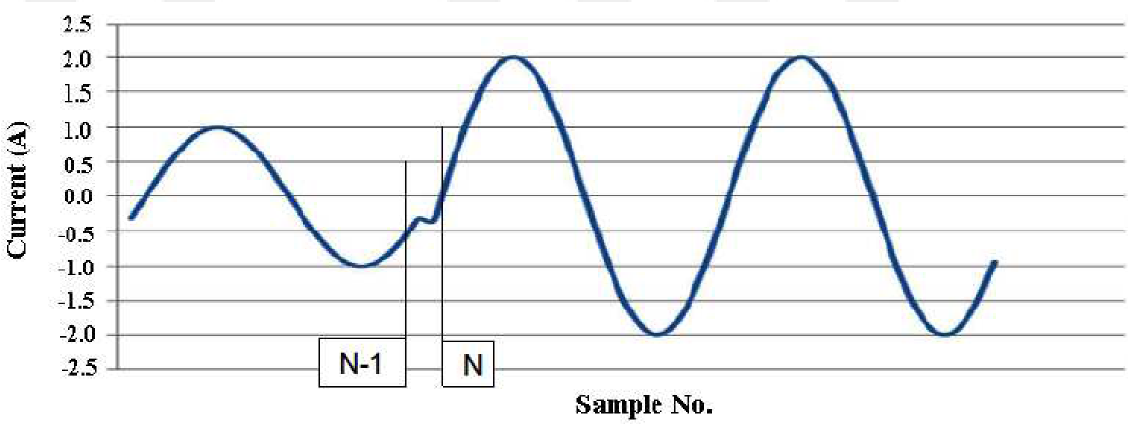

Figure 3.8 Sampling frequency limitation [19]

3.3.5 DC Offset Current

Fault currents in power systems depend on the system voltage, fault impedance and the time when the fault occurs. If it is assumed that the equivalent fault circuit is in R-L series, the fault current is represented by the following [20]:

$$i = (V_{max}/|Z|) \cdot \left[\sin(wt + \alpha - \theta) - \epsilon^{-Rt/L} \sin(\alpha - \theta)\right] \tag{3.10}$$

Where the system voltage is V, the short circuit impedance is $|Z| = \sqrt{R^2 + (wL)^2}$, the power factor angle $\theta = \tan^{-1}(wL/R)$ and α is the angle difference between the initiation of the fault and zero voltage.

Referring to the equation (3.8), the transient dc component of the fault current is:

$$i_{dc} = (V_{max}/|Z|) \cdot \left[-\epsilon^{-Rt/L} \, sin(\alpha - \theta)\right] \tag{3.11}$$

The magnitude and the decay rate of the DC fault current depend on the terms $sin(\alpha - \theta)$ and $-Rt/L$, respectively. The initial peak value of the fault current is said to be most asymmetrical in case of that α equals to 0 º with a particular θ angle.

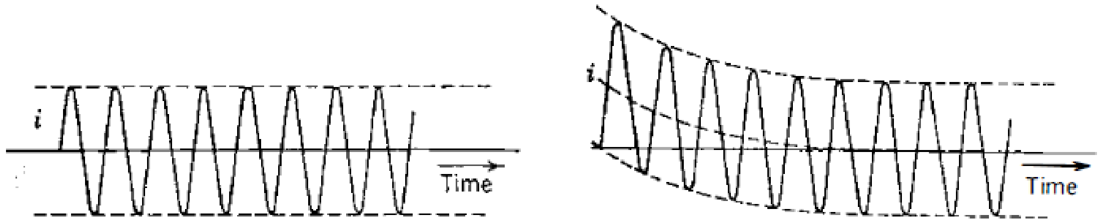

Figure 3.9 Symmetrical and asymmetrical fault currents initiated at t=0 [20]

As shown in Figure 3.9, due to the nature of asymmetric fault, the zero crossing time intervals are no longer 10ms (for a 50hz system) which is a substantial drawback for ZCT method.

Besides, if the phase angle estimation method is performed, it is likely to have a significant estimation error for non-zero DC offset during the fault initiation [21].

In earlier applications, a mimic R-L impedance is connected to the CT secondary winding to eliminate DC offset current. If there is no R-L impedance is connected to CT secondary, a high pass digital filter must be implemented to eliminate the offset current [22].

CHAPTER 4

PROPOSED CURRENT-ONLY DIRECTIONAL PROTECTION METHOD

In transmission lines, superimposed components are extensively used for high speed distance and directional comparison protection. In this work, a current-only directional protection algorithm based on superimposed components is proposed for medium voltage distribution networks.

4.1 Superimposed Components

The concept of utilizing incremental voltages and currents has been being used in directional comparison and distance relays in UHV/EHV transmission lines since the late nineteen-seventies [23, 24]. It offers faster computation speed due to the direct use of time-domain samples instead of using phasors in frequency domain [25].

According to the superposition principle, a faulty network can be split into pre-fault network and pure fault network to estimate the voltage and currents of the faulted circuit [26].

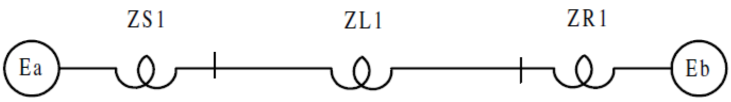

Figure 4.1 Example system single line diagram [26]

In the single line diagram shown in Figure 4.1, considering a fault occurring between two buses through a resistance Rf, the faulted network can be represented as the sum of the pre-fault network and pure fault-network [26]. Faulted network, pre-fault network and pure-fault network are represented in Figure 4.2, Figure 4.3 and Figure 4.4, respectively.

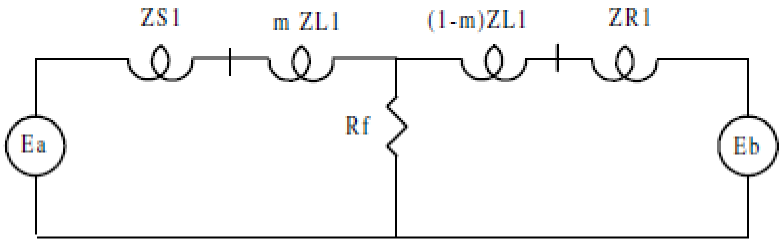

Figure 4.2 Faulted network [26]

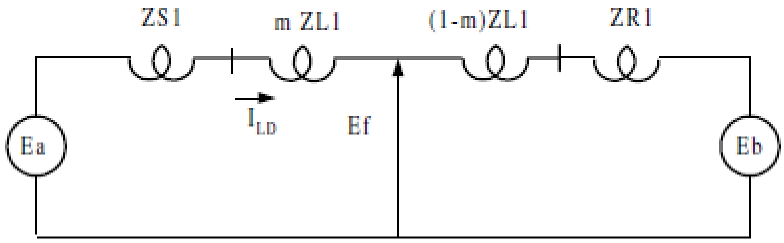

Figure 4.3 Pre-fault network [26]

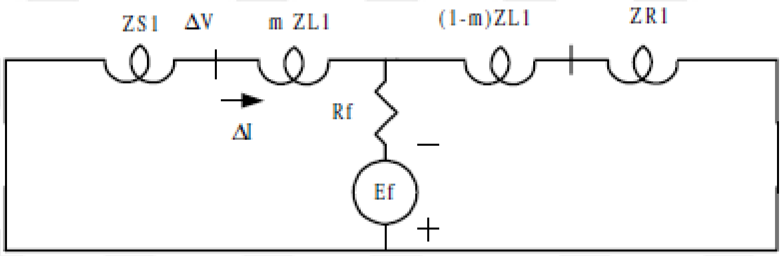

Figure 4.4 Pure-fault network [26]

In the pure fault network, a fictitious voltage Ef, which is equal in magnitude to the pre-fault voltage level at the fault location, is applied at the instant of the fault inception. The current and voltages measured at the relay locations changes in magnitude and phase angle because of this fictitious voltage. Therefore, the changes in current (ΔI) and voltage (ΔI) measured at the relay locations are directly associated with the fault.

As provided by the superposition principle, the changes in voltage and current are defined as:

$$V = V_{\text{pre-fault}} + \Delta V \tag{4.1}$$

$$I = I_{\text{pre-fault}} + \Delta V \tag{4.2}$$

Therefore, the superimposed current (ΔI) and voltage (ΔV) can be expressed as:

$$\Delta V(t) = V(t) - V(t\text{-}T) \tag{4.3}$$

$$\Delta I(t) = I(t) - I(t\text{-}T) \tag{4.4}$$

The superimposed signals ΔV(t) and ΔI(t) only exists during the transient conditions such as faults and load switchings. They don't present in steady state conditions.

