An Approach for Differential Protection of Transmission Lines

Sobhan Babu Katta

A Thesis Submitted to
Indian Institute of Technology Hyderabad
In Partial Fulfillment of the Requirements for
The Degree of Master of Technology

भारतीय प्रौद्योगिकी संस्थान हैदराबाद
Indian Institute of Technology Hyderabad

Department of Electrical Engineering

June, 2016

Declaration

I declare that this written submission represents my ideas in my own words, and where others' ideas or words have been included, I have adequately cited and referenced the original sources. I also declare that I have adhered to all principles of academic honesty and integrity and have not misrepresented or fabricated or falsified any idea/data/fact/source in my submission. I understand that any violation of the above will be a cause for disciplinary action by the Institute and can also evoke penal action from the sources that have thus not been properly cited, or from whom proper permission has not been taken when needed.

K. Sobhan Babu.

(Signature)

SOBHAN BABU KATTA

(Name of the Student)

EE14MTECH11031

(Roll No.)

Approval Sheet

This thesis entitled "**An Approach for Differential Protection of Transmission Lines**" by **Sobhan Babu Katta** is approved for the degree of Master of Technology from IIT Hyderabad.

Dr. Siva Kumar K
Department of Electrical Engineering
IIT Hyderabad
Examiner

Dr. Vaskar Sarkar
Department of Electrical Engineering
IIT Hyderabad
Examiner

Dr. Ravikumar Bhimasingu
Department of Electrical Engineering
IIT Hyderabad
Adviser

Dr. B. Munwar Basha
Department of Civil Engineering
IIT Hyderabad
Chairman

Acknowledgements

First of all, it’s my pleasure to express gratitude towards my supervisor Dr. Ravikumar Bhimasingu for his esteemed guidance in completing my thesis work through his support and advices.

I sincerely thank all the research scholars from PE&PS stream of Electrical Engineering, IIT Hyderabad for their support in clearing doubts related to my thesis work.

I would like to express my thanks to Dr. U.B.Desai, Director of IIT Hyderabad and Dr.Mohammed Zafar Ali Khan, HOD of EE department for providing necessary facilities in laboratories for my research work.

Finally, I would like to thank my parents, sisters and all my friends for their love and moral support towards me.

Dedicated to

The people, who played important role in my life

Abstract

Throughout the history of power system protection, researchers have strived to increase sensitivity and speed of apparatus protection systems without compromising security. In this research work, mainly concentrated on transmission line protection for different topologies submitted to various fault conditions. Firstly, literature review on the existing approaches for the protection of transmission lines related to distance protection and current differential protection has been carried out. Then, study on fault analysis for different topologies like single transmission line and parallel transmission line systems is carried out using matlab/Simulink® . For these two topologies, existing approach in which information of current phasors (i.e. PMR and PAD) and proposed approach of current differential protection (using DC offset component information) are implemented. Results and observations from simulations carried out on matlab/Simulink® and PSCAD are presented and these two approaches are compared to verify reliability of proposed approach. Finally, some suggestions to future work are mentioned.

Nomenclature

GPS	Global Positioning System
ANN	Artificial Neural Network
I_{op}	Operating Current
I_{re}	Restraining Current
I_0	Pick-up Current
K	Restraining Co-efficient
I_s	Sending end Current of the Transmission Line
I_r	Receiving end Current of the Transmission Line
I_s^{ser}	Sending end Series Branch Current of equivalent π-model of Transmission Line
I_r^{ser}	Receiving end Series Branch Current of equivalent π-model of Transmission Line
$I_{s\text{-}DC}$	DC offset Component of Sending end Current of Transmission Line
$I_{r\text{-}DC}$	DC offset Component of Receiving end Current of Transmission Line
PMR	Phasor Magnitudes Ratio
PAD	Phasor Angles Difference

Contents

List of Figures

Page no.

List of Tables

Page No.

Appendices

Chapter 1

Introduction

1.1 Power system protection

Power system protection is a branch of electrical power engineering that deals with the protection of electrical power systems from faults through the isolation of faulted parts from the rest of the electrical network. Figure 1.1 shows the basic structure of traditional power system which includes three stages or systems namely 'Generation', 'Transmission' and 'Distribution'

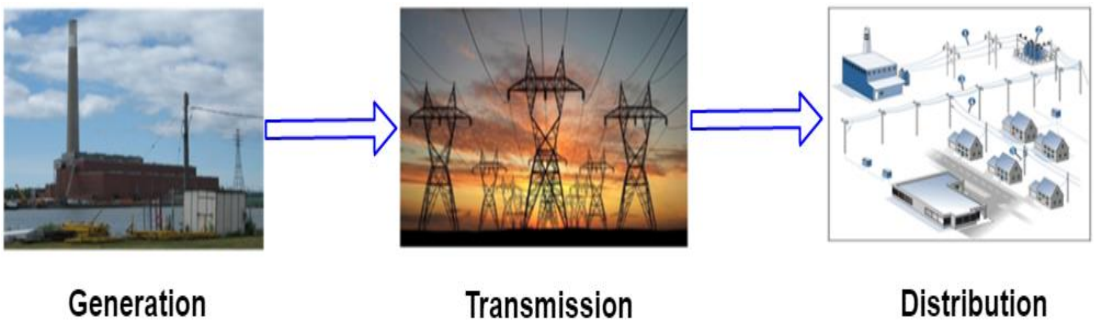


Figure 1.1 Traditional power system structure

[Source for images: online]

The main objective of a 'protection system or scheme' is to keep the power system stable by isolating only the components that are under fault, whilst leaving as much of the network as possible still in operation. Thus, protection schemes must apply with very practical and pessimistic approach to clearing system faults. 'Protection devices' are the devices used to protect the power systems from faults. There are so many protection systems available namely 'Differential', 'Directional', 'Distance', 'Over-current' and 'Over-voltage' etc. **Dependability, Security, Reliability, Selectivity, Sensitivity and Speed** are performance measures for any protection system, to use in power system.

Generally, for protection of 'transmission lines', **distance protection** is used. In distance protection, distance relay which is double actuating quantity relay, measures the distance from relay to the fault based on the **V/I** ratio. In Differential protection, differential relay measures difference between currents of entering and leaving ends of zone, based on this quantity it operates. The 'Differential protection' is 100% selective and only responds to faults within its protected zone.

1.2 Motivation

Generation capacity and transmission capability of power system need to be increased in-order to meet the increased demand nowadays. To increase transmission capability of transmission system, providing series-compensation, constructing parallel lines and inserting FACTS devices are some methods. So, when distance protection is provided for those lines, distance relay unable to measure the correct impedance or distance at which fault occurred which means mal-operation of the distance relay.

It is a well-known fact that differential protection schemes provide sensitive protection with crisp demarcation of the protection zones. In principle, the differential protection is also immune to tripping on power swings. So, differential protection can be reliable solution if we are able to gather synchronized information of current from both sides of line. That can be achieved due to development of technology and advancements in telecommunications. We are able to use differential protection along with GPS to provide protection for transmission lines even though they cover long distance. GPS can provide synchronized measurements of currents on both sides of transmission lines with time stamped. Fiber optic can be considered for data communication.

During this research, the goal is to develop a robust approach to identify protection zone for various fault conditions like high resistance faults, different types of faults and different configurations thereby improve reliability, sensitivity without compromising security compared to existing methods. Scope of work is outlined in next section.

1.3 Scope of work

Research on existing methods for protection of transmission lines to know the conditions where these methods work correctly and to get limitations of existing methods to other topologies possible in transmission system. To verify which method is reliable, sensible and secure under which conditions.

- Defining different topologies for analysis and simulations under different fault conditions
- Analysis of existing methods from literature applied to defined topologies
- Analysis of our approach applied to defined topologies
- Comparing the results obtained from simulations to know which approach is more reliable
- Highlighting some observations made from results

Outline of chapters

This chapter gives an introduction, motivation and objectives of this thesis in precise and orientation of the thesis.

Chapter 2 covers the literature survey on the existing methods for protection of transmission lines.

Chapter 3 covers details about the existing approach for identifying fault location.

Chapter 4 contains different types of faults occur in lines, effect of fault on current through the line and proposed approach to identify fault location.

Chapter 5 deals with simulations and results for different topologies under different fault conditions.

Chapter 6 deals with the conclusions and suggestions for future work.

Chapter 2

Literature Review

A brief introduction and highlighting focus of the thesis was given in the previous chapter. This chapter consists of a brief literature survey, which covers existing methods for protection of transmission lines and transformation of approach for current differential protection of transmission lines.

2.1 Existing methods for transmission line protection

Throughout the history of power system protection, researchers have strived to increase **sensitivity** and **speed** of apparatus protection systems without compromising **security**. Firstly, we'll see about the methods related to **distance protection** which are proposed by small modifications to the basic principle of traditional distance protection and to which particular topologies these methods are applicable.

"**An adaptive zero sequence compensation algorithm"** is presented by '**Heresh Seyedi, Saeed Teimourzadeh** and **Peyman Soleiman Nezhad'** to improve the conventional ground distance relays performance, in double-circuit transmission lines [1]. In this approach, estimated impedance is calculated correctly by correcting the degree of zero sequence compensation of ground distance relays. This scheme is for the standalone distance relays and does not require any communication link. However, it can be applicable to all well-known pilot protection schemes. This method utilizes zero equivalent circuit in order to estimate the compensation term. Afterwards, the estimated impedance is corrected by using a recursive approach. Finally, this method compensates the fault resistance effect. Using this method, the mal-operation of the conventional distance relay because of the mutual coupling is mostly resolved. This method has the ability of compensation, in both the single and double-circuit operation modes. No use in case of not grounded faults. Whatever the methods or approaches existing in literature related to distance protection are applicable to particular topology or case, under certain conditions. For example, "**an adaptive distance protection scheme"** is proposed by **'Borascu Ionut Ciprian** and **Sergiu Stelian Iliescu'** for high resistance phase to phase faults on double-circuit transmission line [2].

With the significant technological advances in wide-area measurement systems, for transmission system protection, current differential scheme outscores alternatives like over-current and distance protection schemes. So, many researchers are concentrating on this concept for providing reliable protection for transmission lines of any topology. Here, some methods or approaches for transmission line protection using current differential protection are briefly explained.

"**An adaptive control of the restraining region in a current differential plane**" is proposed by '**Sanjay Dambhare, S.A. Soman and M.C. Chandorkar**' [3], in which an error analysis of conventional phasor approach for current differential protection is provided using the concept of dynamic phasor. This method is extended to series compensated lines for protection. We'll see about this method in next chapter in detail.

Using phase angle of current phasors, there are some methods proposed by researchers. **Segregated phase comparison technique** is a special form of current differential protection, which takes into account the difference of phase angles of currents entering at one terminal and current leaving out of other terminal. The phase differential protection serves as a better option for transmission line protection due to its simplicity, sensitivity, selectivity and comprehensibility. But line charging current due to capacitance of transmission line causes significant change in phase angle of two end currents of the line. Ref. [4] presents a novel phase comparison technique which compensate for line charging currents in presence of synchronized measurements using equivalent π- model of transmission line. A novel phase differential function is developed using phase co-ordinates. GPS is used for synchronized measurements and fiber optic is considered for data communication.

A new approach to current differential protection of transmission lines is proposed in [5], in which the instantaneous line current(s) transformed by using a **moving window averaging technique**. If the time span of the moving window is equal to one-cycle time, then the steady-state value of the transformed current is zero for a periodic signal which is composed of fundamental and harmonic frequencies. Signal distortions (e.g., a fault) cause the transformed currents to deviate from the nominal zero value, which permits the development of a sensitive, secure, fast and yet simple current differential protection scheme. This scheme can be applied to series compensated transmission lines.

"**An improved scheme based on fuzzy logic**" is proposed in [6], which is used for finding real time fault location and classification in power transmission system. In this scheme, protection algorithm is based on the monitoring of the high frequency components on over-head lines caused by a sudden change in the system, which results a travelling wave, combination of aerial and ground modes, initiated from the fault point. To detect the type of fault, a possible application is proposed based on modal analysis. It is shown that a fuzzy approach can be useful in transmission line protection, whenever fuzzy decisions have to be under taken. This technique processes the high frequency signals without the need of expensive communication channels, in turn cost reduction. This method is independent of fault resistance, which is always difficult to find accurately.

A protection method is proposed in [7] for series-compensated double-circuit transmission lines based on **current transients**. Using this method, the faulted circuit can be identified locally by comparing the polarities of wavelet coefficients of the branch currents. It is shown that this method is faster and more reliable compared to conventional distance and phase comparison protection schemes for the series-compensated double-circuit transmission systems. The security of the relay can be enhanced by exchanging the information of fault direction between the relays at both ends. In this method, fault directions are identified with the aid of initial transients observed on the branch currents. The advantages of this method are more obvious, when it is used for series-compensated lines compared with parallel lines without series-compensation.

A method is presented in [8] for the boundary protection of series-compensated transmission lines, as well as fault classification, in which boundary protection is based on detecting distinct frequency bands contained in the transient current wave. The spectral energies of two bands (captured using **DWT** and db4 as a mother wavelet) are obtained and their ratio is used to determine if the fault is internal or external to the protected zone. Fault classification is done using discrete wavelet transform. Base on the average value of the coefficients of frequency band of each current wave faulted phases can be classified. It is shown that this method is stable under various load switching cases and different levels of compensations.it gives reliable results in the boundary protection and fault classification of series-compensated lines.

