ENG 460

Protection of ungrounded systems using an advanced relay element

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ABSTRACT

The aim of this thesis project is to investigate single line to ground faults in an ungrounded system and determine an effective fault detection method. Ungrounded system analysis is conducted using ICAP simulation.

The fault detection method is focused on three different parts. The first part is used to identify the faulted feeder. Second part is for identifying the faulted phase and the last part is for estimating the fault distance.

After simulating the model of an ungrounded system using ICAP, it can be observed that when a ground fault is present, the voltage magnitude of the unfaulted phase increases. The second observation is that when the fault is present, a zero-sequence voltage and a zero-sequence current are created in the ungrounded system. Therefore zero-sequence components can be used to identify the faults in an ungrounded system.

A direction element is used to identify the faulted feeder of an ungrounded system. The relay measures the zero-sequence voltage (3Vo) and zero-sequence current (3Io) using a broken delta transformer and a current transformer. The relay calculates impedance (Vo/Io), If this impedance value is above the forward threshold then a directional element identifies it as a forward fault.

The simulation result proves the above method and also shows the faulted feeder zero-sequence current lagging the voltage by 90 degrees and the unfaulted feeder zero-sequence current leads the voltage by 90 degrees.

The phase difference between the positive sequence voltage (V_{1A}) of one of the phases and zero-sequence current are used to detect a single line to ground fault on that phase.

The simulation results show the above method is able to identify the faulted phase.

In the final section, the simulation results show the magnitude of the zero-sequence current change according to the faulted distance therefore the single line to ground fault detection algorithm can use this characteristic to measure the fault distance.
ACKNOWLEDGMENTS

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Chapter 1

1 INTRODUCTION

1.1 General Introduction

Ungrounded power systems are attractive because they generate small fault currents when a ground fault occurs. These systems provide a lower safety risk to humans and are able to maintain operation under ground fault events. However, the low fault current makes it difficult to detect ground faults.

As electrical system reliability and continuity of service in an electrical system are the top priorities for most industries, an effective fault detection method is required for these systems.

The traditional method for detecting ground faults in an ungrounded power network is to use simple over-voltage protective relays. For advanced protection systems, simple over voltage relays are not effective elements for detecting faults. This is because traditional relays can not identify the faulted feeder and faulted phase in an ungrounded power system. Instead, a switching method is used to identify the fault. The system operator de-energizes one feeder at a time until the fault disappears. But this process disconnects a number of healthy feeders and disturbs the continuity of the power supply [1].

According to historical fault analysis data, ninety percent of all faults on ungrounded networks are single line to ground faults. This project aims to develop an advanced element to detect and locate single line to ground faults in radial ungrounded systems [1].

In particular, the element will be able to detect:

a) the faulted feeder;

b) the faulted phase, and:

c) the distance to the fault point.

Due to the limitations in traditional fault detection in ungrounded power systems, the Advanced Relay Element fault detection method could play an important role in an industrial environment.
1.2 Scope of the project

The aim of this thesis project is to investigate single line to ground faults in ungrounded systems and investigate an advanced element to detect these faults. The fault identification system will be developed using zero-sequence current and zero-sequence voltage that are formed when single line to ground faults are present. This element will detect the faulted feeder, identify the faulted phase and estimate the distance to the fault location. The simulation is conducted using ICAP simulation software to verify the theoretical results. The advantage and the limitations of this system will also be discussed.

1.3 Topic outline

a) Chapter 1:Introduction
   ➢ An outline of the objectives and need for this thesis project

b) Chapter 2:Background
   ➢ Ungrounded power system
   ➢ Ungrounded system Vs Multigrounded system
   ➢ Relay connections in an ungrounded system
   ➢ The voltage transformer
   ➢ Current Transformer
   ➢ Theoretical background
   ➢ The relay types used in ungrounded systems

c) Chapter 3:The approach
   ➢ Analysing an ungrounded system using the ICAP software
   ➢ Introduction of ICAP software
   ➢ Simulate the ungrounded system using ICAP
   ➢ Assumptions for simulation
   ➢ Simulation results
   ➢ Analysis of the result

d) Chapter 4:The Function of the Relay element
   ➢ Introduction of the block diagram
   ➢ Directional element
   ➢ The Function of the phase selection element
   ➢ The Function of the Distance measuring element