Directional element which is based on superimposed components is used in transmission line protection by measuring the polarity of the transient energy at relay locations [27]. The transient energy obtained by delta quantities is defined by the following formula:

$$S = \int \Delta I \cdot \Delta V \cdot dt \qquad (4.5)$$

By the above formula, the signs of ΔV(t) and ΔI(t) after the fault inception are indicative of whether the fault is in forward or reverse direction as depicted in Figure 4.5.

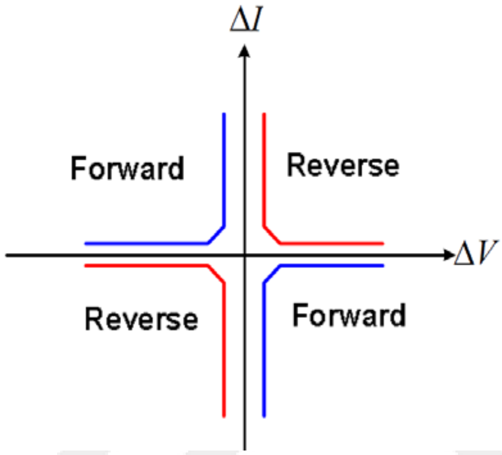

Figure 4.5 Forward and reverse zones [27]

4.2 Fault Current Analysis

A typical fault current is shown in Figure 4.6. Before the fault inception at t=0, ip(t) represents the pre-fault current at the steady state load conditions. After the fault inception for t>0, the measured current i(t) is no longer in steady-state and can be expressed as the sum of the pre-fault current ip(t) and the delta(superimposed) current Δi(t).

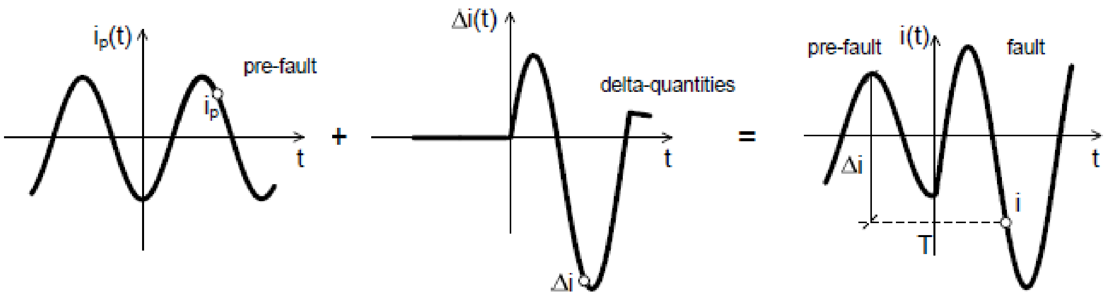

Figure 4.6 Fault current [28]

The initial polarity and magnitude of the superimposed current Δi(t) contains information about the directional characteristics of the fault depending on the pre-fault system conditions such as fault inception angle, polarity of half cycle, fault type and fault location.

In current-only directional protection methods, the fault type (forward or reverse) is defined by comparison between pre-fault and post-fault currents.

The initial sign of the superimposed current resulting from a fault is a function of the polarity of the pre-fault current and the fault type. Thus, it is possible to determine whether the fault is in forward or reverse direction by deriving two parameters after the fault inception:

- Polarity of the half-cycle of the measured current
- Initial sign of the superimposed current

In Figure 4.7, forward(F_F) and reverse(F_R) faults are depicted in a single phase network having normal power flow from source 1 to source 2.

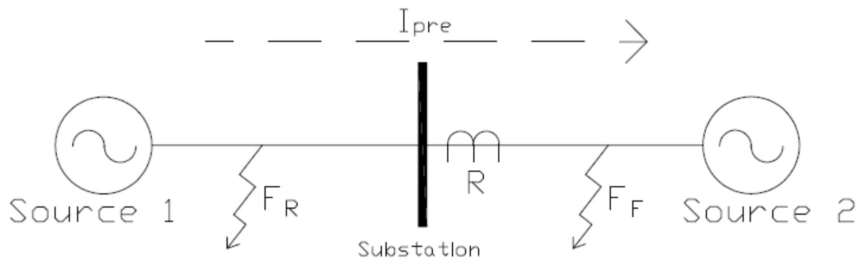

Figure 4.7 Forward and reverse faults

The superimposed component of the current ΔI(t) is obtained from the subtraction of the previous cycle of the fault current I(t-T) from the current I(t) after the fault inception at the measurement location having relay, R. T is equal to 20ms for 50hz system.

For F_F occurred at t=0.281s while I(t) is in positive half-cycle, I(t), I(t-T) and ΔI(t) are shown in Figure 4.8. The superimposed component ΔI(t) goes positive after the fault.

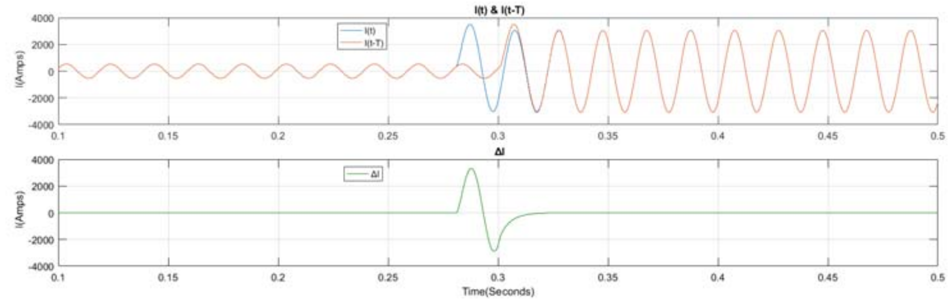

Figure 4.8 Forward fault at positive half cycle

For F_F occurred at t=0.271s while I(t) is in negative half-cycle, I(t), I(t-T) and ΔI(t) are shown in Figure 4.9. The superimposed component ΔI(t) goes negative after the fault.

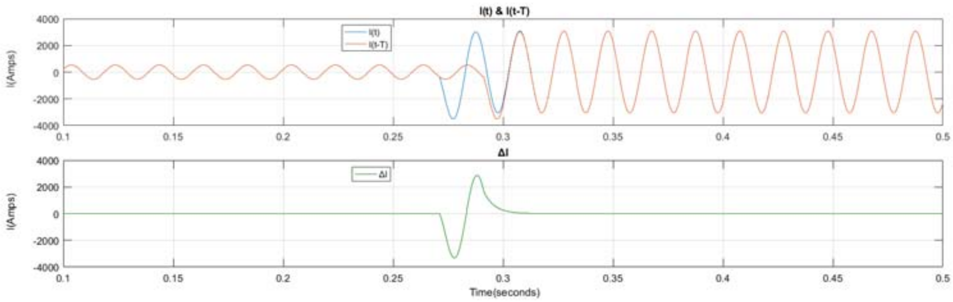

Figure 4.9 Forward fault at negative half cycle

For F_R occurred at t=0.281s while I(t) is in positive half-cycle, I(t), I(t-T) and ΔI(t) are shown in Figure 4.10. The superimposed component ΔI(t) goes negative after the fault.

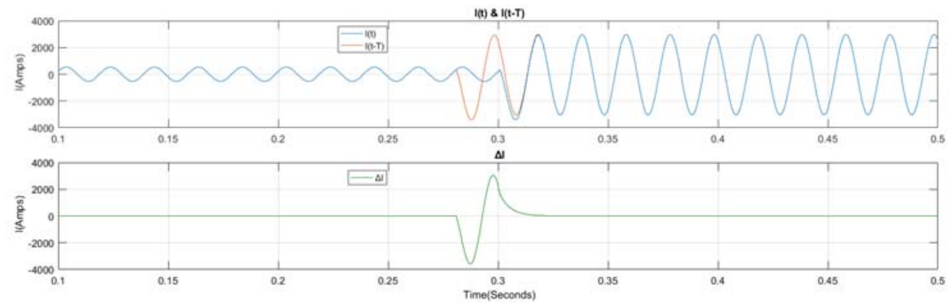

Figure 4.10 Reverse fault at positive half cycle

For F_R occurred at t=0.271s while I(t) is in positive half-cycle, I(t), I(t-T) and ΔI(t) are shown in Figure 4.11. The superimposed component ΔI(t) goes positive after the fault.