Charge comparison technique is proposed in [9] for the protection of transmission lines. It is a form of current differential relaying. Charge comparison resolves the traditional problems of current differential relaying of transmission line: protection lost if channel fails, large channel capacity required and precise channel delay compensation is required. This method is suitable for the protection of two - or three – terminal ac transmission lines, of all lengths and voltage levels, with or without series compensation. So, this method offers a viable alternative to distance based directional comparison schemes for many transmission line applications.

An approach of digital relays for transmission line protection is presented in [10]. This technique consists of a preprocessing module based on discrete wavelet transforms (DWTs) in combination with an artificial neural network (ANN) for detecting and classifying fault events. The DWT acts as an extractor of distinctive features in the input signals at the relay location and this information is fed into an ANN for classifying fault conditions. The ability of wavelets to decompose the signal into frequency bands in both time and frequency allows accurate fault detection. A faster response is obtained since only a quarter of cycle from the occurrence of the fault is required.

2.2 Transformation of approach for current differential protection [5]

Traditionally, current differential protection schemes compare the current at the terminals of a transmission line. If the differential current is not zero, i.e.

$$i_d = i_s + i_r \neq 0 \qquad (1)$$

Then it indicates a fault.

A more abstract view can be taken of current differential protection by comparing transformed currents $\psi(i_s)$ and $\psi(i_r)$ for differential protection, i.e.

$$i_d = \psi(i_s) + \psi(i_r) \qquad (2)$$

Different realizations of current differential protection correspond to different definitions of transformation ψ. Illustrative examples are as follows.

- Traditional current differential protection methods [11] use the following transformation:

  $$\psi(i_s) = I_s(\omega_0) \text{ and } \psi(i_r) = I_r(\omega_0) \qquad (3)$$

  Where $I_s(\omega_0)$ and $I_r(\omega_0)$ are the phasors at the fundamental frequency ω_0. The function ψ described by (3) is a non-invertible linear transformation, as it only filters the fundamental frequency component.

- The phase-angle comparison scheme [12] uses a transformation

  $$\psi(i_s) = \angle I_s \text{ and } \psi(i_r) = \angle I_r \qquad (4)$$

  Where $\angle I_s$ and $\angle I_r$ are the phase angle of phasors I_s and I_r respectively. In this case, the current differential protection is given by the following logic:

  If $\psi(i_s) + \psi(i_r) = \pi$ (5)

  Then there is no fault and else if

  $$\psi(i_s) + \psi(i_r) \neq \pi \qquad (6)$$

  Then there is a fault.

- Enhancements of the current differential protection scheme use transformations which also depend upon the local bus voltage. Phadke and Thorp [13], have suggested that series current I_s^{ser} and I_r^{ser} be used in current differential protection (refer to Figure 2.1) where

$$\psi(i_s, v_s) = I_s - j\frac{B}{2}V_s \qquad (7)$$

$$and \qquad \psi(i_r, v_r) = I_r - j\frac{B}{2}V_r \qquad (8)$$

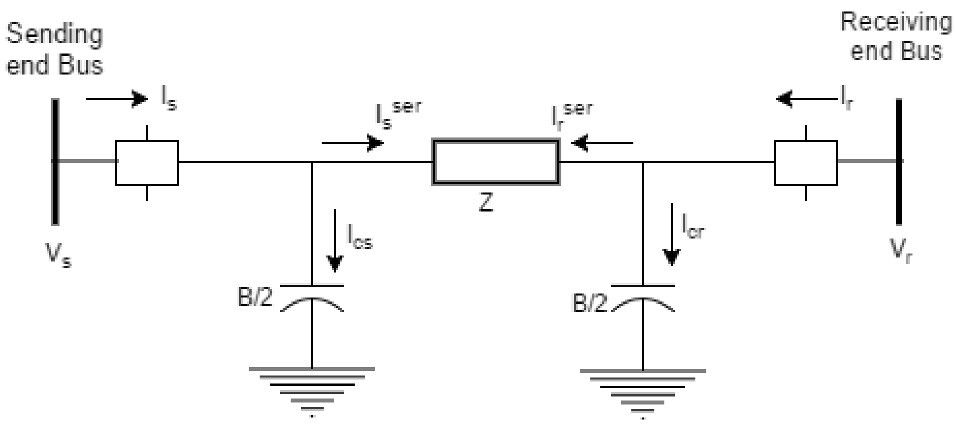


Figure 2.1 Current differential scheme with an equivalent π-model of line

The transformation ψ described by (7) and (8) is again a non-invertible linear transformation. The variant of this approach is suggested in [14] which uses a distributed line model.

- The charge comparison scheme suggested by Ernst *et al.*[9] defines

$$\psi(i) = \int_{t_r}^{t_f} i(t)\, dt \qquad (9)$$

Where t_r and t_f correspond to the recent zero crossing of the rising edge and falling edge of current *i (t).*

- The wavelet-based approach [15] uses the discrete wavelet transformation of *i*, i.e.

$$\psi(i) = \mathrm{DWT}(i, m, n) = \frac{1}{\sqrt{a_0^m}} \sum_k i(k) G^* \left(\frac{n - k a_0^m}{a_0^m} \right) \qquad (10)$$

Where G represents the wavelet function, a_0^m and ka_0^m refer to the dilation and translation of the wavelet, and k and m are the integer constant. The function ψ described by (10) is again a non-invertible linear transformation.

When viewed from this perspective, it appears that the research effort is aimed at correctly defining transformation ψ to improve the sensitivity of current differential protection without compromising its security. The choice of transformation ψ also depends upon the technology constraints. The main challenge lies in synthesizing transformation $\psi(i)$ under more idealized technological conditions to improve dependability, security and speed of the protection system.

Chapter 3

Current Differential Protection: Existing Approach

There are so many methods or approaches discussed to identify the fault occurrence and its location on transmission lines in literature. In this chapter, detailed information about an existing approach to identify the fault and its location (internal or external of protection zone) is given which is presented in [3]. This approach is based on equivalent π-model of transmission line which can be shown as in Figure 3.1.

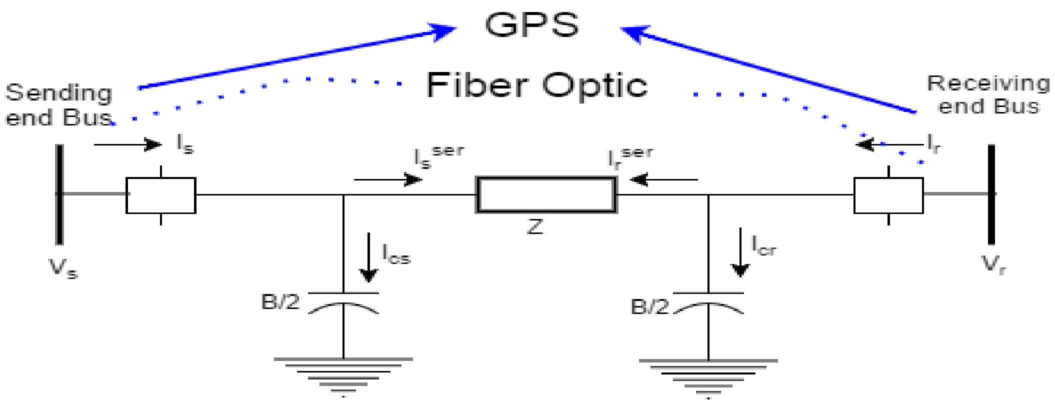


Figure 3.1 GPS-synchronized current differential protection scheme with equivalent π-model of line

With a conventional relay-setting approach, operating current I_{op} and restraining current I_{re} for the current differential scheme can be expressed as follows:

$$I_{op} = |I_s^{ser} + I_r^{ser}|$$

$$I_{re} = |I_s^{ser} - I_r^{ser}|$$

The percentage differential relay pick-up and operate when

$$I_{op} \geq I_0$$

$$I_{op} \geq KI_{re}$$

Where I_0 is a pick-up current and K is the restraining co-efficient (0< K <1). In literature, it has been shown that numerical differential relay can be set more accurately in a current differential plane. Using the phase and magnitude information of series branch current phasors, we calculate

$$ratio = \frac{|I_s^{ser}|}{|I_r^{ser}|}$$

$$ang = \angle(I_s^{ser}) - \angle(I_r^{ser})$$

In absence of an internal fault, we have

ratio= 1 and ang=180^0,

Which is a single point in differential plane. But practically the operating point may deviate from the point (180^0, 1) due to some practical errors. So, boundary conditions for restraining region are defined for the approach in which phasor magnitudes ratio (PMR) and phasor angles difference (PAD) obtained from sending and receiving end current phasors at the fundamental frequency used to identify fault.

Boundary conditions are,

0.4≤PMR≤2.5 and 160^0≤PAD≤200^0

If these boundary conditions of restraining region are satisfied for any system, then we can say there is no fault in the system otherwise fault exists in the system.

Note: In literature, this approach is applied on the equivalent π-model of the line. But in this thesis, existing approach is used for distributed line model because modelling equivalent π-model for long transmission line very difficult practically.

The distributed line model can be shown as in Figure 3.2.

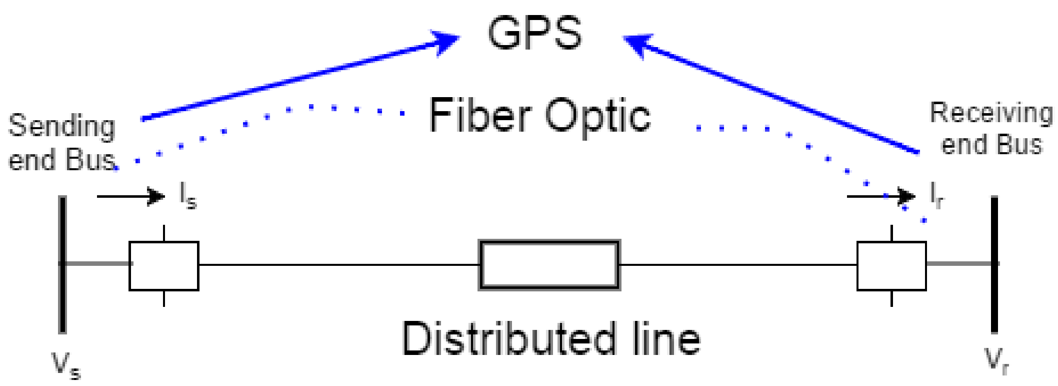


Figure 3.2 Distributed line model used for current differential protection

The existing approach involves taking measured current samples from sending end and receiving end of the transmission line and then to estimate current phasors at fundamental frequency on both sides of the transmission line which are represented by I_s and I_r respectively. Using estimated phasors information, we will calculate PMR and PAD. Now these values are verified with defined boundary conditions of restraining region. From this verification, fault location can be identified as follows:

If boundary conditions satisfied ⇒ Fault is outside of the protection zone

If boundary conditions unsatisfied ⇒ Fault is inside of the protection zone

Since we know the location of fault, now we can use that information to send trip signal to breakers on line if fault occurs inside of the protected zone using this approach for relay logic.

This approach can be shown in step-wise using flow-chart which is shown in Figure 3.3.

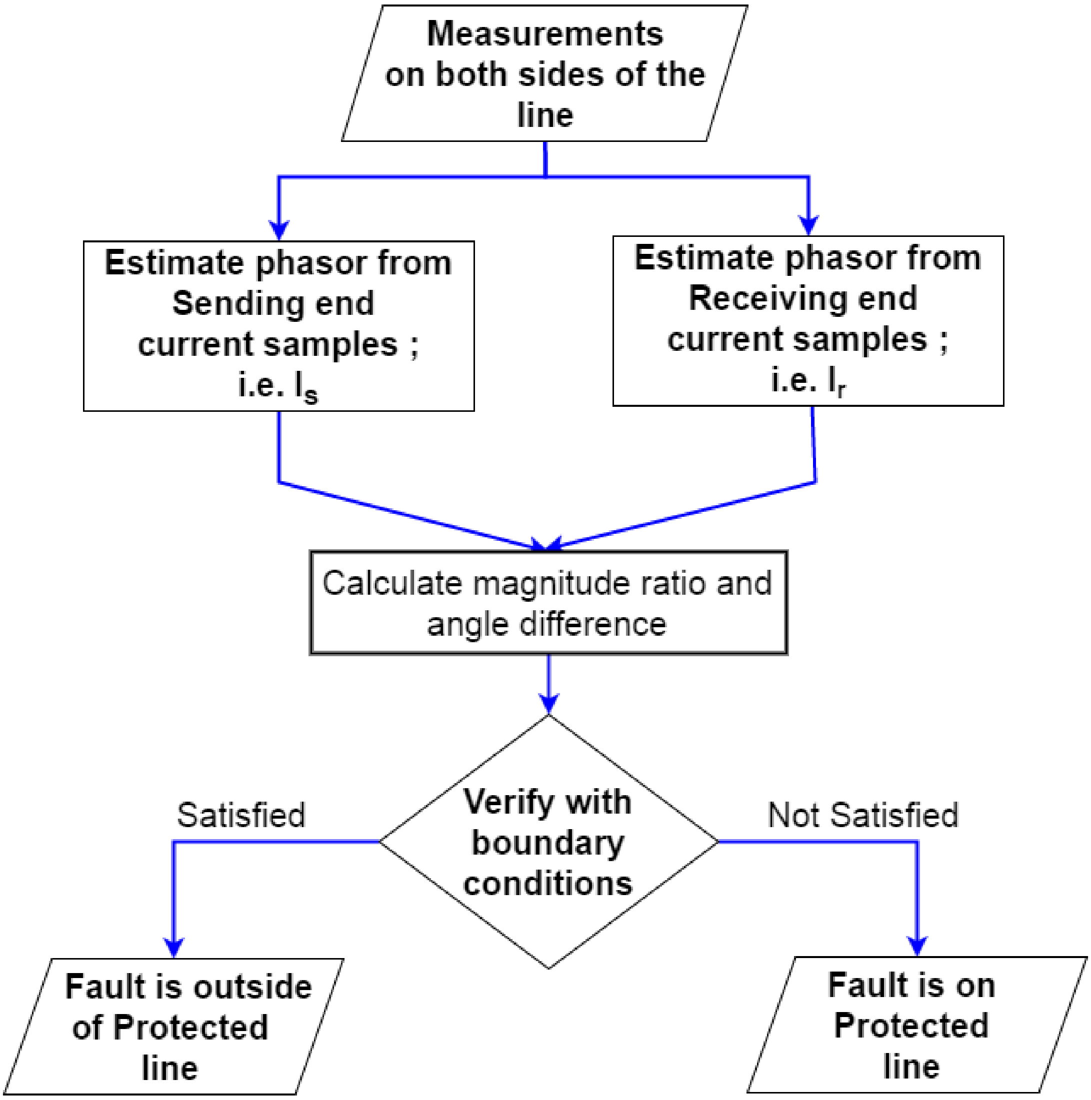


Figure 3.3 Flow chart to identify fault using existing approach (PMR & PAD)

Chapter 4

Current Differential Protection: Proposed Approach

First of all, we'll see about the different types of faults that occur on lines and effect of fault on current through line and then proposed approach to identify fault whether it is inside or outside of protection zone.