e) Chapter 5:Simulation for detecting the faulted feeder
   ➢ Fault feeder detection result
   ➢ Detection of the faulted feeder result
   ➢ Analysis of the results

f) Chapter 6:Simulation for identifying the faulted phase
➢ Simulation results for the faulted phase identification
➢ Analysis of the simulation results

g) Chapter 7: Simulation for estimating the fault distance
   ➢ The fault distance estimation result
   ➢ Analyse of the fault distance results
   ➢ Analyse of the fault distance results

h) Chapter 8: Analysis of the fault Resistance
   ➢ Introduction of the fault resistance
   ➢ Simulation procedure for analysis the fault resistance
   ➢ Result of the fault resistance
   ➢ Analyse the fault resistance result

i) Chapter 9: Fault detection sensitivity discussion

j) Chapter 10: Conclusion and future recommendations
Chapter 2

2 Background

2.1 Ungrounded Power System

The most popular ungrounded power distribution system in current industries is the three phase three-wire delta connected ungrounded power system. In this ungrounded system, there is no intentional ground connection in any part of the electrical system. However, each line of the system is coupled to ground through a per-phase capacitance as show in figure 1.

The figure has been removed

The advantage of this system is that the loads are connected phase to phase and therefore a single line-to-ground fault does not effect the load operation. Thus the system can operate with a ground fault in one phase. This avoids the need for an immediate shutdown of the system [1].

In an ungrounded system, when the first line to ground fault occurs a very low fault current flows and the healthy phases rise to the line-to-line voltage $\sqrt{3}$ times the phase voltage. Therefore a second ground fault would be very dangerous because the system has high potential phases [1].

However, the ungrounded systems have attractive characteristics such as, safety for humans and ability to operate with single line ground faults. Therefore mine sites and Navy ships commonly use ungrounded systems for their power system applications [9].
2.2 Ungrounded system Vs Multigrounded system

Figure 2: Ungrounded System [2]  Figure 3: Multigrounded system [2]

Figure 2 shows an ungrounded distribution feeder, it has no neutral conductor running though the system. The phase-to-ground distribution capacitance determines the magnitude of the fault current. The loads are connected phase to phase.

Figure 3 shows a four wire multigrounded distribution feeder. The neutral wire is typically grounded at each distribution transformer point. In this system service loads can be connected phase to phase or phase to neutral. The zero-sequence current can create an imbalance of the loads. When a fault is present the relay measures the zero-sequence current created by the load imbalance and fault current. The multigrounded systems often become unbalanced because the loads are mostly connected phase to neutral.

In the ungrounded system, fault current (If) depends on the line-to-ground capacitance of the unfaulted power system phases. This is the most important difference between a single line to ground fault on an ungrounded system compared to a multigrounded power system [2].
2.3 Relay connections in an ungrounded system

Figure 4 shows the wiring connection of the new relay. This is a radial ungrounded power distribution network system. Therefore only one node is feeding power to the system and power will flow top to bottom. In this system all loads are connected phase to phase. The lengths of the conductors are less than 80km. It has three feeders; each feeder is monitored with a relay.

The broken delta transformer (BDVT) and current transformers are connected to the relays as shown in figure 4. The connection of the broken delta transformer and current transformers to the relays are shown in figure 5 and figure 6 respectively [2].

![Diagram of three-phase simplified representation of an ungrounded distribution system.](image)

Figure 4: Three-phase simplified representation of an ungrounded distribution system.
2.3.1 The voltage transformer

2.3.1.1 Introduction of voltage transformer
Three different types of voltage transformer are used in relays. They are three-phase four-wire, open-delta and broken delta. The figure 5 shows the broken delta voltage transformer (VT) connection of the voltage transformer. This method is very suitable for ungrounded and resonant-grounded system directional element applications. Using this method the relay can measure each phase voltage and calculate the zero-sequence voltage (3Vo) for the directional element and phase selection element [3].

2.3.1.2 Advantages of the Broken Delta Transformer Connection.
The relay can measure directly each individual phase voltage and calculate the necessary sequence components. The wire connection is also simpler than the traditional system.

This advanced broken Delta Connection is used to measure zero-sequence voltage of the relay element in the project.