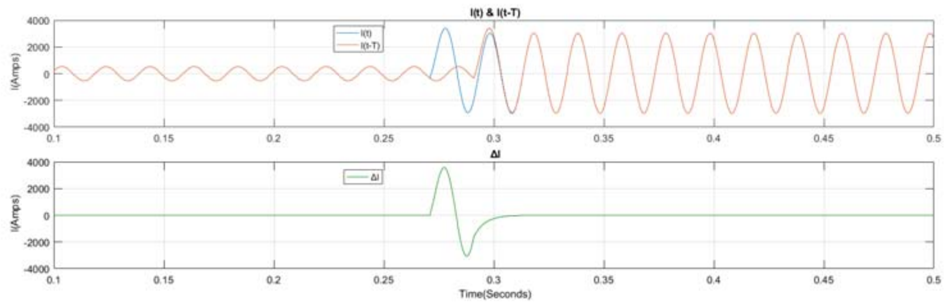

Figure 4.11 Reverse fault at negative half cycle

According to the plottings shown in Figure 4.8, Figure 4.9, Figure 4.10, Figure 4.11, the initial sign of the superimposed current and the polarity of half-cycle of the current are indicative of the fault location based on the assumption that the pre-fault power flow direction is fixed and remains unchanging at the relay location. If these two parameters are the same, the fault is in forward direction; if opposite, it is a reverse fault.

Table 4.1 summarizes the indicative two parameters to determine the fault current direction for a single phase system.

Table 4.1 Sign analysis for forward and reverse type faults

Polarity of Half Cycle at Fault Inception	Initial Polarity of Delta Current	Fault Direction
+	+	**Forward**
-	-	**Forward**
+	-	**Reverse**
-	+	**Reverse**

4.3 Principle of Operation

4.3.1 Faulty Line Detection by Directional Parameter Comparison

In order to determine the faulty line, reversal of the pre-fault current at the relay locations must be considered. Forward and reverse fault positions change in case the pre-fault current direction varies at the relevant measurement location. Therefore, each relay at a particular measurement point have to compare its local directional information with the remote end. If forward or reverse fault types determined by these local and remote relays contradicts, a short circuit fault is identified between those relays.

In Figure 4.12, fault F_1 between R3 and R4 and fault F_2 between R1 and R2 are shown in a distribution system.

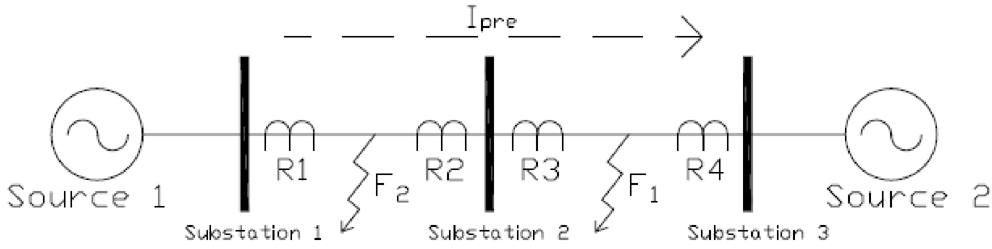

Figure 4.12 F1 and F2 faults

If the pre-fault power flow is from source 1 to source 2, the fault types detected by the relays are listed in Table 4.2:

Table 4.2 Fault types for pre-fault power flow from source 1 to source 2

Relay	**Fault Type for F_1**	**Fault Type for F_2**
R1	**Forward**	**Forward**
R2	**Forward**	**Reverse**
R3	**Forward**	**Reverse**
R4	**Reverse**	**Reverse**

If the pre-fault current reverses, which is from source 2 to source 1, the fault types detected by the relays are listed in Table 4.3:

Table 4.3 Fault types for pre-fault power flow from source 2 to source 1

Relay	**Fault Type for F_1**	**Fault Type for F_2**
R1	**Reverse**	**Reverse**
R2	**Reverse**	**Forward**
R3	**Reverse**	**Forward**
R4	**Forward**	**Forward**

It can be interpreted from Table 4.2 and Table 4.3 that as a result of the fault F1 between R3 and R4 and the fault F2 between R1 and R2:

- The fault types detected by the relays are same independent of the initial load current direction at the line's both ends if the fault is internal between two measurement points.
- The fault types detected by the relays are opposite independent of the initial load current direction at the line's both ends if the fault is external between two measurement points.

By the above analysis, whatever the load flow direction prior to the fault inception is, a faulty line can be detected by comparing the fault types at the line's both ends. For this purpose, a communication logic between local and remote ends is necessary. Instead of performing direct comparison of measured current values, forward or reverse status of the faults are logically compared. Therefore, a decentralized communication system requiring a transmitter and receiver group at both line ends must be implemented, which is similar to non-unit pilot protection shemes as shown in Figure 4.13.

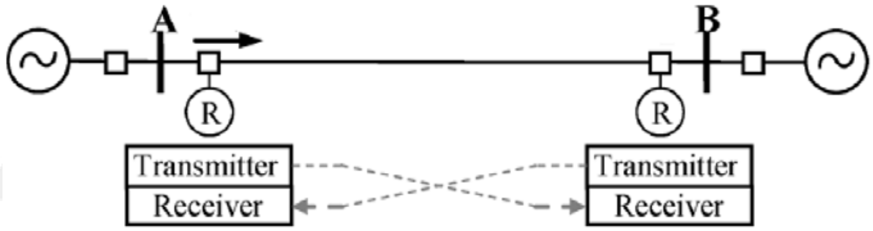

Figure 4.13 Communication scheme for directional comparison protection [30]

4.3.2 Overcurrent Element

Superimposed current signals are not only generated from the system faults, but also the transient conditions resulting from load disturbances such as noise, load switchings may lead to generate superimposed current signals. Therefore, superimposed components cannot be used to distinguish disturbances from fault events. For this reason, a non-directional overcurrent element irrespective of directional detection is necessary to detect fault inception by operating in coordination with the directional element.

Non-directional overcurrent relays are typically employed for overcurrent detection in radial distribution lines. Instantaneous or definite/inverse time delay tripping characteristics are chosen depending on power system characteristics [30]. The operating time for high-speed relays are generally less than 3 cycles [31]. Then, the tripping command can be sent based on whether the overcurrent element triggers a trip signal by obtaining directional information from local and remote ends of protected line. By this way, the tripping signal is not sent under load disturbances and the directional information would be reset.

4.3.3 Algorithm

The proposed algorithm utilizes time domain samples which makes the computation faster and simpler compared to the other methods. The flowchart of the algorithm is shown in Figure 4.14.

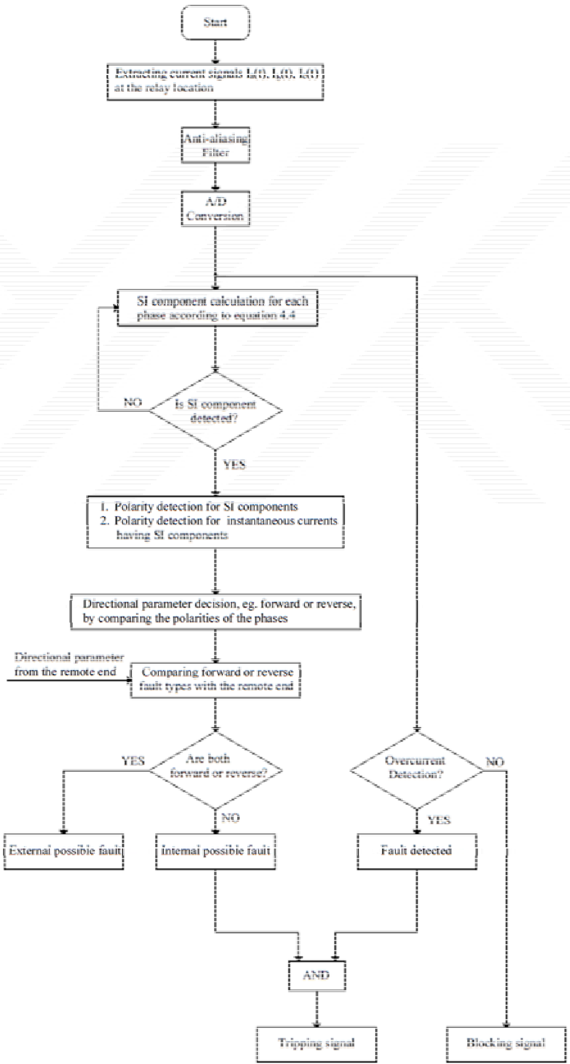

Figure 4.14 The proposed directional relay algorithm

For three phase operation, the phase currents $I_a(t)$, $I_b(t)$, $I_c(t)$ are obtained from local measurement points. An anti-aliasing filter is required to remove high-frequency components from the analog signals before they are converted to sampled signals in the analog to digital converter.