4.1 Different types of faults occur on lines

There are four major types of faults may occur in transmission lines

- Single line to ground (SLG): This is an unsymmetrical fault, where there is a sudden rise in phase current and fall in the faulted phase voltage. It is most common fault in transmission lines compared to other types of faults.
- Double line to ground (LLG): This is also an unsymmetrical fault shows the same tendency as LG fault involving two faulted phases.
- Line to Line fault (LL): Unsymmetrical fault where the trend is to see a depression in phase voltage and sharp rise in currents on all the three phase voltages and currents and does not include any zero sequence component.
- Triple line (LLL): This is a symmetrical fault in which there will be collapse of all three phase voltages and sudden rise in all the three phase currents.

.

4.2 Effect of fault on current through the line

During fault, we can observe sudden rise in current, due to presence of DC component which is exponentially decaying component with respect to the time. Presence of DC component can be explained using the RL-network as shown in Figure 4.1

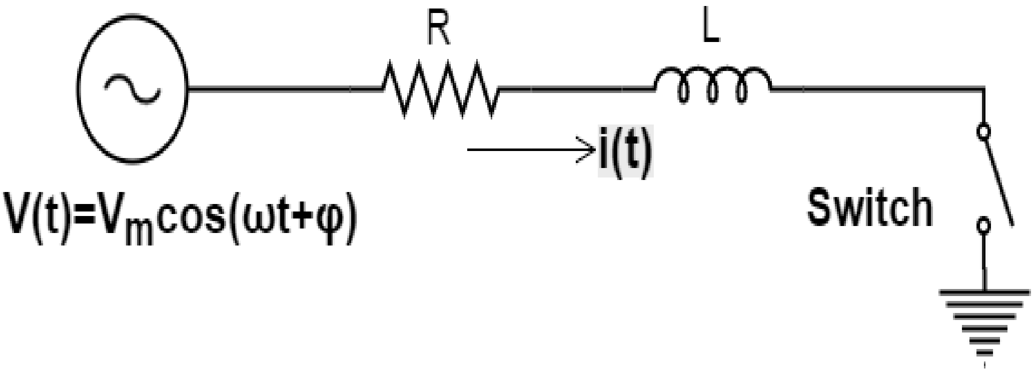


Figure 4.1 Effect of fault on simple RL-network with single phase AC-supply

In figure **4.1**, V (t) is the supply voltage connected to the RL network, switch is closed at the time t_0 and i (t) is the current through the elements R and L elements.

Current i (t), consists of two parts namely, transient and steady state components.

Equation of the current i (t) is,

For $t \leq t_0$,

i (t) =0 ;

For $t > t_0$,

$$i(t) = -I_m \underbrace{\cos(\omega t_0 + \varphi - \theta)\, e^{-\frac{t-t_0}{\tau}}}_{\text{Transient component}} + I_m \underbrace{\cos(\omega t + \varphi - \theta)}_{\text{Steady State component}}$$

Where, ω - frequency of the supply

Φ - Initial phase displacement w.r.t. cosine

Θ - Impedance angle i.e. $\tan^{-1}(\omega L/R)$

$I_m = (V_m/|Z|)$; here $Z= (R+j\omega L)$

Transient component (first-order) will be zero only if **($\omega t_0+\varphi-\theta$) = π/2 or 3π/2**. At remaining positions of cycle, transient component i.e. DC offset component will present and it will be maximum at **($\omega t_0+\varphi-\theta$) = 0 or π or 2π**. So, existence of DC offset component is more likely present and very much high during fault condition.

Generally, transmission line is represented by resistance (R), inductance (L) and capacitance (C) elements respectively. So, when sudden RLC-network is submitted to sudden change, the current through the network consists of transient component, which is of second order and steady state component. So, it will be very difficult to say the exact location where DC offset will be zero. So, the existence of DC offset component during fault condition can be considered as reliable to identify fault. So, DC offset component is considered as decisive parameter for proposed approach in this research work.

4.3 Proposed approach

As mentioned earlier, the main parameter that considered in proposed approach to identify fault location is DC offset component peak value.

In proposed approach, measured current samples from sending end and receiving end of transmission line which needs to be protected are taken. From those samples, we'll extract fundamental components of sending end current, receiving end current and DC offset components. During this research, we use FFT to extract required information from measured current samples.

Let I_{s-Dc}, I_{r-DC} represent extracted DC offset components and I_s, I_r are represent current phasors at fundamental frequency extracted from current samples of sending end and receiving end of the line, respectively. Now compare signs of I_{s-DC} & I_{r-DC} peak values. From signs, we can identify location of fault whether it is inside or outside of protection zone as follows:

- $I_{s-DC} > 0$ and $I_{r-DC} > 0$ ⟹ Fault is outside of the protection zone
- $I_{s-DC} < 0$ and $I_{r-DC} < 0$ ⟹ Fault is outside of the protection zone

- $I_{s-DC} > 0$ and $I_{r-DC} < 0$ ⟹ Fault is inside of the protection zone
- $I_{s-DC} < 0$ and $I_{r-DC} > 0$ ⟹ Fault is inside of the protection zone

Since we know the location of fault, now we can use that information to send trip signal to breakers on line if fault occurs inside of the protected zone. We can use proposed approach to design relay logic for more reliable and faster operation.

This proposed approach can be briefly explained using flow-chart as shown in Figure 4.2

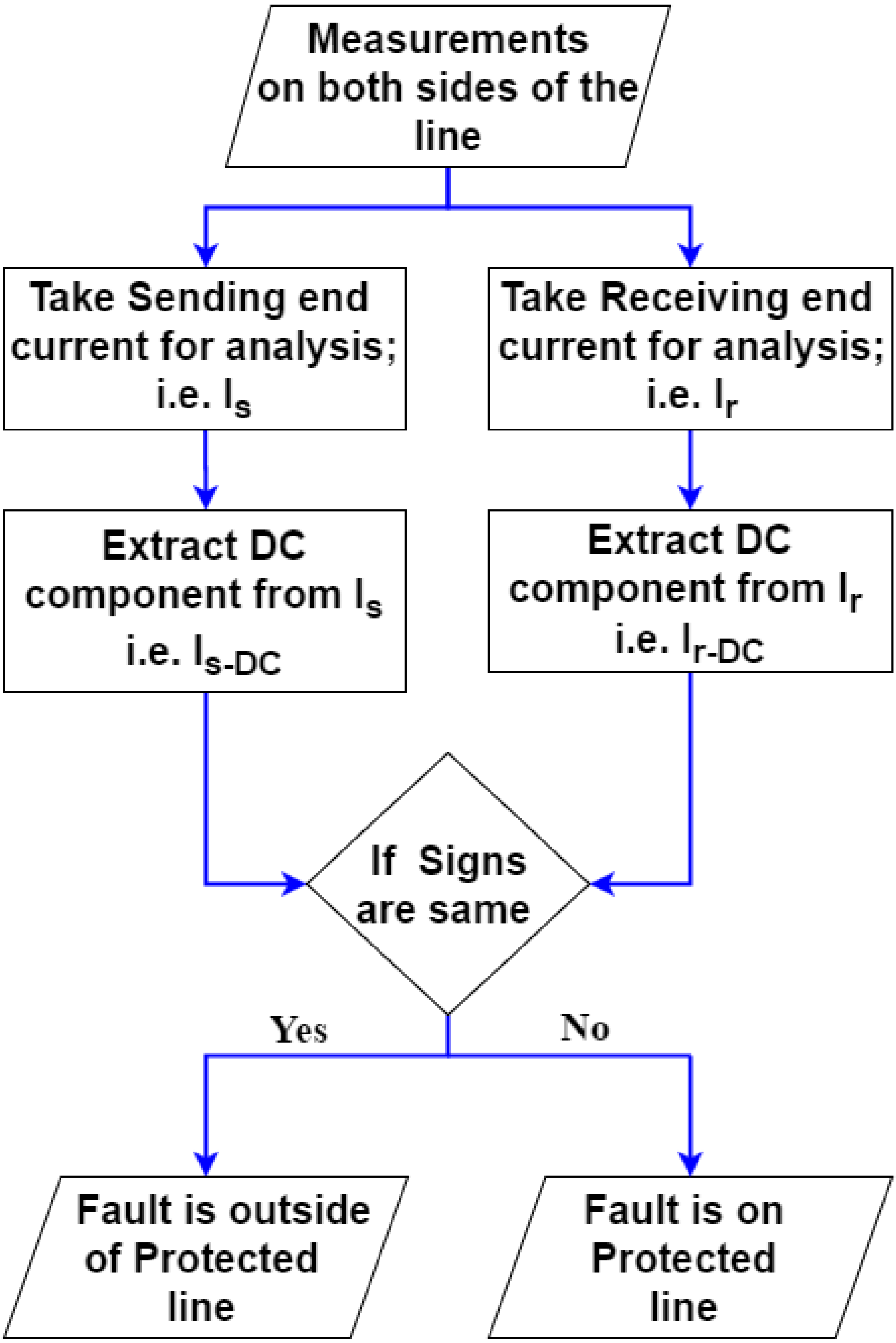


Figure 4.2 Flow chart to identify fault using proposed approach

Chapter 5

Simulations and Results

5.1 Simulations

During this research, simulations are done for the system model of four-generators, 10-buses [16] in the form of two topologies:

Topology-1: Single transmission line system [Appendix-1]

Topology-2: Parallel transmission line system [Appendix-2]

The single line diagrams for the above mentioned topologies are as shown in Figures 5.1 and 5.2 respectively.

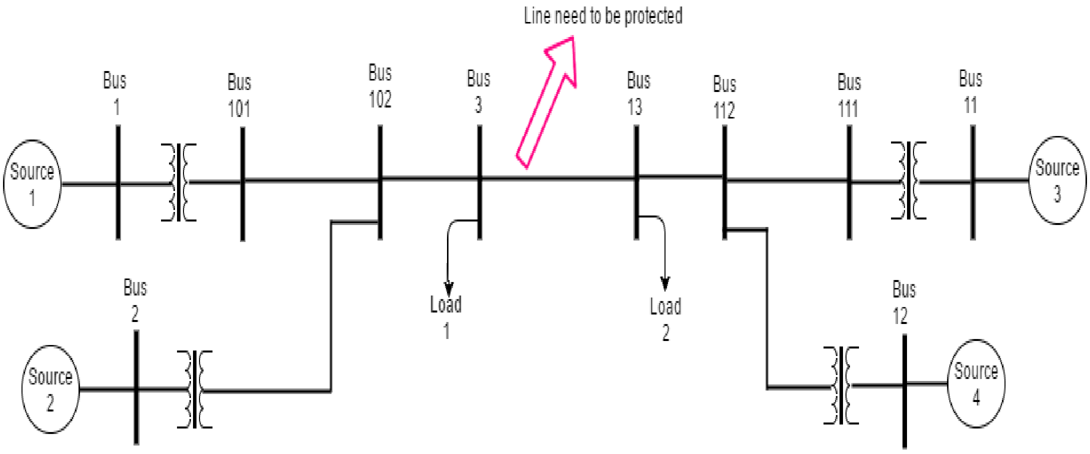


Figure 5.1 Topology-1: Single transmission line system

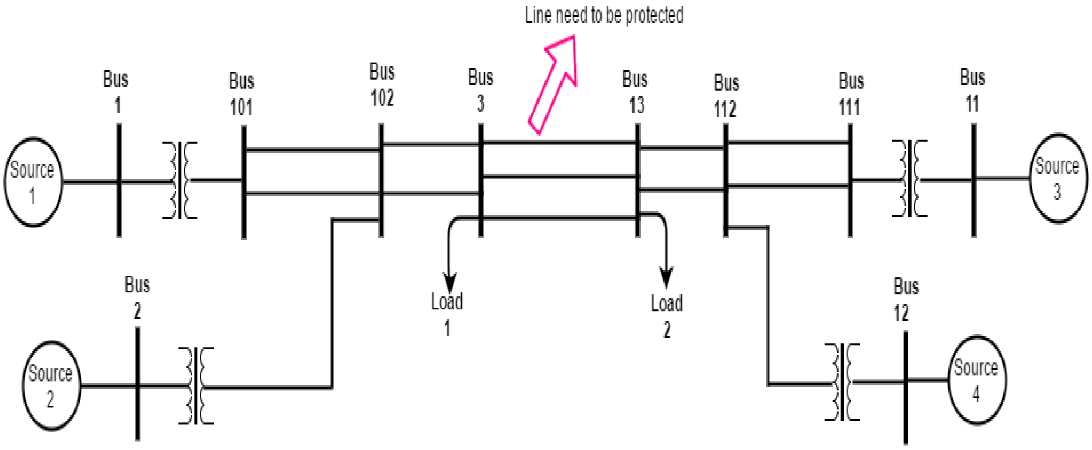


Figure 5.2 Topology-2: Parallel transmission line system

These two topologies are simulated for various fault conditions like different fault resistances, different types of faults, different fault locations and different approaches.