Figure 5: Single-Line Diagram and New Broken-Delta VT Connection Diagram [3]
2.3.1.3 Current Transformer

The figure has been removed

Figure 6: Current transformer arrangement [1]

The current–transformer arrangement for zero-sequence current is shown in Figure 6. The relay can measure Ia, Ib and Ic that will be used for the directional element, phase selection element and distance measuring element [1].

2.4 Theoretical background

2.4.1 Sequence components
In 1918 C.L. Fortescue developed the method of symmetrical components. This is a very powerful method for analysing unbalanced three-phase systems. He identified a linear transformation from phase components to a new set of components called symmetrical components. The symmetrical components method facilitates the analysis of the complicated unbalance phenomena in a relatively simple manner [6].

2.4.2 Sequence voltage
According to Fortescue, phase voltages can be converted into three sets of sequence components, zero sequence, positive sequence and negative sequence.
1. Zero-sequence components

\[ V_{a0}, V_{b0}, V_{c0} \]

The set of zero-sequence components consist of the three phasors \((V_{a0}, V_{b0}, V_{c0})\) with equal magnitudes and zero phase displacements such that

\[ V_{a0} = V_{b0} = V_{c0} = V_0 \]

2. Positive-sequence components.

Positive-sequence components consist of three phasors with equal magnitudes and 120° phase displacement in a positive sequence [12].

\[ V_{a1} = V_1 \]
\[ V_{b2} = aV_2 = V_2 \angle 120^0 \]
\[ V_{c2} = a^2V_2 = V_2 \angle 240^0 \]

3. Negative-sequence components.

Negative-sequence components consist of three phases with \((V_{a2}, V_{b2}, V_{c2})\) equal magnitudes, 120° phase displacement and negative sequence [12].

\[ V_{a2} = V_2 \]
\[ V_{b1} = a^2V_1 = V_1 \angle 240^0 \]
\[ V_{c1} = aV_1 = V_1 \angle 120^0 \]
The phase voltages can be written as follows

\[ V_a = V_o + V_1 + V_2 \]  \hspace{1cm} (1)  
\[ V_b = V_o + a^2 V_1 + a V_2 \]  \hspace{1cm} (2)  
\[ V_c = V_o + a V_1 + a^2 V_2 \]  \hspace{1cm} (3)  

The sequence voltage can be obtained from the phase voltage using the transformation.

\[ V_o = \frac{1}{3} (V_a + V_b + V_c) \]  \hspace{1cm} (4)  
\[ V_1 = \frac{1}{3} (V_a + a V_b + a^2 V_c) \]  \hspace{1cm} (5)  
\[ V_2 = \frac{1}{3} (V_a + a^2 V_b + a V_c) \]  \hspace{1cm} (6)  

### 2.4.3 Sequence Currents

#### 1. Zero-sequence current components

The set of zero-sequence current components consist of the three phasors \((I_{ao}, I_{bo}, I_{co})\) with equal magnitudes and zero phase displacements such that

\[ I_{ao} = I_{bo} = I_{co} = I_o \]

#### 2. Positive-sequence current components

Positive-sequence components consist of three phasors with equal magnitudes and 120° phase displacement in a positive sequence[12].

\[ I_{a1} = I_1 \]
\[ I_b = a^2 I_1 = I_1 \angle 240^\circ \]
\[ I_{c1} = a I_1 = I_1 \angle 120^\circ \]
3. Negative-sequence current components

Negative-sequence components consist of three phases with \( (I_{a2}, I_{b2}, I_{c2}) \) with equal magnitudes, 120° phase displacement and negative sequence.

\[
I_{a2} = I_2
\]

\[
I_{b2} = aI_2 = I_2 \angle 120^\circ
\]

\[
I_{c2} = a^2I_2 = I_2 \angle 240^\circ
\]

The symmetrical component transformation can also be applied to currents, as follows:

\[
I_a = I_o + I_1 + I_2 \quad (7)
\]

\[
I_b = I_o + a^2I_1 + aI_2 \quad (8)
\]

\[
I_c = I_o + aI_1 + a^2I_2 \quad (9)
\]

The sequence current can be obtained from the phase currents using the transformation:

\[
I_o = \frac{1}{3} (I_a + I_b + I_c) \quad (10)
\]

\[
I_1 = \frac{1}{3} (I_a + aI_b + a^2I_c) \quad (11)
\]

\[
I_2 = \frac{1}{3} (I_a + a^2I_b + aI_c) \quad (12)
\]