The outputs of the converted signals are passed to pre-fault current (I_a(t-T), I_b(t-T), I_c(t-T)) calculation, then the superimposed components ((Δ_a(t), Δ_b(t), Δ_c(t)) are calculated by extracting the pre-fault currents from the current phase values.

The polarities of superimposed components and half-cycles are obtained, then these polarities are transferred to binary information; e.g. ”1” for positive values, “0” for negative values. After comparing the logical statuses of superimposed components and half-cycles the directional parameter decision is determined; e.g. “1” for forward, “0” for reverse direction. Afterwards, the directional parameter status of the local measurement is compared to the remote end’s status by using EX-NOR gate in order to check whether both statues are same or not. If same, the tripping logic triggers a trip signal provided that overcurrent is detected by the overcurrent element.

CHAPTER 5

SIMULATION STUDIES

In this study, the proposed current-only directional protection method is modelled and simulated for various cases such as fault types, fault locations and load disturbances by using in MATLAB/Simulink.

5.1 Studied System

A MV ring network having four substations is studied throughout the simulations. The topology of the network is depicted in Figure 5.1.

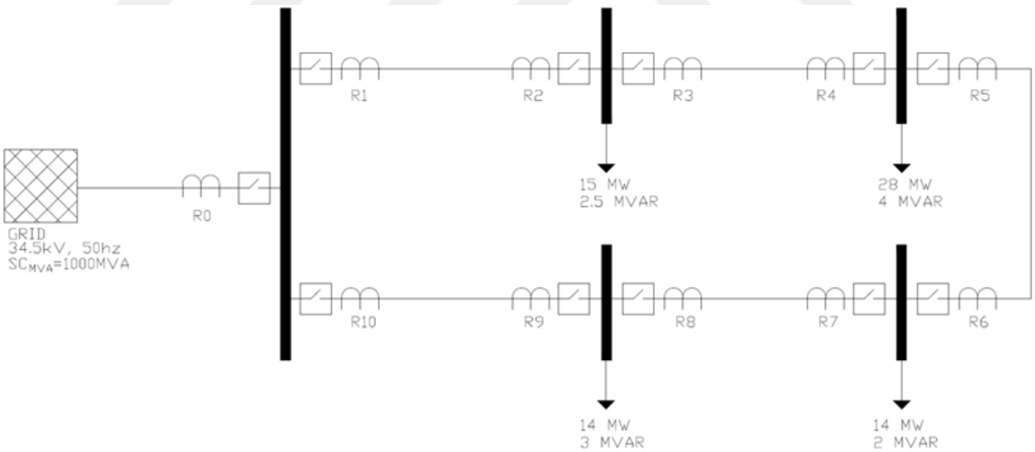

Figure 5.1 The studied ring network

In the network, four substations have their respective loads allowing bidirectional power flow along the relays (R1…. R10) depending on various loading scenarios.

5.2 Simulink Model

The Simulink model illustrating the system is shown in Figure 5.2.

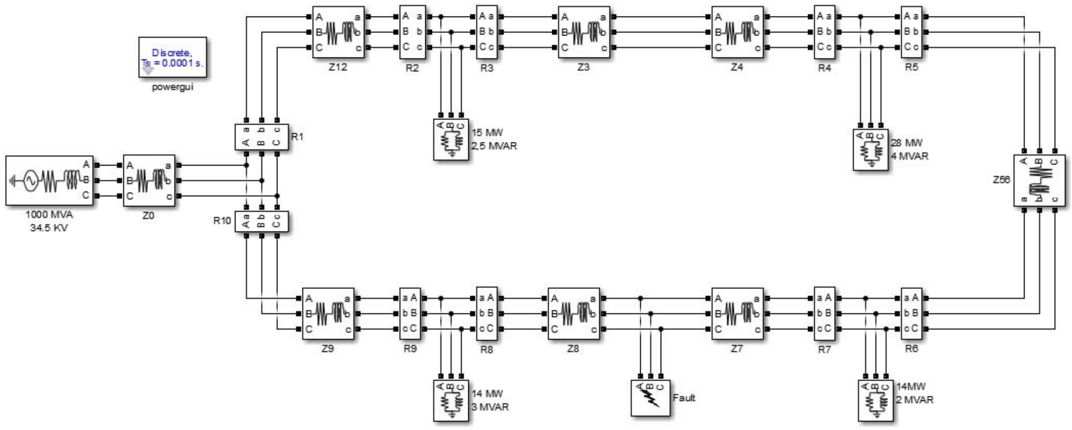

Figure 5.2 Simulink model

To acquire superimposed components, by using equation (4.4), the pre-fault current values are obtained by applying 200 samples delay, one period for Ts=10^{-4}s, to phase currents, then the pre-fault currents are extracted from the present current values to form delta filters as shown below.

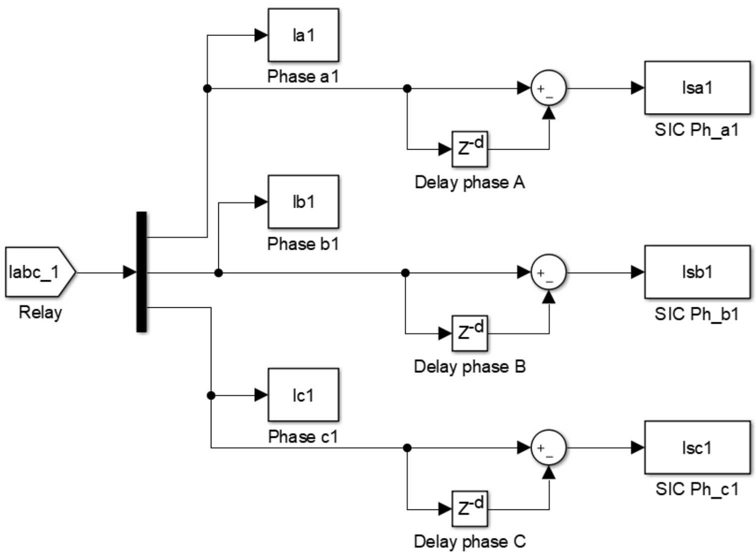

Figure 5.3 Delta filters

5.3 Simulation Results

Simulations has been performed for two conditions, short circuit faults and load disturbances.

5.3.1 Short Circuit Faults

In the ring network in Figure 5.1, a three phase short circuit is created at the line between R7 and R8 at t=0.355s. The pre-fault power flows directions are shown in Figure 5.4.

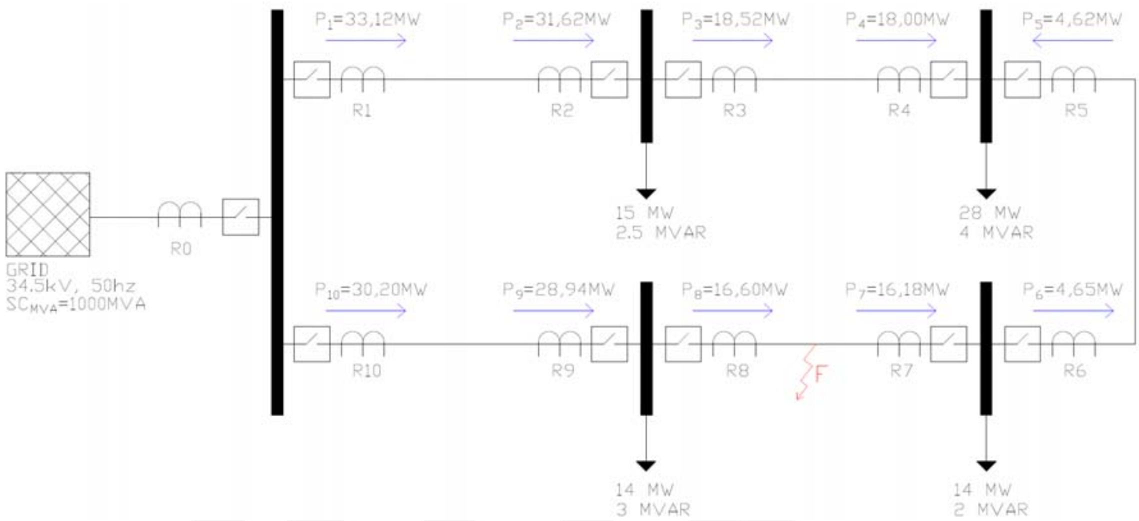

Figure 5.4 Pre-fault power flow directions

Accordingly, after the fault, the power flow directions reverse towards the fault point at relays R5, R6 and R7, while the power flow directions remain same at the other relays, R1, R2, R3, R8, R9, R10.

For phase A, the initial superimposed components are shown in Figure 5.5 for R1 and R2.