- Fault resistances are:
  0.001Ω, 5 Ω, 10 Ω, 50 Ω, 100 Ω, 200 Ω and 500 Ω

- Types of faults:
  LLL, LLG, LL and SLG

- Fault positions or locations:
  - Fault is on the line need to be protected:
    At a distance from bus-3 on line: **5%, 25%, 50%, 60%, 75%, 90% and 95%**
  - Fault is outside of the zone:
    i.e.
    1) On the line left side of bus-3
    At a distance from bus-3: **5%, 10% and 15%**
    2) On the line right side of bus-13
    At a distance from bus-13: **5%, 10% and 15%**
    3) On the parallel line (only foe topology-2)
    At a distance from bus-3: **5%, 60% and 95%**

- Approaches
  - Existing approach
  - Proposed approach

Procedure followed for implementing these two approaches is given below.

1) First, Simulink model is simulated for corresponding case.
2) Measured current samples from both sides of the transmission line i.e. I_s & I_r are exported to PSCAD for FFT analysis.
3) FFT is applied to both signals (I_s & I_r) to get fundamental phasor magnitudes, phasor angles and DC offset component.
4) Using this information, calculate PMR,PAD and DC offset component

5) PMR and PAD are used for existing approach. But just after fault, PMR and PAD have transients. So, we take settled values of PMR & PAD for decision making by verifying with defined boundary conditions.

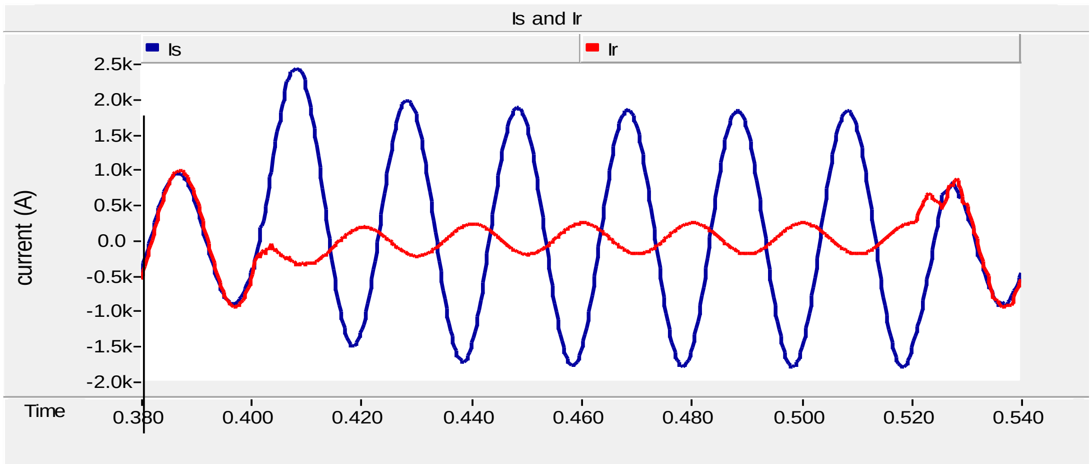
6) DC offset component direction (sign) is used for proposed approach. We can take this information just after fault but in this thesis, DC offset component peak value is considered for proposed approach.

5.2 Results & Observations

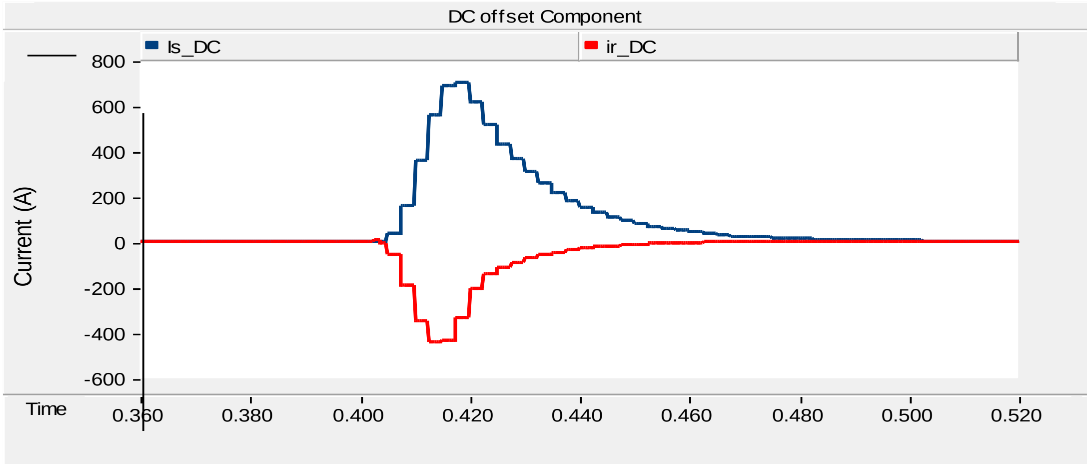
Results and observations from simulations are noted for previously mentioned cases. For all cases, simulation time is 2.0 sec, fault is applied at 0.40 sec and cleared at 0.52 sec (i.e. fault exists for 6 cycles of time). Some cases for which waveforms and observations are given in this report, which will show success of proposed approach and existing approaches and for some cases, mal-operation of existing approach can be observed.

Case-1: LLL, at 50% of length of the line, 10 Ω resistance for topology-1

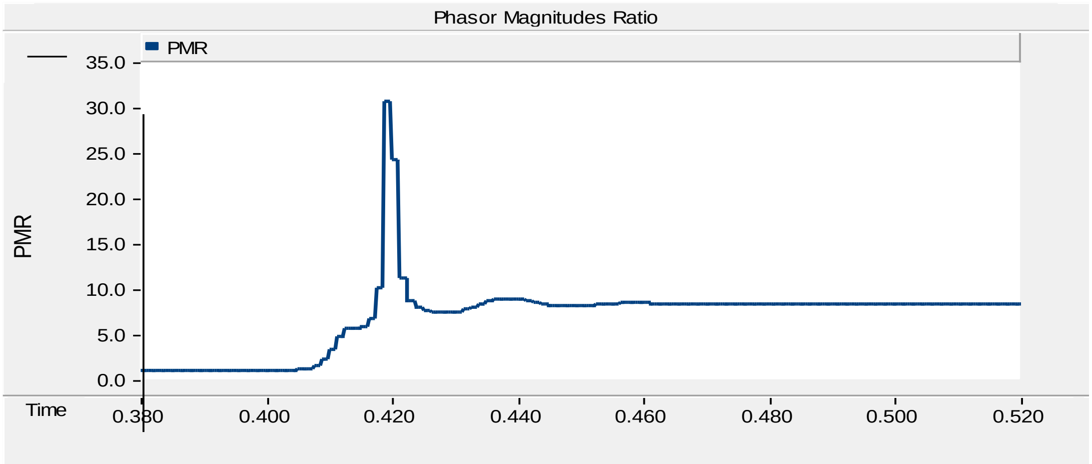
In this case, LLL fault is applied at 50% of the length (from bus-3) of the protected line in-between bus-3 and bus-13, with fault resistance of 10 Ω for single transmission line system (topology-1) which implemented in matlab/Simulink®. Procedure which is mentioned in previous section is followed. Waveforms (I_s & I_r, DC offset component, PMR and PAD) obtained from simulations are shown in Figure 5.3.



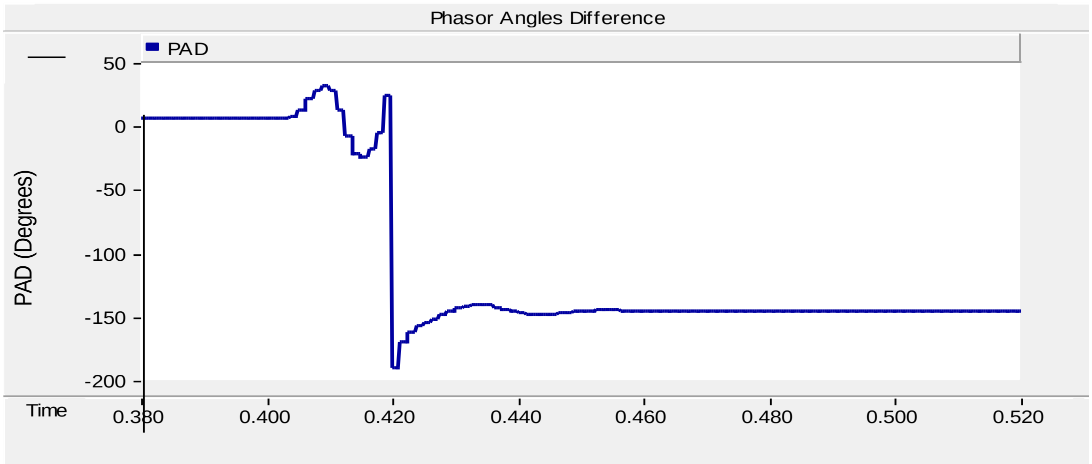
(a) Sending and receiving end current waveforms



(b) Sending and receiving end DC offset component waveforms



(c) Phasor Magnitudes Ratio - waveform



(d) Phasor Angles Difference - waveform

Figure 5.3 I_s & I_r, DC offset components, PMR and PAD waveforms for Case-1

From Figure 5.3,

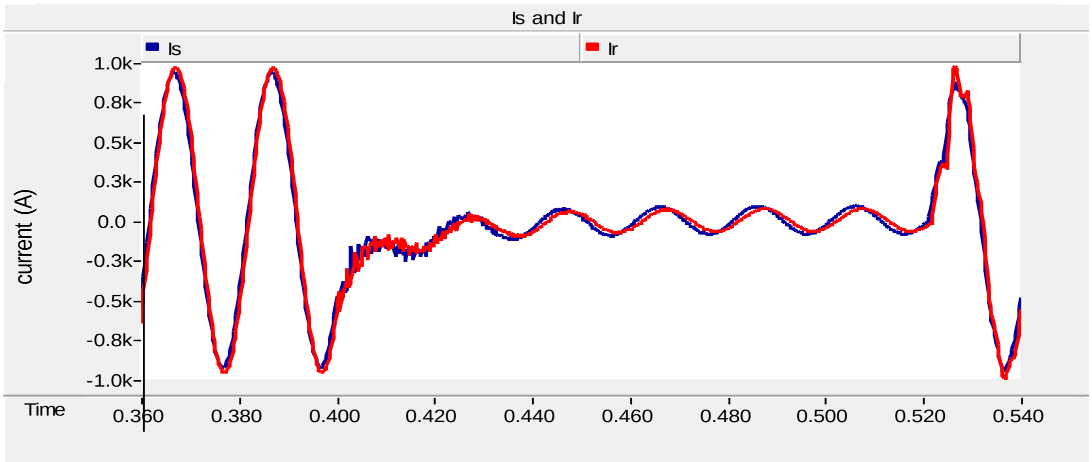
Extracted DC offset component peak values observed from sending and receiving end DC offset components waveforms are: $I_{s\text{-}DC}$= 697.50 A (+ve) & $I_{r\text{-}DC}$ = -445.50 A (-ve). This shows sending end and receiving end currents flow in different directions, which means fault is occurred on the line, inside of the protection zone according to proposed approach.

PMR = 8.23 & PAD = -146.62^0 are the settled values taken from Phasor Magnitudes Ratio & Phasor Angles Difference – waveforms, which shows (PAD,PMR) is in outside of restrain region defined by boundary conditions : 0.4 ≤ PMR ≤2.5 & -20^0 ≤ PAD ≤ 20^0. It means that the fault occurred inside of the protection zone according to existing approach.

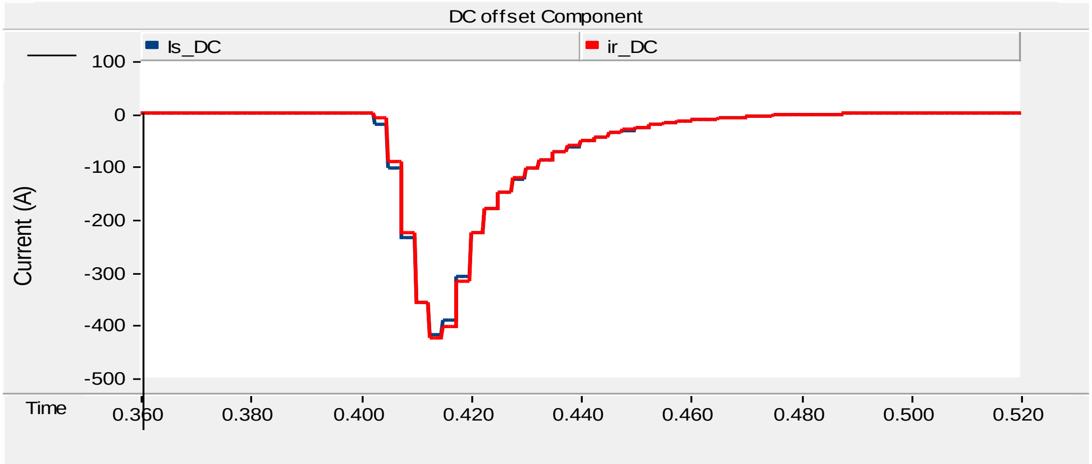
From observations, proposed & existing approach both operate correctly (show that the fault is applied on inside of zone).