The positive-sequence quantities are present during balanced three-phase conditions. Negative-sequence quantities can be measured only when the power system is unbalanced. Zero-sequence quantities can be observed only in ground fault conditions. Therefore negative and zero-sequence components are only present in unbalanced systems with ground faults. Therefore the zero-sequence current and zero-sequence voltage can be used to detect faults in ungrounded power system relays. Thus zero-sequence current and voltage are used to develop the single line to ground fault detection element in this thesis project [6].
2.5 The relay types used in ungrounded systems

2.5.1 The 59N scheme
The 59N is the most popular over voltage protective relay for ungrounded power distribution networks. It uses the zero-sequence voltage component to detect single line to ground faults. The disadvantage of the 59N relay is that it can not detect the faulted feeder or faulted phase. This is because when a ground fault is present any one of the feeders faulted produces the same magnitude of zero-sequence voltage. The 59N systems are still in use in several industrial applications [1].

2.5.2 The SEL-351 Relay
The Schweitzer Engineering Laboratories developed the SEL-351 Relay for ungrounded systems and other power system applications. The SEL-351 has a very high sensitivity. It includes an advanced directional element for ungrounded systems. This relay responds to the quadrature component of the dot product of the zero-sequence voltage and current. However this relay has no fault location identification system [5].

2.5.3 Numerical Relay (for ETESAL)
This relay has desirable elements to detect faults in ungrounded systems. It uses an advanced current transformer to identify the ground faults [1].

2.5.4 Ground-fault location algorithm for ungrounded radial distribution systems
The Department of Electrical Engineering of the Myongji University has proposed a single phase-to-ground fault location algorithm for an ungrounded radial distribution system. This algorithm uses the voltage equation from the relay location to the fault location. Zero-sequence current, fault resistance and fault distance are the unknowns. The fault resistance is removed by extracting the components orthogonal to the zero-sequence current from the equation. Finally the fault distance can be calculated [13].

2.5.5 Application of Practical Criterion for Single-phase-ground Fault in Ungrounded Power System
The School of Automation and Electrical Engineering at Lanzhou Jiao Tong University, in China built an intelligent protection device. This element can identify the faulted phase in an ungrounded system rapidly and accurately according to the system structure and operating characteristics.
In this intelligent device, phase-to-ground voltage changes during pre-and-post fault condition in the ungrounded power system are used as criteria of searching for the faulted phase.

The intelligent protection device detects the circular changes in the three phase-to-ground voltages and zero-sequence voltage. If the zero-sequence voltage goes beyond the limits of the set value the device will determine the faulted phase [14].
Chapter 3

3 Analysing an ungrounded system using the ICAP

3.1 Introduction to ICAP software
The Intusoft Company provides IsSpice4 simulation software. This software is based on Berkeley SPICE 3F.2. SPICE 3F.2 was developed by the Department of Electrical Engineering and Computer Science at University of California, USA [15].

IsSpice4 simulation software is a simulation package designed to be user friendly and highly interactive. It can be used to explain power system operation to a non-technical audience. Therefore it is a better simulation tools for analysis of sinusoidal the sine waveforms of an ac power electrical distribution system than other simulation packages. This particular software tool will be used to analyses the single line to ground faults in the ungrounded power system networks used in this thesis project.

3.2 Simulating the ungrounded system using ICAP

3.2.1 Introduction the simulation diagram
The ICAP simulation diagram model for a one feeder ungrounded system is shown in Figure 7. There are three phases with a feeder each. V1, V2 and V3 are the voltage sources, generating 50Hz sine wave with phase angle shift of 0,120 and 240 respectively. The line resistances are represented by R1, R2 and R3. The line inductance are represented by L1, L2 and L3. The line capacitances are represented by C1, C2 and C3. The values for the transmission line parameters were taken from reference [13].

The Trigger switch is used to create a single line to ground fault. In this analysis line three is selected as phase A. The resister R4 (1MΩ) is used to overcome a simulation problem of using ungrounded voltage source. R4 is a very large resistance so that the system functions effectively as an ungrounded system.
The voltage source points V4, V5 and V6 are used as test points to measure zero-sequence current. The two components in the bottom of the diagram are used to calculate zero-sequence current and zero-sequence voltage from the system when the single line to ground fault is present in A-phase.