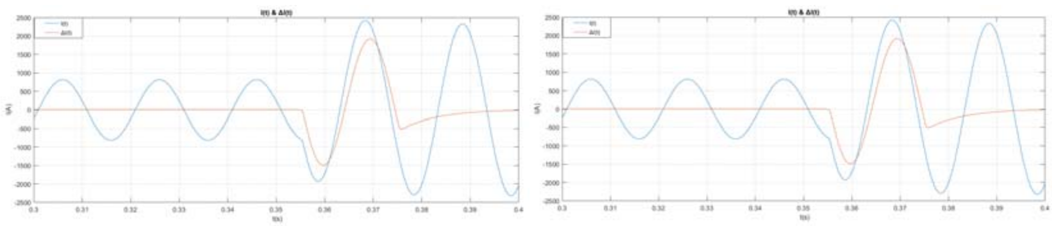

Figure 5.5 Superimposed components for at R1(left) and R2(right)

For R3 and R4:

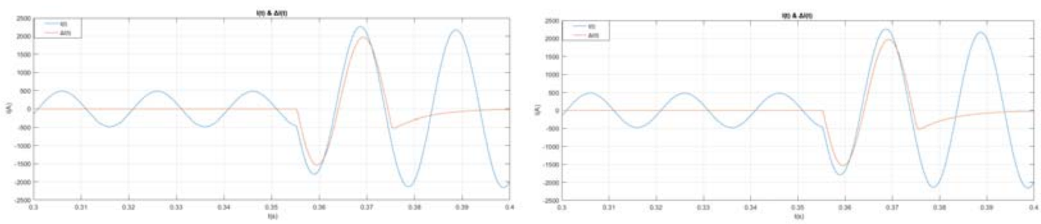

Figure 5.6 Superimposed components for at R3(left) and R4(right)

For R5 and R6:

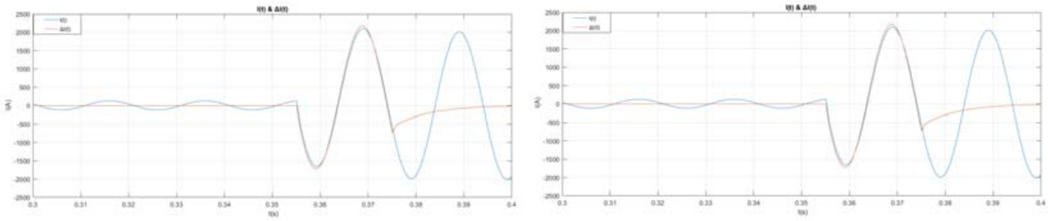

Figure 5.7 Superimposed components for at R5(left) and R6(right)

For R7 and R8:

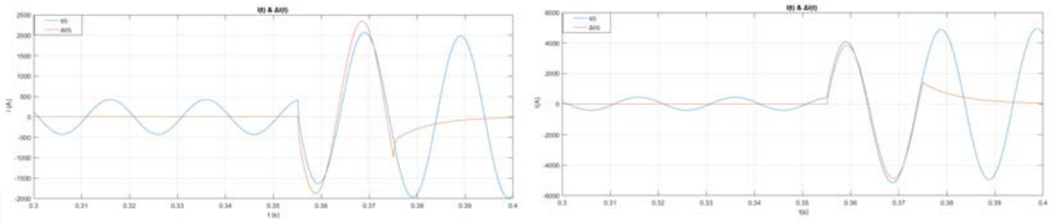

Figure 5.8 Superimposed components for at R7(left) and R8(right)

For R7 and R8:

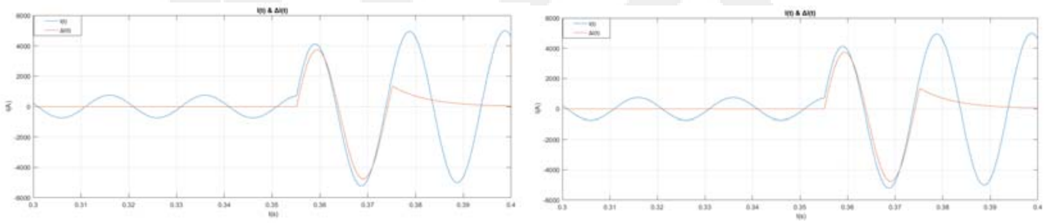

Figure 5.9 Superimposed components for at R9(left) and R10(right)

The initial superimposed component polarities, half cycle polarities and fault directions obtained from relays are summarized on the Table 5.1 for the fault between R7 and R8.

Table 5.1 Initial SIC, half cycle polarities and fault directions for phase A

Relay	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10
Half Cycle Polarity	-	-	-	-	+	+	+	+	+	+
Initial SIC Polarity	-	-	-	-	-	-	-	+	+	+
Fault Direction	Forward	Forward	Forward	Forward	Reverse	Reverse	Reverse	Forward	Forward	Forward

For other phases, B and C, the initial superimposed component polarities, half cycle polarities and fault directions obtained are shown on the Table 5.2 and Table 5.3, respectively.

Table 5.2 Initial SIC, half cycle polarities and fault directions for phase B

Relay	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10
Half Cycle Polarity	+	+	+	+	-	-	-	-	-	-
Initial SIC Polarity	+	+	+	+	+	+	+	-	-	-
Fault Direction	Forward	Forward	Forward	Forward	Reverse	Reverse	Reverse	Forward	Forward	Forward

Table 5.3 Initial SIC, half cycle polarities and fault directions for phase C

Relay	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10
Half Cycle Polarity	+	+	+	+	-	-	-	-	-	-
Initial SIC Polarity	+	+	+	+	+	+	+	-	-	-
Fault Direction	Forward	Forward	Forward	Forward	Reverse	Reverse	Reverse	Forward	Forward	Forward

Another short circuit fault, phase A, B to ground is applied between relays R3 and R4 at t=0.277s. This time, the power flow direction reverses only at R4. At other relays, it doesn't change.

For phase A, the initial superimposed components are shown in Figure 5.9 for R1 and R2.

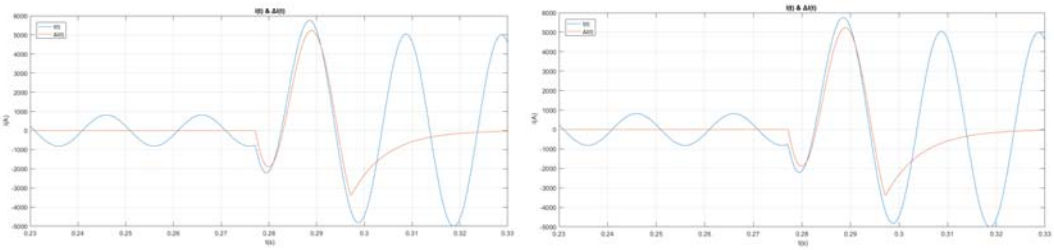

Figure 5.10 Superimposed components for at R1(left) and R2(right)

For R3 and R4,

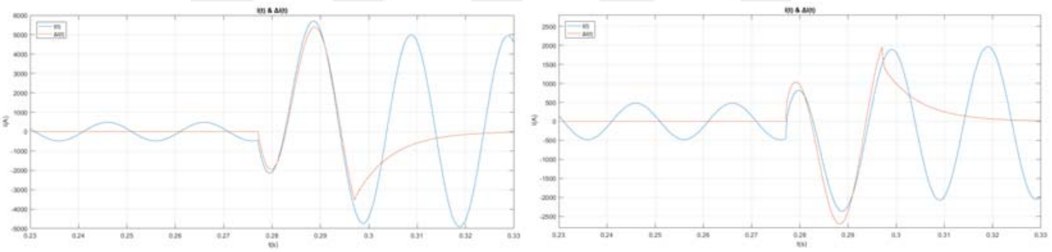

Figure 5.11 Superimposed components for at R3(left) and R4(right)

For R5 and R6,

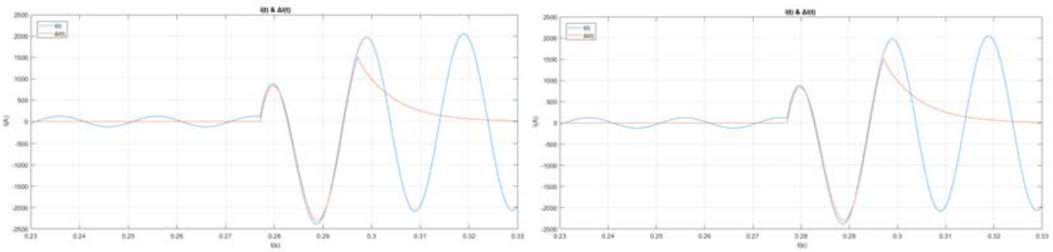

Figure 5.12 Superimposed components for at R5(left) and R6(right)