Case-2: LL, at 10% of line on left side of bus-3, 5 Ω resistance for topology-1

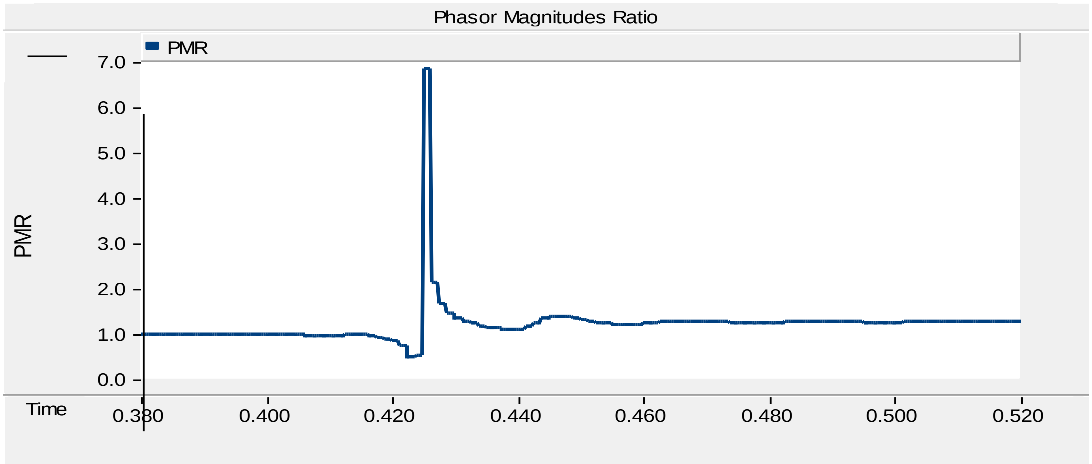
In this case, LL fault is applied at 10% of the length (from bus-3) of the line on left side of bus-3, with fault resistance of 5 Ω for single transmission line system (topology-1) which implemented in matlab/Simulink®. Procedure which is mentioned in previous section is followed. Waveforms (I_s & I_r, DC offset component, PMR and PAD) obtained from simulations are shown in Figure 5.4.



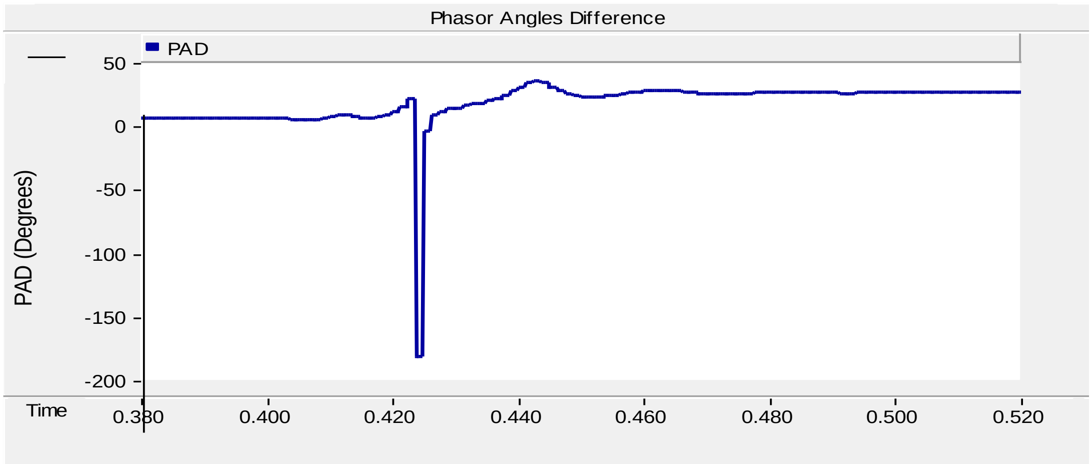
(a) Sending and receiving end current waveforms



(b) Sending and receiving end DC offset component waveforms



(c) Phasor Magnitudes Ratio - waveform



(d) Phasor Angles Difference – waveform

Figure 5.4 I_s & I_r, DC offset components, PMR and PAD waveforms for Case-2

From Figure 5.4,

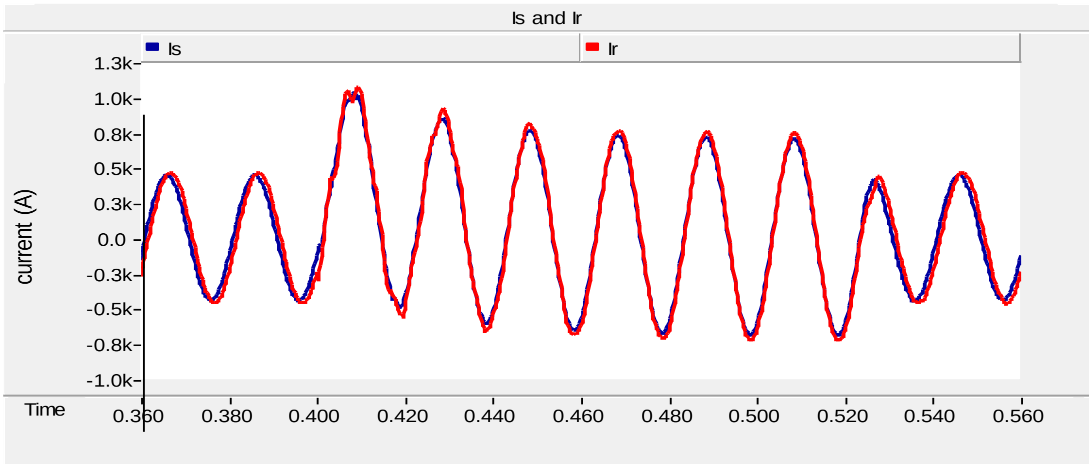
Extracted DC offset component peak values observed from sending and receiving end DC offset components waveforms are: I_{s-DC}= -418.89 A (-ve) & I_{r-DC} = -426.69 A (-ve). This shows sending end and receiving end currents flow in same direction which means fault is occurred on the line, outside of the protection zone according to proposed approach.

PMR = 0.87 & PAD = 8.72^0 are the settled values taken from Phasor Magnitudes Ratio & Phasor Angles Difference – waveforms, which shows (PAD,PMR) is on the restrain region defined by boundary conditions : $0.4 \leq$ PMR ≤ 2.5 & $-20^0 \leq$ PAD $\leq 20^0$. It means that the fault occurred outside of the protection zone according to existing approach.

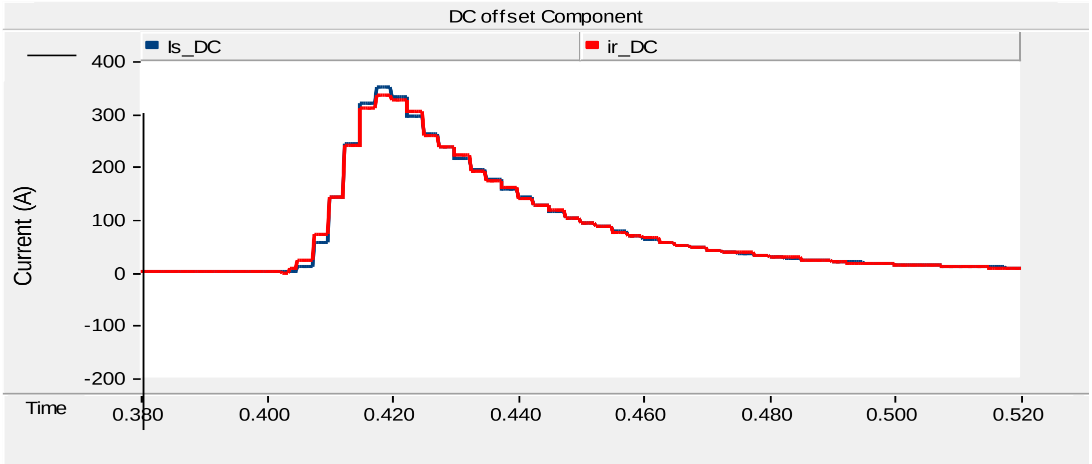
From observations, proposed & existing approach both operate correctly (show that the fault is applied on outside of zone).

Case-3: SLG, at 5% of line on right side of bus-13, 0.001 Ω resistance for topology-2

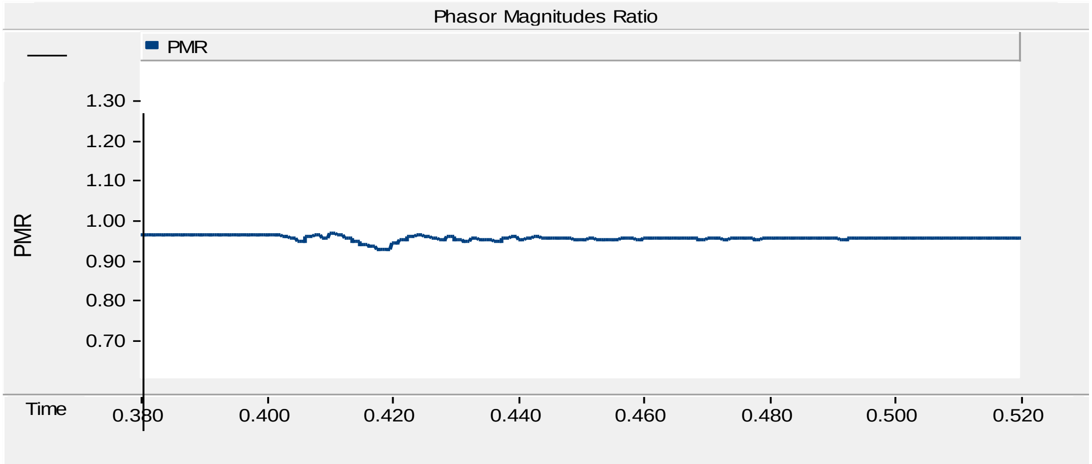
In this case, SLG fault is applied at 5% of the length (from bus-13) of the line on right side of bus-13, with fault resistance of 0.001 Ω for parallel transmission line system (topology-2) which implemented in matlab/Simulink®. Procedure which is mentioned in previous section is followed. Waveforms (I_s & I_r, DC offset component, PMR and PAD) obtained from simulations are shown in Figure 5.5.



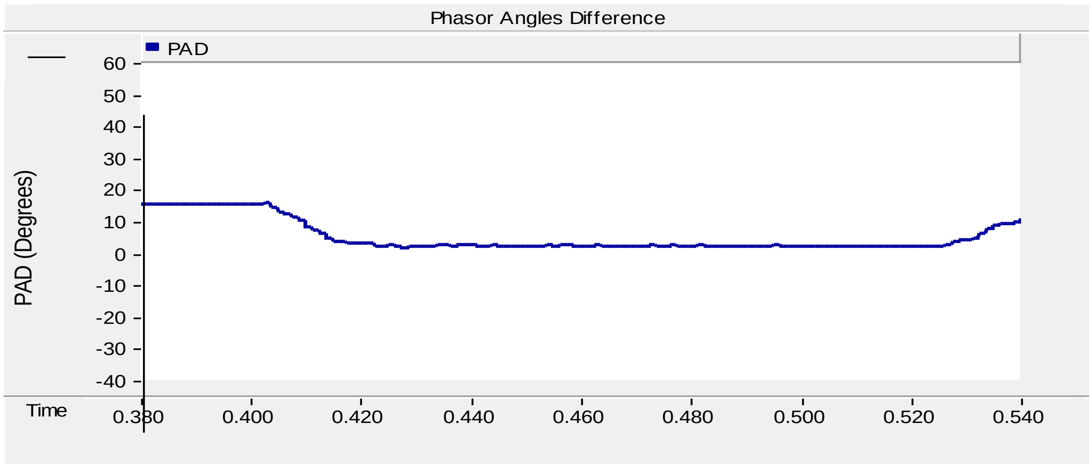
(a) Sending and receiving end current waveforms



(b) Sending and receiving end DC offset component waveforms



(c) Phasor Magnitudes Ratio - waveform



(d) Phasor Angles Difference – waveform

Figure 5.5 I_s & I_r, DC offset components, PMR and PAD waveforms for Case-3

From Figure 5.5,

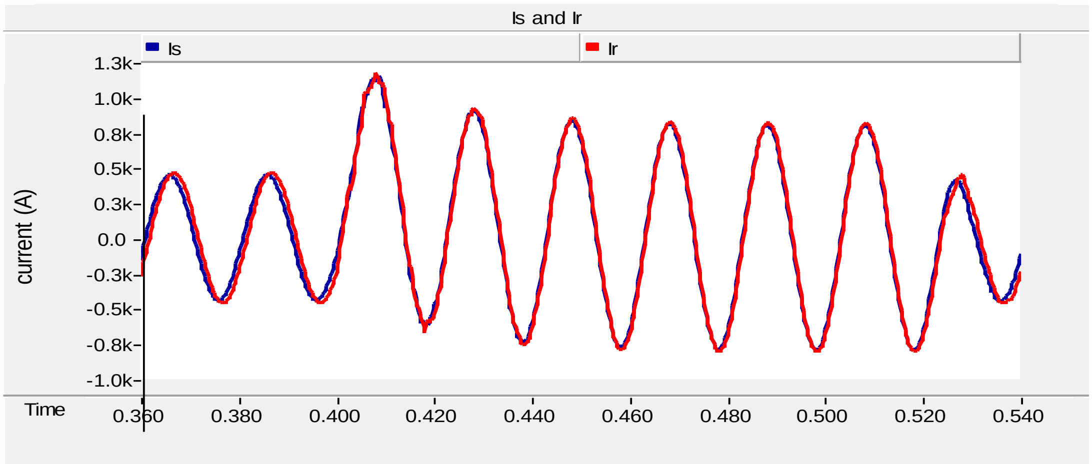
Extracted DC offset component peak values observed from sending and receiving end DC offset components waveforms are: $I_{s\text{-}DC}$= 346.66 A (+ve) & $I_{r\text{-}DC}$ = 331.16 A (+ve). This shows sending end and receiving end currents flow in same direction which means fault is occurred on the line, outside of the protection zone according to proposed approach.