### 3.2.2 Required model Data

The line impedance use values given in Table 1

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>1.1028 Ω/km</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>3.8295 mH/km</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>0.0040 µF/km</td>
<td></td>
</tr>
</tbody>
</table>

**Table 1: Distribution line parameters (refer to [13], pp 506)**

![Diagram](image-url)

**Figure 7: Icap simulation diagram for a one kilometer ungrounded power system (feeder 1)**
3.3 Assumptions for simulation

- The single line to ground faults is not affected by the loads in an ungrounded power system. This is because the system loads are connected phase to phase. Therefore the loads are not included in this ICAP simulation.
- For this analysis the ground resistance is equal to zero.
- All transmission lines are the same type.

3.4 Approach-1

3.4.1 Procedure

3.4.1.1 Investigate the single line to ground fault effect

The system in Figure 7 was used to investigate the single line to ground fault behaviour in the system. The simulation is conducted and the wave form of the A-phase, B-phase and C-phase are recorded. Distribution line parameters shown in Table 1 are used in the simulation model. Figure 8 shows the outputs of the three phases.
3.5 Results (the single line to ground fault effect)

Volts

Figure 8: A-phase, B-phase and C-Phase waveforms after A-phase to ground fault in an ungrounded system

3.6 Result Analysis (the single line to ground fault effect)

The number (1-black), (2-blue) and (3-green) are A-phase, B-phase and C-phase simulation output waveforms respectively. The vertical line [1] represents the start of the ground fault event. It is clear that after the ground fault occurred, the A-phase voltage drops to zero. Also the B-phase and C-phase voltages are increased by the A-phase ground fault. The increase in the values is approximately equal to the $\sqrt{3}$ times the pre-fault voltages.

The simulation proves the case that the unfaulted phases can reach $\sqrt{3}$ times their normal magnitude. This characteristic of an ungrounded system can be used to identify the faulted phase.
3.7 Approach-2

3.7.1 Procedure

3.7.1.1 Investigate zero-sequence current and zero-sequence voltage

The ungrounded system model in Figure 7 is used to analyse the zero-sequence current and zero-sequence voltage of an ungrounded system. The simulation is conducted and the waveforms of the zero-sequence current and zero-sequence voltage are recorded. The Table 1 distribution line parameters are used for the simulation line models. Figure 9 shows the results of the simulation.

3.8 Results (zero-sequence current and zero-sequence voltage waveform)

Volts

![Figure 9: zero-sequence current and zero-sequence voltage waveform (A-phases to ground Fault)](image)

3.8.1 Introduction of the results

Black Waveform- Zero-sequence current (3Io)

Blue Waveform- Zero-sequence voltage (3Vo)

3.8.2 Results Analysis

According to the results in Figure 9, after the fault, zero-sequence current and zero-sequence voltage are created in the ungrounded system. Therefore, these zero-sequence components can be used to detect the single line to ground fault in an ungrounded system.
Chapter 4

Method

4 The Function of the Relay element

4.1 Introduction
The block diagram in Figure 10 shows the internal functions of the new relay. Phase voltages (Va,Vb,Vc) and line currents in each phases (Ia,Ib,Ic) feed in to the relay though an open delta transformer connection and current transformer. Then the function of the direction element begins. It measures the impedance (Vo/Io) value. If the measured impedance is above the forward threshold the fault is declared forward.

If the fault is in front of the relay then the direction element sends a signal to the phase selection element. The phase selection element detects the zero-sequence current and zero-sequence voltage extracted from the feeder. Then the phase selection element starts analysing the phase angle between zero-sequence current and positive sequence voltage(V1a) of the phase-A(source voltage of A-phase in used as reference).According to the phase different between the zero-sequence current and positive sequence voltage(V1a)of phase-A, the faulted phase can be determined.

After selecting the faulted phase the selection element and the directional element send signals to the AND gates. After receiving these two high inputs the AND gate gives a high output to the distance measuring element. Then the distance measuring element starts the operation that calculates the distance (km) from feeder to the fault point.

If the fault presents in front of the relay it detects the fault and gives an output of the faulted condition. The display unit represented in Figure 10 shows the output of the relay. From this display unit, the relay operator or any other authority is able to identify the faulted feeder, faulted phase and distance to the fault. They can disconnect only the faulted phase without disturbing other power supplies of the ungrounded system.