For R7 and R8,

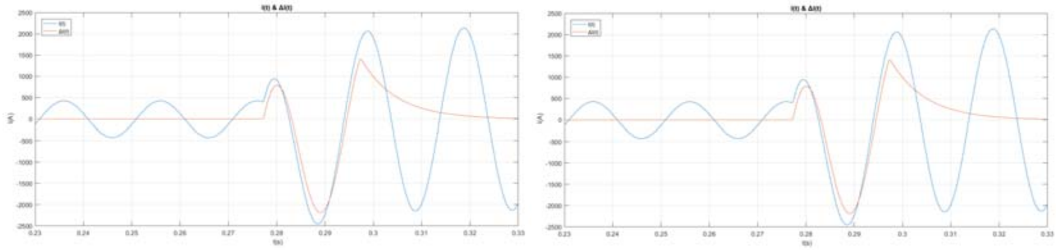

Figure 5.13 Superimposed components for at R7(left) and R8(right)

For R9 and R10,

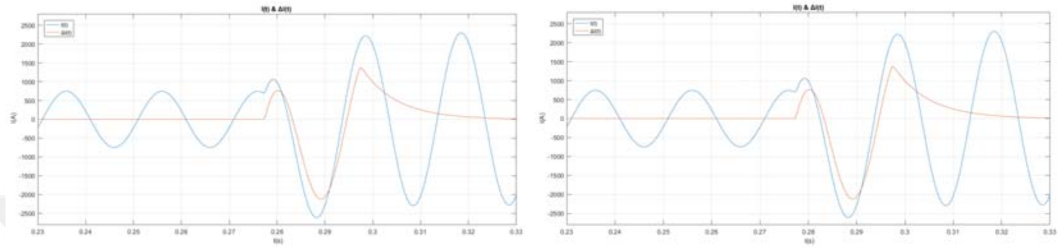

Figure 5.14 Superimposed components for at R9(left) and R10(right)

For the fault is between R3 and R4, the initial superimposed component polarities, half cycle polarities and fault directions obtained from relays are summarized on Table 5.4 and Table 5.5 for the phases A and B, respectively.

Table 5.4 Initial SIC, half cycle polarities and fault directions for phase A

Relay	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10
Half Cycle Polarity	-	-	-	-	+	+	+	+	+	+
Initial SIC Polarity	-	-	-	+	+	+	+	+	+	+
Fault Direction	Forward	Forward	Forward	Reverse	Forward	Forward	Forward	Forward	Forward	Forward

Table 5.5 Initial SIC, half cycle polarities and fault directions for phase B

Relay	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10
Half Cycle Polarity	+	+	+	+	-	-	-	-	-	-
Initial SIC Polarity	+	+	+	-	-	-	-	-	-	-
Fault Direction	Forward	Forward	Forward	Reverse	Forward	Forward	Forward	Forward	Forward	Forward

5.3.2 Load Switchings

In chapter 4.3.2, it was said that the proposed current-only directional detection method cannot be used for overcurrent detection. The reason for this is that the superimposed components become non-zero not only in fault conditions, they may become non-zero in case of load disturbances such as noise, load switchings in the network.

In Figure 5.14, the total load of the substation is switched off. Hence, the load flowing on the relays changes which leads to generate superimposed current quantities.

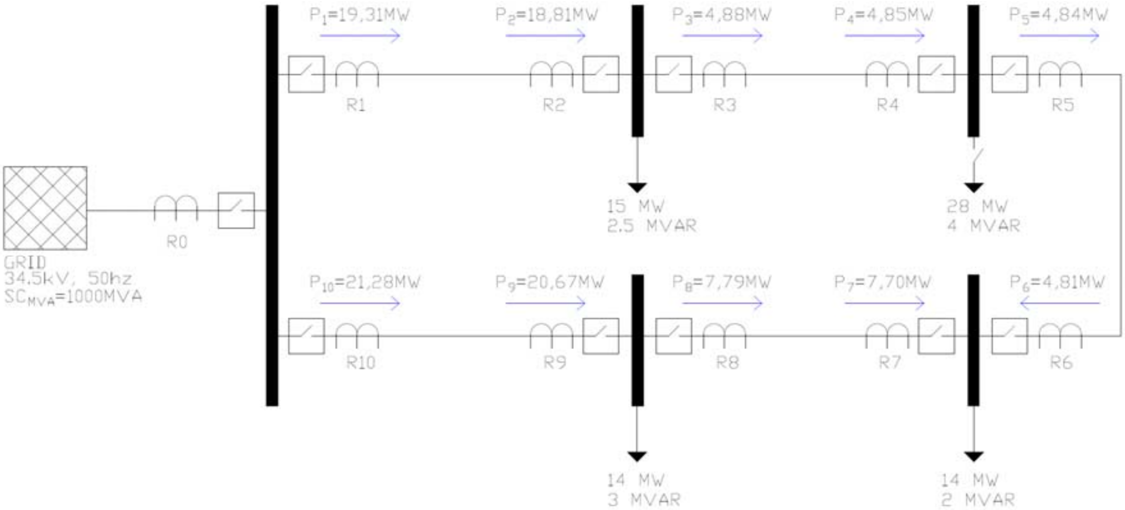

Figure 5.15 Load switching

The superimposed current quantities generated due to the load switching are shown in the figures below.

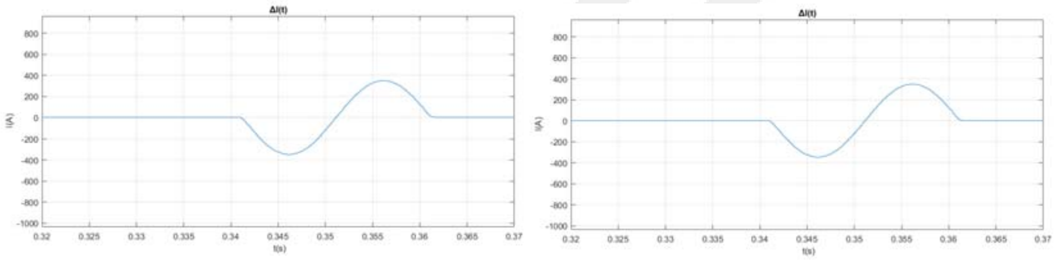

Figure 5.16 Superimposed components for at R1(left) and R2(right)

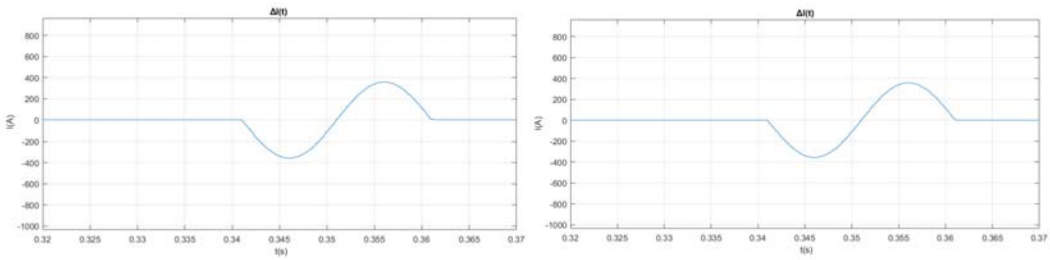

Figure 5.17 Superimposed components for at R3(left) and R4(right)

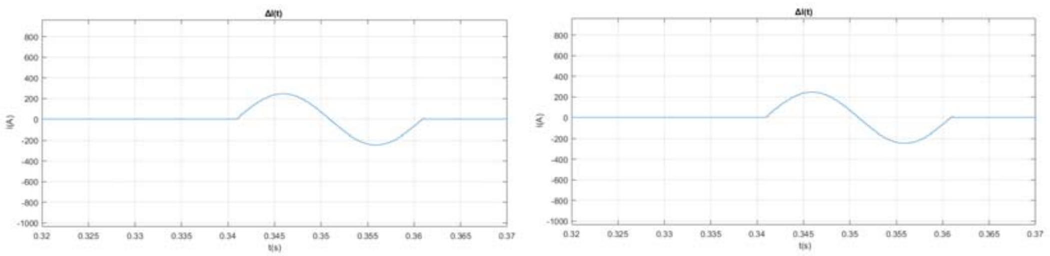

Figure 5.18 Superimposed components for at R5(left) and R6(right)