PMR = 0.95 & PAD = 2.06^0 are the settled values taken from Phasor Magnitudes Ratio & Phasor Angles Difference – waveforms, which shows (PAD,PMR) is on the restrain region defined by boundary conditions : $0.4 \leq$ PMR ≤ 2.5 & $-20^0 \leq$ PAD $\leq 20^0$. It means that the fault occurred outside of the protection zone according to existing approach.

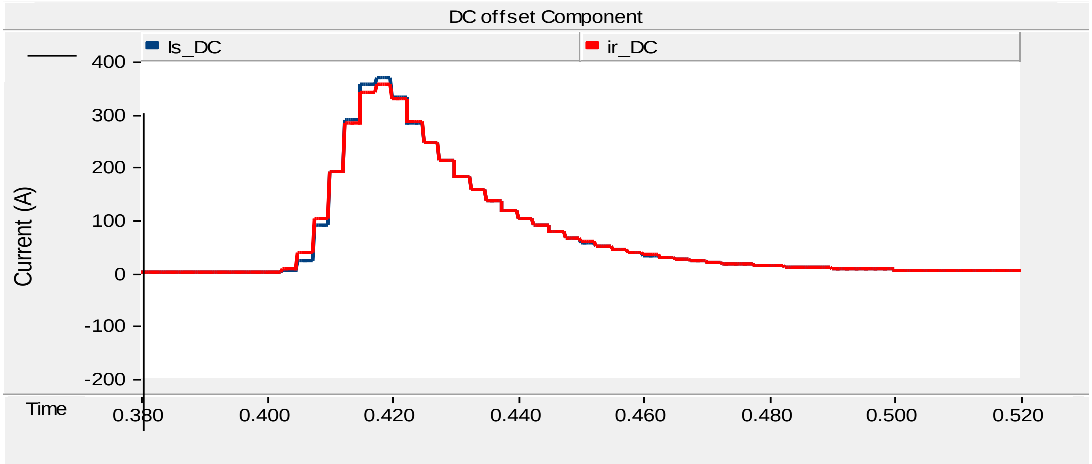
From observations, proposed & existing approach both operate correctly (show that the fault is applied on outside of zone).

Case-4: LLG, at 95% of parallel line, 5 Ω resistance for topology-2

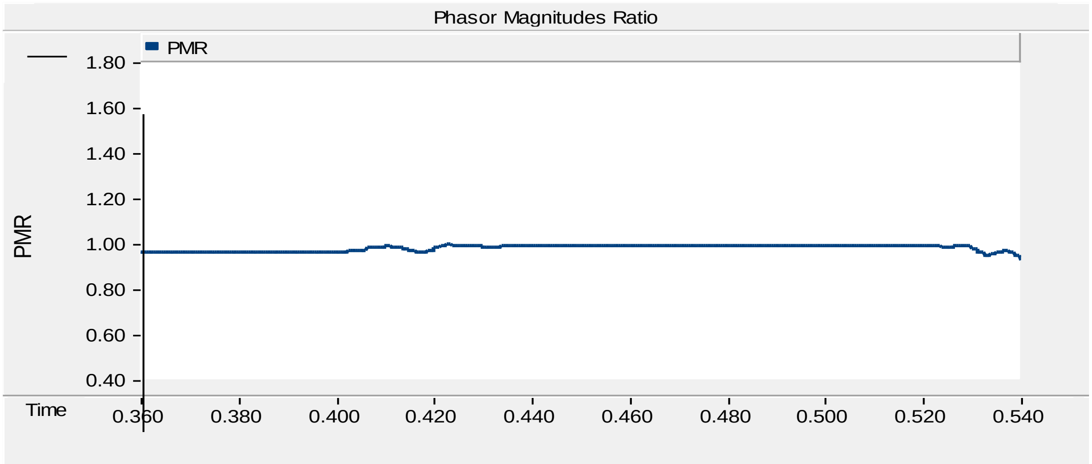
In this case, LLG fault is applied at 95% of the length (from bus-3) of the parallel line in-between bus-3 and bus-13, with fault resistance of 5 Ω for parallel transmission line system (topology-2) which implemented in matlab/Simulink®. Procedure which is mentioned in previous section is followed. Waveforms (I_s & I_r, DC offset component, PMR and PAD) obtained from simulations are shown in Figure 5.6.



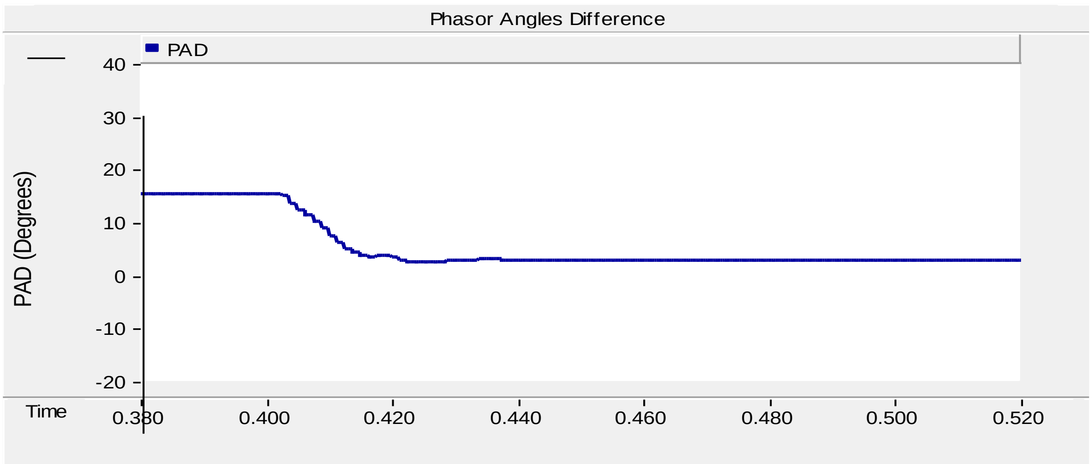
(a) Sending and receiving end current waveforms



(b) Sending and receiving end DC offset component waveforms



(c) Phasor Magnitudes Ratio – waveform



(d) Phasor Angles Difference – waveform

Figure 5.6 I_s & I_r, DC offset components, PMR and PAD waveforms for Case-4

From Figure 5.6,

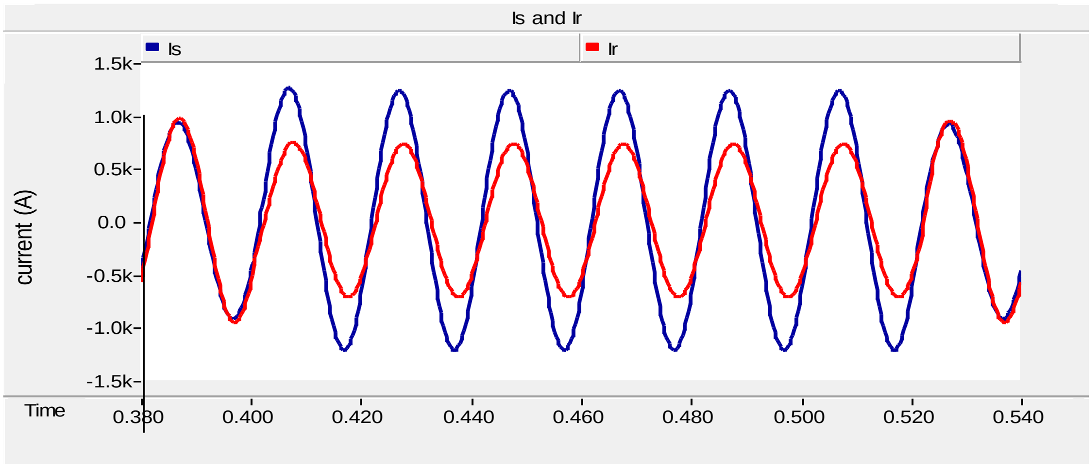
Extracted DC offset component peak values observed from sending and receiving end DC offset components waveforms are: $I_{s\text{-}DC}$= 365.74 A (+ve) & $I_{r\text{-}DC}$ = 352.60 A (+ve). This shows sending end and receiving end currents flow in same direction which means fault is occurred on the line, outside of the protection zone according to proposed approach.

PMR = 0.98 & PAD = 2.68^0 are the settled values taken from Phasor Magnitudes Ratio & Phasor Angles Difference – waveforms, which shows (PAD,PMR) is on the restrain region defined by boundary conditions : $0.4 \leq PMR \leq 2.5$ & $-20^0 \leq PAD \leq 20^0$. It means that the fault occurred outside of the protection zone according to existing approach.

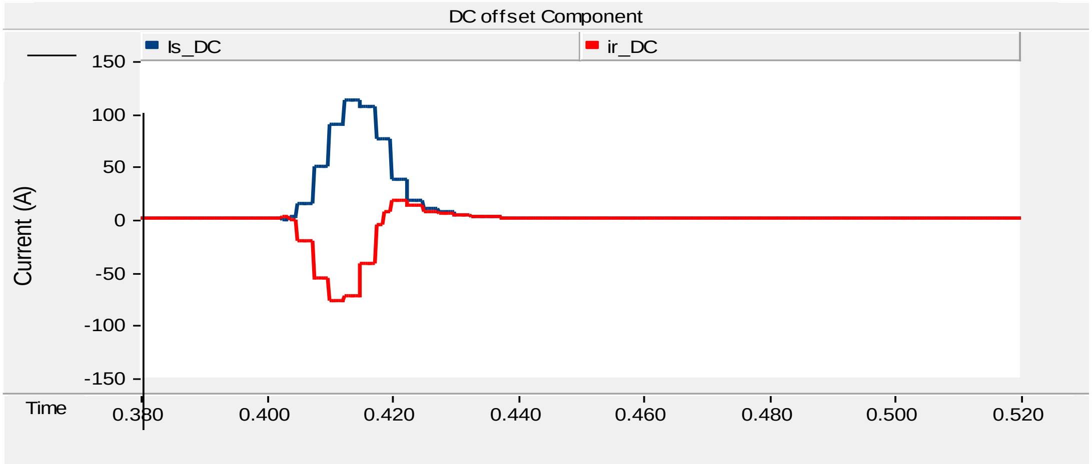
From observations, proposed & existing approach both operate correctly (show that the fault is applied on outside of zone).

Case-5: LLL, at 50% of length of line, 200 Ω resistance for topology-1

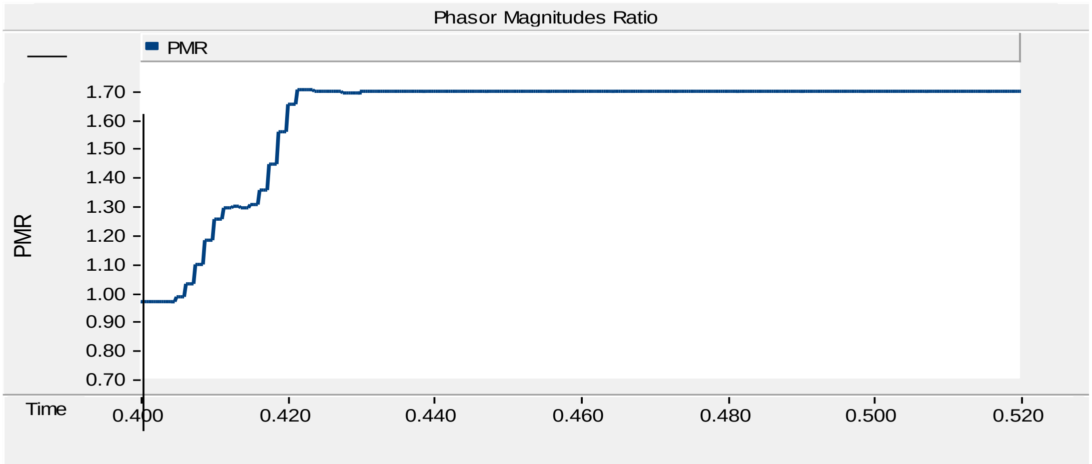
In this case, LLL fault is applied at 50% of the length (from bus-3) of the protected line in-between bus-3 and bus-13, with fault resistance of 200 Ω for single transmission line system (topology-1) which implemented in matlab/Simulink®. Procedure which is mentioned in previous section is followed. Waveforms (I_s & I_r, DC offset component, PMR and PAD) obtained from simulations are shown in Figure 5.7.