It is desirable to discuss the function of the each block of the system separately. The following sections discuss the functions of each function block.
Figure 10: Functional block diagram of advanced relay element

4.2 The Functional of the Blocks

4.2.1 Directional Element (faulted feeder detection)
The function of the directional element is to determine forward and reverse conditions of the fault. It functions according to the impedance-plane directional element characteristics as shown in Figure 11.
The phase voltages $V_a$, $V_b$ and $V_c$ are input to the relay from a broken delta voltage transformer. Phasor currents $I_a$, $I_b$ and $I_c$ are input to the relay from current transformer. Then the relay is able to measure the zero-sequence voltage and zero-sequence current according to the equations

$$V_o = \frac{1}{3} (V_a + V_b + V_c) \quad (13)$$

$$I_o = \frac{1}{3} (I_a + I_b + I_c) \quad (14)$$

The relay then calculates the impedance ($Vo/Io$). If this impedance value is above the forward threshold then the directional element identifies it as a forward fault. If the measured impedance value is above the reverse fault threshold then the directional element identifies it as a reverse fault [4].

Figure 11: Impedance-plane directional element characteristics [4]

The figure has been removed

Figure 12: Zero-sequence network for the forward ground fault [3]
XC_{OS} - zero-sequence capacitive reactance of the remaining system.

XC_{OL} - zero-sequence capacitive reactance of the protected line

Z_{OL} - zero-sequence line impedance

The Figure 11 shows the impedance-plane directional element characteristics. The Figure 12 shows the zero-sequence network for the forward ground fault.

According those two figures

➢ If the zero-sequence current lags zero-sequence voltage by 90 degrees and

\[ Z_O = \frac{V_o}{I_o} = +X_{COS} \]

then the relay interprets this as a forward fault

➢ If the zero-sequence current leads the zero-sequence voltage by 90 degrees and

\[ Z_O = \frac{V_o}{I_o} = -X_{COL} \]

then the relay interprets this as a reverse fault

If the directional element identifies the fault in front of the relay measuring point then these element sends a signal to the phase selection element to identify the faulted phase.

If a reverse fault is found the fault detection does not continue within this relay, as the fault could be in any other place within the ungrounded system [3].

4.2.2 Assumptions

➢ The zero-sequence impedance of an ungrounded system has a very high magnitude. Therefore the positive and negative sequence impedances can be neglected. There is no significant loss of accuracy in this calculation.

➢ It is assumed that \( XC_{OL} \gg Z_{OL} \) and then \( V_o = -jX_{COL}I_o \)

4.2.3 Phase Selection Element

After detecting the faulted feeder, the next step is to select the faulted phase. When selecting the faulted phase, the value of phase difference between positive sequence
voltage ($V_{1A}$) of A-phase (source voltage of A-phase is used as reference) and zero-sequence current need to be considered.

If the single line to ground fault is in front of the relay measuring point, the algorithm illustration in Figure 13 is used to select the faulted phase, (The A-phase is considered as the reference in calculating the value of the positive sequence voltage $V_1$.)

### 4.2.4 Assumptions
For this calculation, positive sequence and negative sequence impedances are negligible.

The figure has been removed

**Figure 13: Single line to ground faults in front of relay measuring point [1]**

In figure 13, $V_{1a}$ is the positive sequence voltage of the A-phase (A-phase source voltage as reference), and $I_0$ is the zero-sequence current.

The angle ($\theta$) is the phase difference between positive sequence voltage ($V_{1A}$) and zero-sequence current. When the angle ($\theta$) is between $-5^\circ$ and $95^\circ$ the relay identifies the A-phase as faulted. And also if the angle ($\theta$) is between $-25^\circ$ and $-125^\circ$ the relay identifies the B-Phase faulted. If the angle ($\theta$) is between $125^\circ$ and $145^\circ$ the relay identifies the C-Phase faulted.

After detecting the faulted feeder the phase selection element and feeder selection element send a signal to the distance measuring element.

### 4.2.5 The Distance Measuring Element
After receiving a signal from the phase selection element and the directional element, the fault distance measuring element starts its operation.