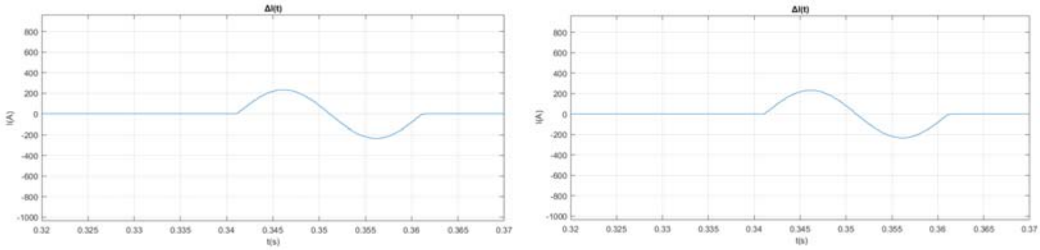

Figure 5.19 Superimposed components for at R7(left) and R8(right)

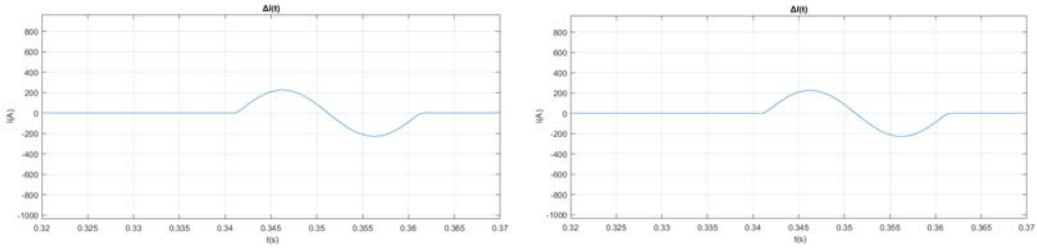

Figure 5.20 Superimposed components for at R9(left) and R10(right)

Table 5.6 Initial superimposed component polarities for phase A

Relay	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10
Initial SIC Polarity	-	-	-	-	+	+	+	+	+	+

In the figures above, it is observed that both sign changes in the initial superimposed signals are same for the local and remote line ends.

In Figure 5.20, a compensation system is applied in the substation.

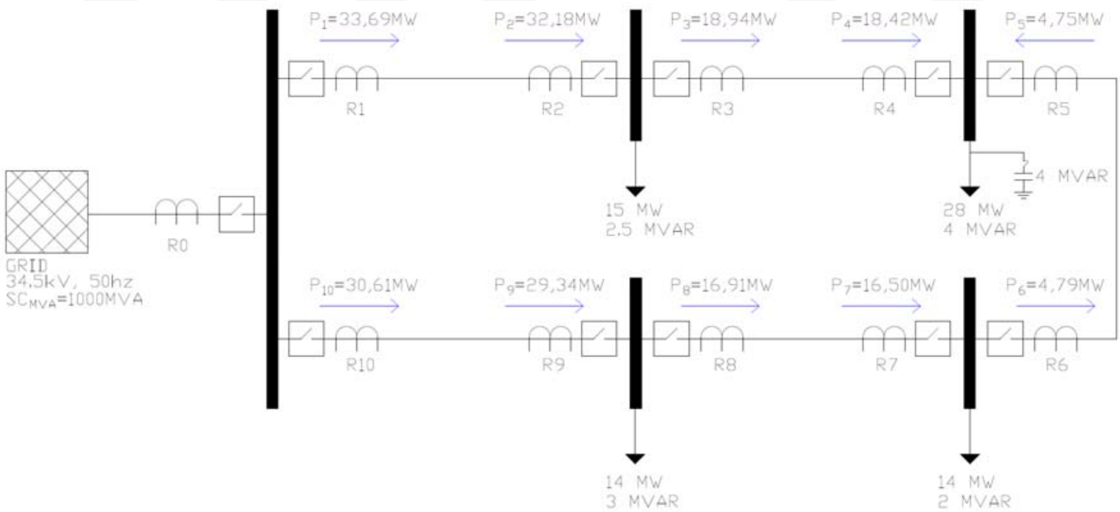

Figure 5.21 Capacitive switching

The superimposed current quantities generated due to the capacitive switching at relays are shown in the figures below.

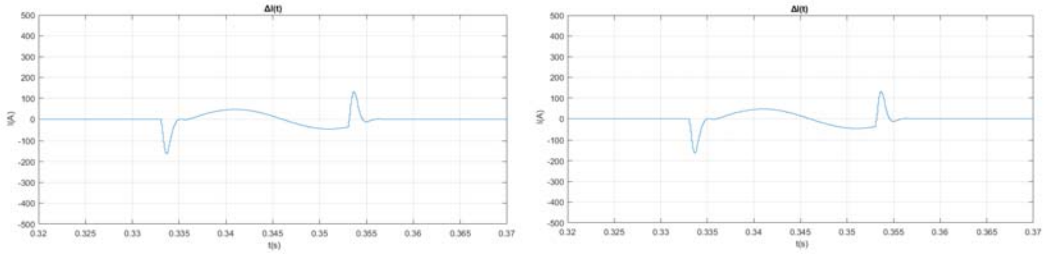

Figure 5.22 Superimposed components for at R1(left) and R2(right)

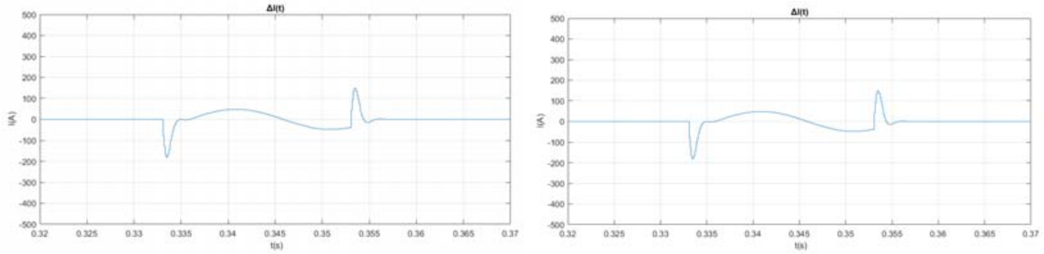

Figure 5.23 Superimposed components for at R3(left) and R4(right)

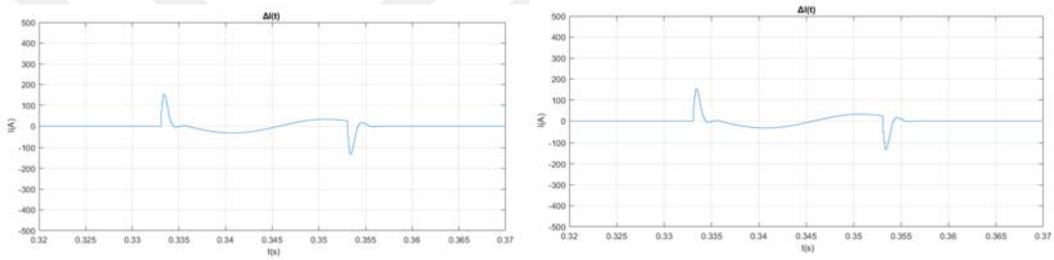

Figure 5.24 Superimposed components for at R5(left) and R6(right)

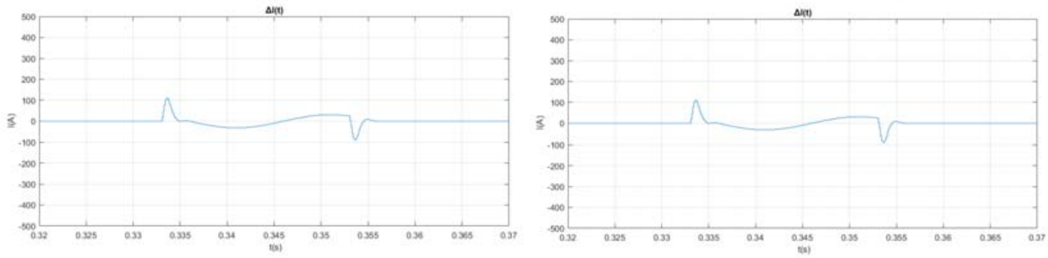

Figure 5.25 Superimposed components for at R7(left) and R8(right)

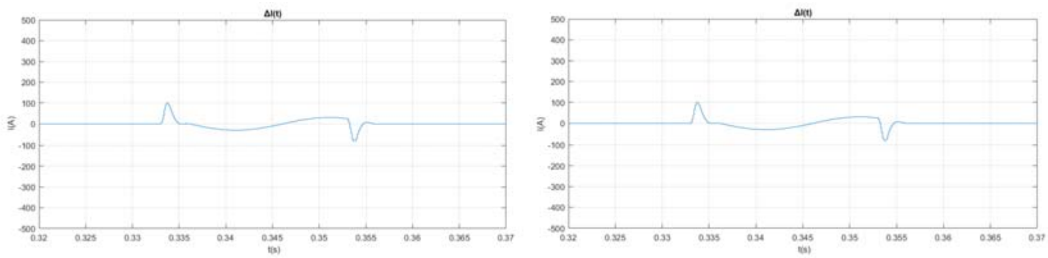

Figure 5.26 Superimposed components for at R9(left) and R10(right)

Table 5.7 Initial superimposed component polarities for phase A

Relay	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10
Initial SIC Polarity	-	-	-	-	+	+	+	+	+	+

In the figures above, it is observed that both sign changes in the initial superimposed signals are same for the local and remote line ends.