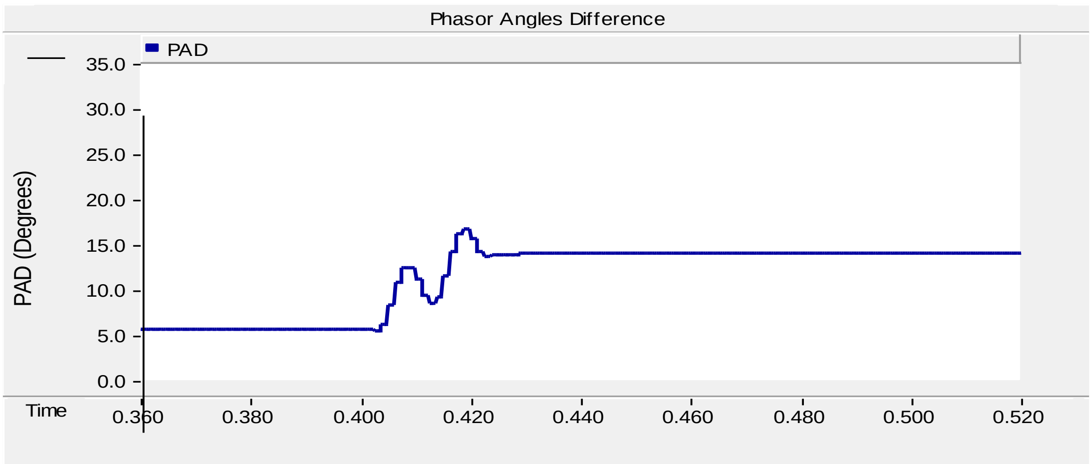
(a) Sending and receiving end current waveforms



(b) Sending and receiving end DC offset component waveforms



(c) Phasor Magnitudes Ratio – waveform



(d) Phasor Angles Difference – waveform

Figure 5.7 I_s & I_r, DC offset components, PMR and PAD waveforms for Case-5

From Figure 5.7,

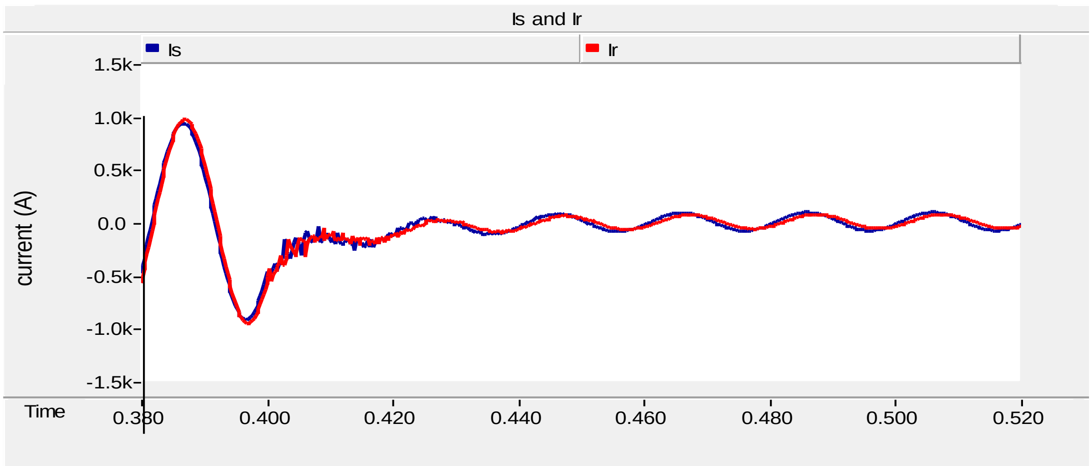
Extracted DC offset component peak values observed from sending and receiving end DC offset components waveforms are: $I_{s\text{-}DC}$= 112.10 A (+ve) & $I_{r\text{-}DC}$ = -78.30 A (-ve). This shows sending end and receiving end currents flow in opposite directions which means fault is occurred on the protected line, inside of the protection zone according to proposed approach.

PMR = 1.69 & PAD = 13.85^0 are the settled values taken from Phasor Magnitudes Ratio & Phasor Angles Difference – waveforms, which shows (PAD,PMR) is on the restrain region defined by boundary conditions : 0.4 ≤ PMR ≤2.5 & -20^0 ≤ PAD ≤ 20^0. It means that the fault occurred outside of the protection zone according to existing approach.

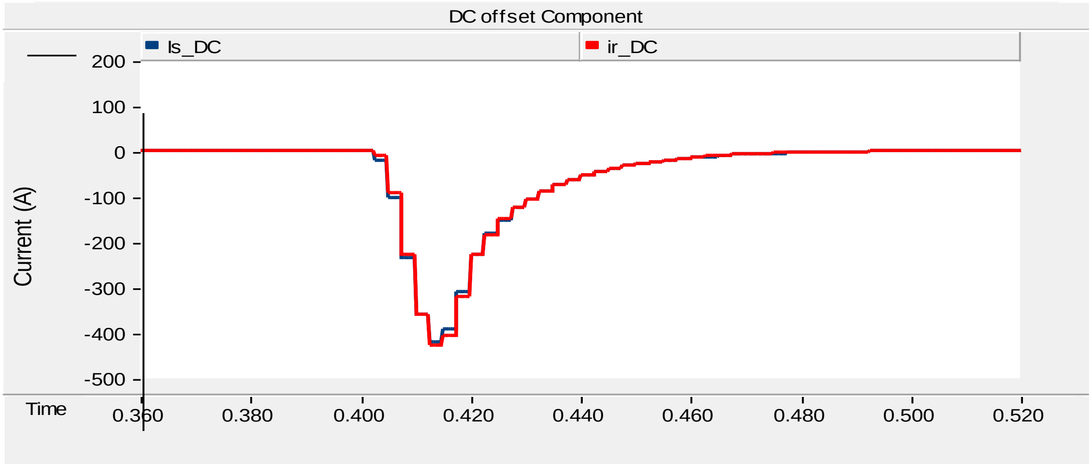
From observations, proposed approach operate correctly (shows fault is inside of zone) & existing approach operate in-correctly (shows fault is outside of zone).

Case-6: LLG, at 5% of line on left side of bus-3, 5 Ω resistance for topology-1

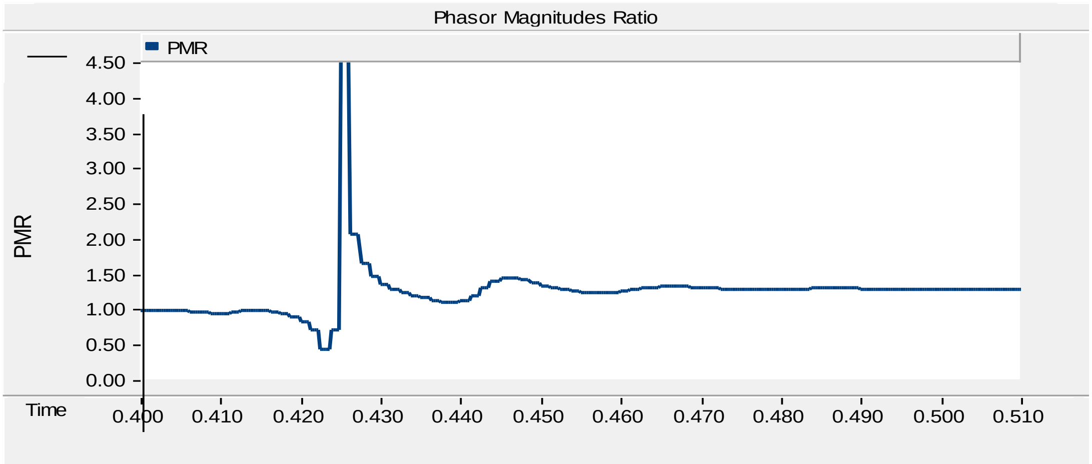
In this case, LLG fault is applied at 5% of the length (from bus-3) of the line on left side of bus-3, with fault resistance of 5 Ω for single transmission line system (topology-1) which implemented in matlab/Simulink®. Procedure which is mentioned in previous section is followed. Waveforms (I_s & I_r, DC offset component, PMR and PAD) obtained from simulations are shown in Figure 5.8.



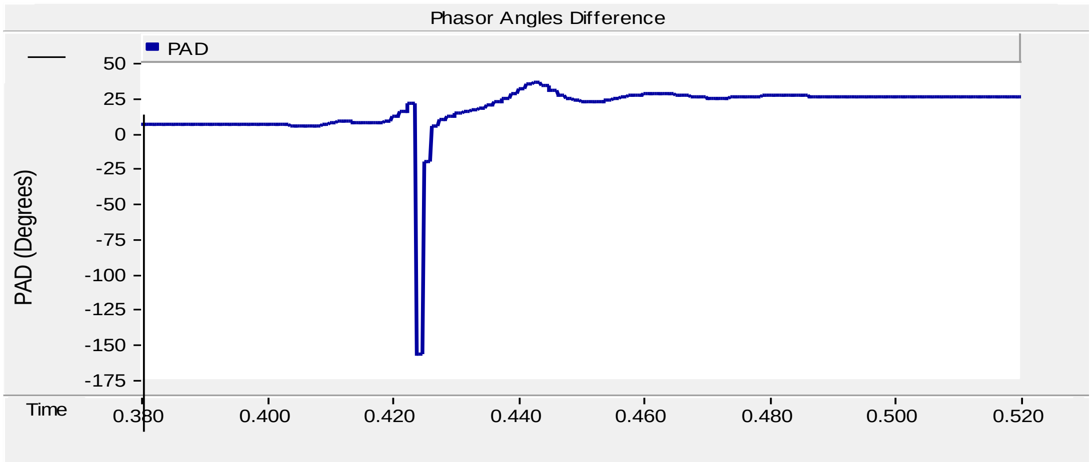
(a) Sending and receiving end current waveforms



(b) Sending and receiving end DC offset component waveforms



(c) Phasor Magnitudes Ratio - waveform



(d) Phasor Angles Difference – waveform

Figure 5.8 I_s & I_r, DC offset components, PMR and PAD waveforms for Case-6

From Figure 5.8,

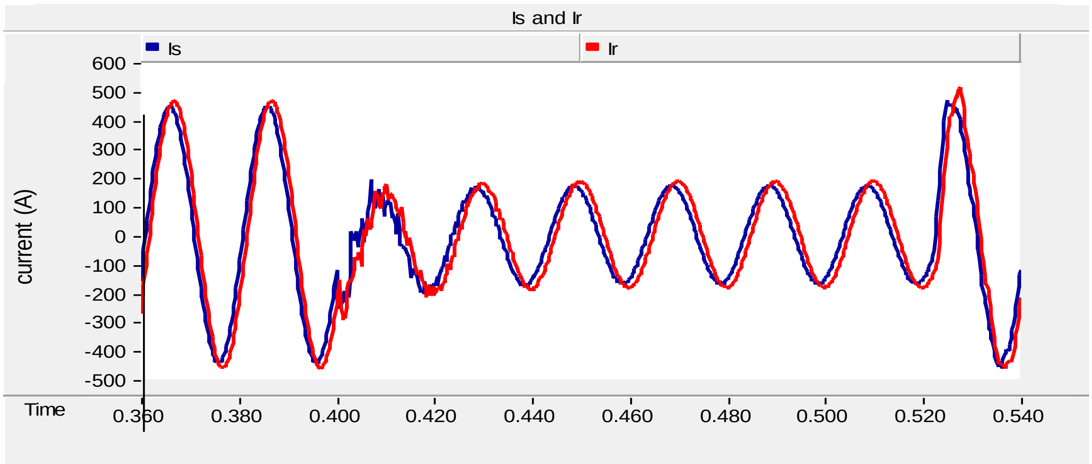
Extracted DC offset component peak values observed from sending and receiving end DC offset components waveforms are: $I_{s\text{-}DC}$= -420.01 A (-ve) & $I_{r\text{-}DC}$ = -428.45 A (-ve). This shows sending end and receiving end currents flow in same direction which means fault is occurred on the line, outside of the protection zone according to proposed approach.

PMR = 1.27 & PAD = 25.13^0 are the settled values taken from Phasor Magnitudes Ratio & Phasor Angles Difference – waveforms, which shows (PAD,PMR) is on outside of the restrain region defined by boundary conditions : $0.4 \leq PMR \leq 2.5$ & $-20^0 \leq PAD \leq 20^0$. It means that the fault occurred inside of the protection zone according to existing approach.