When presenting the single line to ground fault the magnitude of the zero-sequence current is used to measure the fault distance.
4.2.4.1 Relevant equation

Applying Kirchoff’s Current Law to the single line to ground fault sequence diagram, the ground fault algorithm can be written [13].

\[\sum_{k=0}^{2} V_k - d \sum_{k=0}^{2} Z_{lk} I_k - 3R_f I_{fo} = 0\]  \hspace{1cm} (15)

- \(V_k\)-relay voltage
- \(d\)-fault distance
- \(Z_{lk}\)-line impedance
- \(I_k\)-relay current
- \(R_f\)-fault resistance
- \(I_{fo}\)-zero-sequence fault current

4.2.4.2 Assumptions

The following assumptions are made for calculating the fault distance.

- The zero-sequence impedance of an ungrounded system has a very high magnitude. Therefore the positive and negative sequence impedances can be neglected. There is no significant loss of accuracy in this calculation.

- It is assumed that the fault resistance is equal to zero.

Therefore the equation can be written;

\[V_0 + V_1 + V_2 - dZ_{L0}I_0 = 0\]  \hspace{1cm} (16)

\[d = \frac{(V_o + V_1 + V_2)}{Z_{L0}I_o}\]  \hspace{1cm} (17)

where

- \(d\)-fault distance
- \(V_0\)-zero-sequence voltage
- \(V_1\)-positive sequence voltage
- \(V_2\)-Negative sequence voltage
- \(Z_{L0}\)-Line impedance in zero sequence(per unit length)
- \(I_0\)-Zero-sequence current
4.2.4.3 Sequence voltage calculation

The broken delta voltage connects to the relay $V_a$, $V_b$, and $V_c$, thus using these voltages, the relay can calculate the zero-sequence voltage, the negative sequence voltage and the positive sequence voltage as [6]:

$$V_o = \frac{1}{3} (V_a + V_b + V_c)$$  
(18)

$$V_1 = \frac{1}{3} (V_a + aV_b + a^2 V_c)$$  
(19)

$$V_2 = \frac{1}{3} (V_a + a^2V_b + aV_c)$$  
(20)

The zero-sequence line impedance per unit length can be written as [16]:

$$Z_{LO} = (R + j\omega L)$$  
(21)

4.2.4.4 Estimation of the fault distance

Substituting the zero-sequence current magnitude value, $V_o$, $V_1$, $V_2$ and $Z_{LO}$ to the equation (10), the fault distance can be estimated.

$$d = \frac{(V_o + V_1 + V_2)}{(R + j\omega L)I_o}$$  
(22)

**Verify the method using simulation**

According to equation (21), only the zero-sequence current will vary with distance to the fault. Therefore the equation can be written as follows

$$d = \frac{K}{I_o}$$  
(23)

d- fault distance
K-constant
$I_o$-zero-sequence current
Chapter 5

5 Simulation for detecting the faulted feeder

5.1 Feeder 1 A-phase to ground fault

The ICAP simulation diagram model is shown in Figure 14. There are three phases for each feeder. V1, V2 and V3 are the voltage sources. The line resistance is represented as by notation R; L signifies the line inductance. The notation C represents the line ground capacitance. The values for these transmission line elements were given in Table 1 of chapter 3.

The Trigger switch is used to create the single line to ground fault. In this analysis, line three is selected as the A-phase. The voltage points V4, V5 and V6 are used to measure the zero-sequence current from feeder one. The V8, V9 and V10 voltage points are used to measure the zero-sequence current from feeder two. V11, V12 and V13 are used to measure the zero-sequence current from feeder three. The 1MEG resistor is used to overcome simulation problem. The 1MEG is a very large resistance, therefore the system function runs effectively as an ungrounded system.
5.2 Assumptions

- The single lines to ground faults are not affected by the loads in an ungrounded power system. This is because the system loads are connected phase to phase. Therefore the loads are not included in this ICAP simulation.
- Fault resistance equal to zero.
5.3 Results (detection of the faulted feeder)

5.3.1 Introduction to the results

Feeder 1:

(1) Black line—zero-sequence current (3Io)
(2) Blue line—zero-sequence voltage (3Vo)

The zero-sequence current [3Io] lags the zero-sequence voltage [3Vo]

Feeder 2:

(3) Green line—zero-sequence current(3Io)
(4) Red line—zero-sequence voltage(3Vo)

The zero-sequence current [3Io] leads the zero-sequence voltage [3Vo]
Feeder 3:

(5) Black line–zero-sequence current (3Io)
(6) Blue line –zero-sequence voltage(3Vo)

The zero-sequence current [3Io] leads the zero-sequence voltage [3Vo]

5.3.2 General overview of the results
The zero-sequence voltage (3Vo) and zero-sequence current (3Io) waveforms are represented in Figure 15 when the A-phase to ground fault is present in feeder one. The vertical line [1] represents the start time of the single-line to ground fault event. After that time, the zero-sequence [3Vo] current and zero-sequence voltage [3Io] are created in each feeder. These two waveforms are sinusoidal.