According to two cases examined, it is observed that the load switchings generate superimposed components, which have the same polarities for both line ends. Thus, an internal fault signal is not sent. However, since the real time signals are susceptible to noise, the method may generate false directional information. Thus, a non-directional overcurrent element is required by monitoring the duration and magnitude of excessive currents.

CHAPTER 6

RESULTS AND DISCUSSION

The modern distribution protection systems require directional protection schemes more than before due to the integration of DG sources and the conversion networks from radial to meshed structure, which requires additional voltage transformers and their particular relays. The cost of equipment and installation for these systems are considerably high especially in distribution systems, which mostly equipped with non-directional protection systems. Therefore, directional overcurrent protection with no voltage transformer would bring about a great improvement in smart distribution grids.

In this thesis, so far proposed current-only directional overcurrent relaying methods are examined and a new time-domain approach is suggested. The main limitation associated with the previously proposed methods is the reversal of pre-fault power flow direction. It is because the forward and reverse fault definitions interchange while the pre-fault power flow direction reverses. To overcome this drawback, a communication scheme between the relays at local and remote ends to compare the directional information is proposed.

In order to identify the fault directional parameter, which is forward or reverse with respect to the pre-fault current, superimposed phase current quantities are utilized. The initial polarity of the fault generated superimposed signal and the polarity of the instantaneous phase current during the fault are compared to determine whether the fault is forward or reverse type. Subsequently, the faulty line is detected by comparison between the fault directional parameters of the relays located at both line ends. For internal faults, both relays have opposite parameters; while for external faults, they have identical ones.

Simulation studies were also performed to demonstrate that the proposed method is independent of fault types and positions. It was also observed that load switchings in the network also generate superimposed quantities. However, the comparison of the superimposed component polarities enables it to detect if there is an internal fault at the protected line. Furthermore, in real time signals, the presence of noise signals leads to generate superimposed quantities which can produce false internal fault signal in the proposed method. For this, a non-directional overcurrent element is also suggested in order to supervise the overcurrent duration and magnitude to provide a trip trigger.

REFERENCES

[1] Shea, J.J., (2005). Protection of Electricity Distribution Networks, Second Edition, The Institution of Engineering and Technology, London.

[2] Elmore, A.E., (2003). Protective Relaying Theory and Applications, Second Edition, CRC Press, New York.

[3] Mason, C.R., (2015). The Art & Science of Protective Relaying, General Electric, Michigan.

[4] Blackburn, J.L. and Domin, T.J., (2006). Protective Relaying Principles and Applications, Third Edition, CRC Press, New York.

[5] Horak, J., (2006). "Directional Overcurrent Relaying (67) Concepts", IEEE Rural Electric Power Conference, 4-6 April 2006, Albuquerque.

[6] IEEE Power System Relaying Committee, (2006). Loss of ac voltage considerations for line protection.

[7] Horowitz, S.H. and Phadke, A.G., (2014). Power System Relaying, Fourth Edition, Wiley, Chennai.

[8] Zimmerman, K. and Costello, D., (2010). "Fundamentals and improvements for directional relays", 63rd Annual Conference for Protective Relay Engineers, 29 March-1 April 2010, Collage Station.

[9] IEEE Std 242-2001, (2001). Recommended Practice for Protection and Coordination of Industrial and Commercial Power Systems (IEEE Buff Book), Revision of IEEE Std 242-1986, New York.

[10] Ukil, A., Deck, B. and Shah, V.H., (2011). "Current-Only Directional Overcurrent Relay", IEEE Sensors Journal, 11(6):1403-1404.

[11] Pradhan, A. K., Routray, A. and Gudipalli, S.M., (2007). "Fault Direction Estimation in Radial Distribution System Using Phase Change in Sequence Current", IEEE Transactions on Power Delivery, 22(4):2065-2071.

[12] Ukil, A., Deck, B. and Shah, V.H., (2013). Fault Direction Parameter Indicator Device and Related Methods. U.S Patent Application No. 0221977A1.

[13] Eissa, M.M., (2005). "Evaluation of a new current Directional Protection Technique Using Field Data", IEEE Transactions on Power Delivery, 20(2):566-572.

[14] Bo, Z.Q., Klimek, A., Dong, X.Z., He, J.H. and Zhang, B.H., (2008). "Developments of Transient and Integrated Protection for Power System", Third International Conference on Electric Utility Deregulation and Restructuring and Power Technologies, 6-9 April 2008, Nanjing.

[15] Fitzgerald, P., Bishop, P., Bo, Z.Q., Denning, L., Weller, G. and O'Keefe, M., (2001). "A New Directional Relay for Distribution Network Protection Using Transient Comparison Technique", Seventh International Conference on Developments in Power System Protection (IET), 9-12 April 2001, Amsterdam.

[16] Jain, P., (2017). "Phasor Estimation Methods in the Presence of Harmonics and Noise: A Comparative Analysis", Innovations in Power and Advanced Computing Technologies (i-PACT), 21-22 April 2017, Vellore.

[17] Rodrigues, N.M., Janeiro, F.M. and Ramos, P.M., (2018). "Digital Filter Performance for Zero Crossing Detection in Power Quality Embedded Measurement Systems", IEEE International Instrumentation and Measurement Technology Conference (I2MTC), 14-17 May 2018, Houston.

[18] Phadke, A.G. and Thorp, J.S., (2008). Synchronized Phasor Measurements and Their Applications, Second Edition, Springer, New York.

[19] Ukil, A., Deck, B. and Shah, V.H., (2012). "Current-Only Directional Overcurrent Protection for Distribution Automation: Challenges and Solutions", IEEE Transactions on Smart Grid, 3(4):1687-1694.

[20] Grainger, J. J., and Stevenson, W. D., (1994). Power System Analysis, First Edition, McGraw-Hill, New York.

[21] Phadke, A.G. and Thorp, J.S., (2008). Synchronized Phasor Measurements and Their Applications, Second Edition, Springer, New York.

[22] Kirpane, R. and Bedekar, P.P., (2016). "Removal of DC Offset Using Digital Mimic Filtering Technique", International Conference on Global Trends in Signal Processing, Information Computing and Communication, 22-24 December 2016, Jalgaon.

[23] Vitins, M., (1981). "A Fundamental Concept for High Speed Relaying", IEEE Transactions on Power Apparatus and Systems, 100(1):163-173.

[24] Engler, F., Lanz, O.E., Hanggli, M. and Bacchini, G., (1985). "Transient Signals and Their Processing in an Ultra High-Speed Directional Relay for EHV/UHV Transmission Line Protection", IEEE Power Engineering Review, 5(6):55-56.

[25] Benmouyal, G. and Chano, G., (1997). "Characterization of Phase and Amplitude Comparators in UHS Directional Relays", IEEE Transactions on Power Systems, 12(2): 646-653.

[26] Benmouyal, G. and Roberts, J., (1999), "Superimposed Quantities: Their True Nature and Application in Relays", Proceedings of the 26th Annual Western Protective Relay Conference, October 26–28 1999, Spokane.

[27] Tan, J., Tholomier, D., Bin, G. and Hua, W., (2007). "Sensitivity and Stability of Superimposed Component Based Directional Comparison Protection", Canadian Conference on Electrical and Computer Engineering, 22-26 April 2007, Vancouver.

[28] Blumschein, J., Dzienis, C. and Kereit, M., (2014). "Directional Comparison Based on High-Speed Distance Protection Using Delta Quantities", 41st Annual Western Protective Relay Conference, 14-16 October 2014, Spokane.

[29] Hashemi, S.M., Hagh, M.T. and Seyedi, H., (2013). "Transmission-Line Protection: A Directional Comparison Scheme Using the Average of

Superimposed Components", IEEE Transactions on Power Delivery, 28(2): 955-964.

[30] Anderson, P., (1998). Power System Protection, First Edition, IEEE press, Hoboken.

[31] Elmore, A.E., (2003). Protective Relaying Theory and Applications, Second Edition, CRC Press, New York.

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