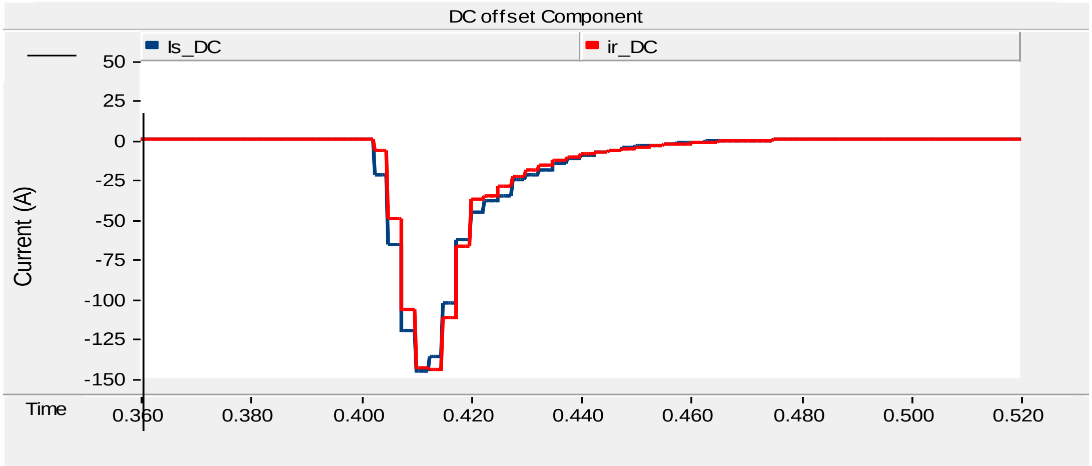
From observations, proposed approach operate correctly (shows fault is outside of zone) & existing approach operate in-correctly (shows fault is inside of zone).

Case-7: LL, at 5% of parallel line, 5 Ω resistance for topology-2

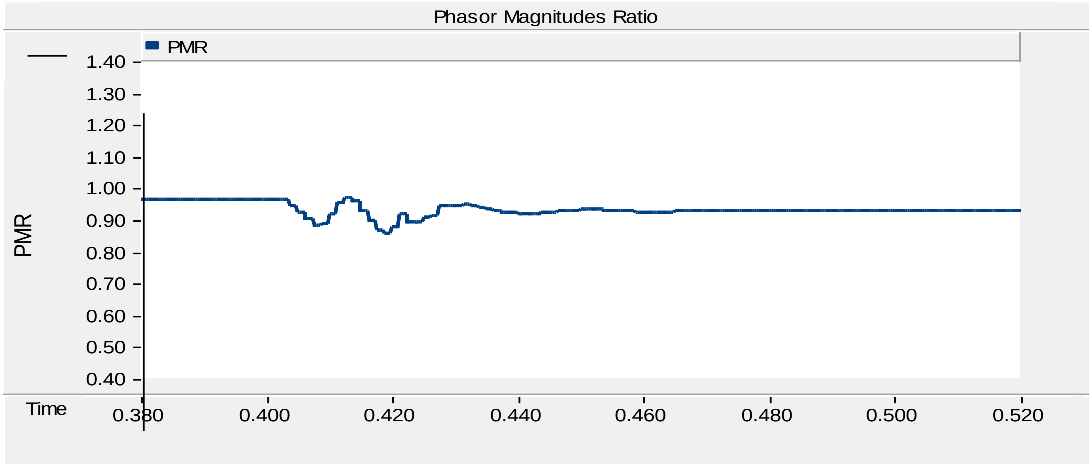
In this case, LL fault is applied at 5% of the length (from bus-3) of the parallel line in-between bus-3 and bus-13, with fault resistance of 5 Ω for parallel transmission line system (topology-2) which implemented in matlab/Simulink®. Procedure which is mentioned in previous section is followed. Waveforms (I_s & I_r, DC offset component, PMR and PAD) obtained from simulations are shown in Figure 5.9.



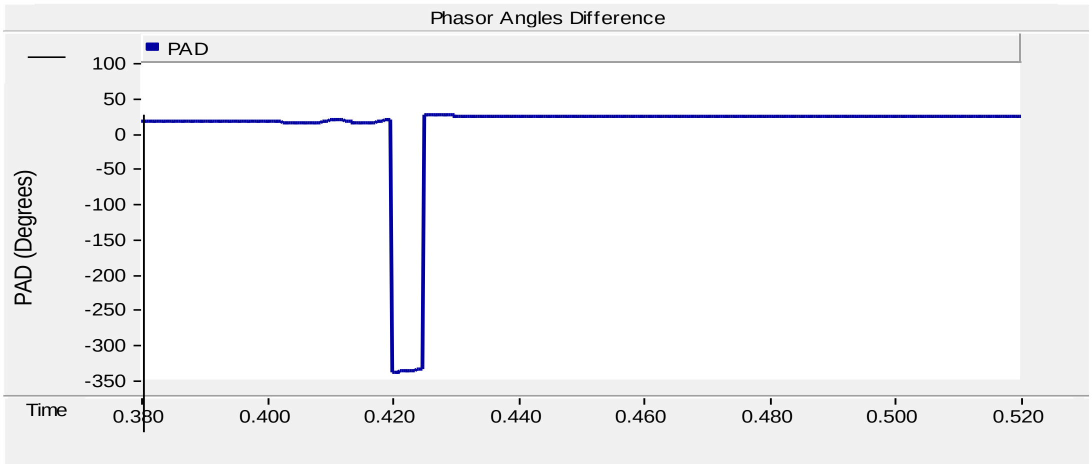
(a) Sending and receiving end current waveforms



(b) Sending and receiving end DC offset component waveforms



(c) Phasor Magnitudes Ratio - waveform



(d) Phasor Angles Difference – waveform

Figure 5.9 I_s & I_r, DC offset components, PMR and PAD waveforms for Case-7

From Figure 5.9,

Extracted DC offset component peak values observed from sending and receiving end DC offset components waveforms are: $I_{s\text{-}DC}$= -145.72 A (-ve) & $I_{r\text{-}DC}$ = -145.20 A (-ve). This shows sending end and receiving end currents flow in same direction which means fault is occurred on the line, outside of the protection zone according to proposed approach.

PMR = 0.92 & PAD = 22.13^0 are the settled values taken from Phasor Magnitudes Ratio & Phasor Angles Difference – waveforms, which shows (PAD,PMR) is on outside of the restrain region defined by boundary conditions : $0.4 \leq PMR \leq 2.5$ & $-20^0 \leq PAD \leq 20^0$. It means that the fault occurred inside of the protection zone according to existing approach.

From observations, proposed approach operate correctly (shows fault is outside of zone) & existing approach operate in-correctly (shows fault is inside of zone).

Chapter 6

Conclusion

Extraction DC offset component peak is faster than the estimation of correct phasors of currents from both sides of the line due to transients in signals. Because DC offset component peak can be obtained within first cycle and correct estimation of phasor possible only after first cycle. No precision in estimation of DC offset value is required as the proposed method depends on the sign of the DC offset but precision in estimation of PMR & PAD is required as the existing method depends on the boundary conditions defined for restrain region.

Proposed approach operates correctly for every simulated case but existing approach mal-operates for some cases, which can be shown with Table-1 as below.

Table-1: Comparison between proposed & existing approaches

	Proposed approach	**Existing approach**
No. of cases simulated	812	812
No. of cases satisfied by	812	720
Accuracy (%)	100	88.67

From Table-1, we can conclude that proposed approach is reliable and dependable compared to the existing approach.

Capacitive nature of transmission line definitely effect in defining boundary conditions for restraining region of existing approach more compared with proposed approach. So, proposed approach can be said as robust and reliable approach to identify fault.

Future work

1) Work can be done on efficient extraction methods for DC offset component from signals
2) This approach can be extended to series-compensated transmission lines (topology-1 and topology-2).

References

[1] H. Seyedi, S. Teimourzadeh and P. S. Nezhad, "Adaptive zero sequence compensation algorithm for double-circuit transmission line protection," in *IET Generation, Transmission & Distribution*, vol. 8, no. 6, pp. 1107-1116, June 2014.

[2] I. C. Borascu and S. S. Iliescu, "Adaptive Distance Protection Scheme for High Resistance Phase to Phase Faults on Double-Circuit Transmission Line," *2015 20th International Conference on Control Systems and Computer Science*, Bucharest, 2015, pp. 972-977.

[3] S. Dambhare, S. A. Soman and M. C. Chandorkar, "Adaptive Current Differential Protection Schemes for Transmission-Line Protection," in *IEEE Transactions on Power Delivery*, vol.24, no.4, pp.1832-1841, Oct.009.

[4] T. P. Hinge and S. S. Dambhare, "Accurate phase comparison scheme with synchronized measurements," *2015 IEEE Power & Energy Society General Meeting*, Denver, CO, 2015, pp.1-6.

[5] S. Dambhare, S. A. Soman and M. C. Chandorkar, "Current Differential Protection of Transmission Line Using the Moving Window Averaging Technique," in *IEEE Transactions on Power Delivery*, vol. 25, no. 2, pp. 610-620, April 2010.

[6] M. Jamil, M. S. Thomas, Moinuddin and P. Kumar, "An improved scheme based on fuzzy logic for EHV transmission line protection," *High Voltage Engineering, 1999. Eleventh International Symposium on (Conf. Publ. No. 467)*, London, 1999, pp. 360-364 vol.1.

[7] N. Perera and A. D. Rajapakse, "Series-Compensated Double-Circuit Transmission-Line Protection Using Directions of Current Transients," in *IEEE Transactions on Power Delivery*, vol.28, no.3, pp.1566-1575, July2013.

[8] A. I. Megahed, A. M. Moussa and A. E. Bayoumy, "Usage of wavelet transform in the protection of series-compensated transmission lines," in *IEEE Transactions on Power Delivery*, vol.21, no.3, pp.1213-1221, July2006.

[9] L. J. Ernst, W. L. Hinman, D. H. Quam and J. S. Thorp, "Charge comparison protection of transmission lines-relaying concepts," in *IEEE Transactions on Power Delivery*, vol.7, no.4, pp.1834-1852, Oct1992.

[10] F. Martin and J. A. Aguado, "Wavelet-based ANN approach for transmission line protection," in *IEEE Transactions on Power Delivery,* vol. 18, no. 4, pp. 1572-1574, Oct. 2003.

[11] S. C. Sun and R. E. Ray, "A current differential relay system using fiber optics communications," *IEEE Trans. Power App. Syst.*, vol. PAS-102, no. 2, pp. 410–419, Feb. 1983.

[12] B. Kasztenny, I. Voloh, and E. Udren, "Rebirth of the phase comparison line protection principle," in *Proc. 59th Annual Conf. Protective Relay Engineers*, Apr. 2006, pp. 193–252.

[13] A. G. Phadke and J. S. Thorp, *Computer Relaying for Power Systems*. Taunton, Somerset, U.K.: Research Studies Press Ltd., 1988.

[14] Z. Y. Xu, Z. Q. Du, L. Ran, Y. K. Wu, Q. X. Yang, and J. L. He, "A current differential relay for a 1000-kv UHV transmission line," *IEEE Trans. Power Del.*, vol. 22, no. 3, pp. 1392–1399, Jul. 2007.

[15] C. K. Wong, C. W. Lam, K. C. Lei, C. S. Lei, and Y. D. Han, "Novel wavelet approach to current differential pilot relay protection," *IEEE Trans. Power Del.*, vol. 18, no. 1, pp. 20–25, Jan. 2003.

[16] K. R. Padiyar, *Power System Dynamics*, 2nd ed. Hyderabad, India: BS Publications, 2002.

Appendices

Appendix-1 (Data for topology-1)

Generator-1:

900MVA, 25KV and X/R=7, f=50Hz

Generator-2:

800MVA, 25KV, X/R=7 and f=50Hz

Generator-3:

100MVA, 25KV, X/R=7 and f=50Hz

Generator-4:

200MVA, 25KV, X/R=7 and f=50Hz

Transformer-1 & 2:

900MVA, 25KV/230KV

Transformer-3:

100MVA, 25KV/230KV

Transformer-4:

200MVA, 25KV/230KV

Transmission line parameters:

Resistance per unit length, [r1 r0] = [0.026732 0.21804] Ω/km

Inductance per unit length, [l1 l0] = [0.00094745 0.0038076] H/km

Capacitance per unit length, [c1 c0] = [1.2184×10-8 5.6258×10-9] F/km

Length of transmission line between bus-101 and bus-102 = 100 km

Length of transmission line between bus-102 and bus-3 = 100 km

Length of transmission line between bus-111 and bus-112 = 100 km

Length of transmission line between bus-112 and bus-13 = 100 km

Length of transmission line between bus-3 and bus-13 = 200 km (need to be protected)

Load-1: (Dynamic load) at bus-3

230 KV, 50Hz

P_0 = 50MW and Q_0 =25Mvar

V_0 =0.95∠0.1635^0

Load-2: at bus-13

230 KV, 50Hz

500MW, +100Mvar and -100var

Appendix-2 (Data for topology-2)

Generators data and transformers data are same as in appendix-1. Additionally,

No. of transmission lines between bus-101 and bus-102 = 2

No. of transmission lines between bus-102 and bus-3 = 2

No. of transmission lines between bus-111 and bus-112 = 2

No. of transmission lines between bus-112 and bus-13 = 2

No. of transmission lines between bus-3 and bus-13 = 3

Transmission line parameters:

Resistance per unit length, [r1 r0] = [0.026732 0.21804] Ω/km

Inductance per unit length, [l1 l0] = [0.00094745 0.0038076] H/km

Capacitance per unit length, [c1 c0] = [1.2184×10-8 5.6258×10-9] F/km

Length of transmission line between bus-101 and bus-102 = 100 km

Length of transmission line between bus-102 and bus-3 = 100 km

Length of transmission line between bus-111 and bus-112 = 100 km

Length of transmission line between bus-112 and bus-13 = 100 km

Length of transmission line between bus-3 and bus-13 = 200 km (need to be protected)

Load-1: (Dynamic load) at bus-3

230 KV, 50Hz

P_0 = 50MW and Q_0 =25Mvar

$V_0 = 0.95\angle 0.1635^0$

Load-2: at bus-13

230 KV, 50Hz

500MW, +100Mvar and -100var