5.3.3 Errors appear in the results
It can be observed the error in the zero-sequence current and zero-sequence voltage waveform. Prior to the fault the zero-sequence currents and voltages have a sinusoidal component where they should be zero.

Right after the fault occurs, the zero-sequence current (3Io) sinusoidal wave form has oscillations on each feeder current.

The oscillations can create in fault situation of the system.

5.3.4 Calculated data of the results
Table 2 shows, the angle difference between the zero-sequence current and zero-sequence voltage in the three feeders.

<table>
<thead>
<tr>
<th>Feeder</th>
<th>Angle deference 3Vo and 3Io</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Zero-sequence current lags zero-sequence voltage by 86.4 degrees</td>
</tr>
<tr>
<td>2</td>
<td>Zero-sequence current leads zero-sequence voltage by 89.2 degrees</td>
</tr>
<tr>
<td>3</td>
<td>Zero-sequence current leads zero-sequence voltage by 86.2 degrees</td>
</tr>
</tbody>
</table>

Table 2: Angle deferent zero-sequence current and zero-sequence voltage

Note: - Refer to Appendix A for calculations of the angle difference between zero-sequence current and zero-sequence voltage
### Table 3: impedance (Vo/Io)

<table>
<thead>
<tr>
<th>Feeder</th>
<th>(Vo/Io)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$+Z_{m1}j$</td>
</tr>
<tr>
<td>2</td>
<td>$-Z_{m2}j$</td>
</tr>
<tr>
<td>3</td>
<td>$-Z_{m3}j$</td>
</tr>
</tbody>
</table>

$Z_{m1}$-zero-sequence impedance at feeder 1

$Z_{m2}$- zero-sequence impedance at feeder 2

$Z_{m3}$- zero-sequence impedance at feeder 3

**Note:** - Please refer to the Appendix A for calculation

### 5.4 Analysis of Results

#### 5.4.1 General Analysis

- The zero-sequence current and zero-sequence voltage are generated in all three feeders after the A-phase to ground fault.
- In the faulted feeder, zero-sequence current lags the zero-sequence voltage by 90 degrees. In the other two feeders, the zero-sequence current leads the voltage by 90 degrees. Therefore using the above method a faulted feeder can be identified in an ungrounded power system.

#### 5.4.2 Analysis of the Directional element function

The Table 3 shows the ratio between Vo and Io (impedance). It can be observed that the faulted feeder (feeder 1) value is $Z_{m1}j$. According Figure 11, if the measured impedance is above the forward fault threshold then the fault is declared forward. (According to the directional element theory $Z_{m1}$ are equal to $XC_{OS}$).

For feeder 2 and feeder 3, the ratio between Vo and Io (impedance) are $-Z_{m2}j$ and $-Z_{m3}j$ respectively. According to Figure 4, the measured impedance is above the reverse fault threshold therefore the fault is declared reverse (According to the directional element theory $Z_{m2}$ and $Z_{m3}$ are equal to $XC_{OL}$).

It is clear that using the impedance-plane directional element, the faulted feeder can be identified.
5.4.3 Analysis of the errors in the result
According to results in Figure 15, zero-sequence current and zero-sequence voltage sinusoidal wave forms can be observed in the pre-faulted situation. In pre-faulted situation the system should operate as a balanced system. Zero-sequence current and zero-sequence voltage should not be generated in a balanced system, therefore it is clear that some errors in the simulation before A-phase to ground fault in feeder 1.

Right after the fault at feeder 1 the zero-sequence current (3Io) waveform has some oscillations due to the fault. The smooth zero-sequence current sinusoidal waveform can be observed after 120 milisecond.

In the figure 9, right after the fault at feeder 1 the zero-sequence current (3Io) and the zero-sequence voltage (3Vo) have some oscillations due to the fault.

However these errors are not large enough to affect the final results of identifying the faulted feeder. Therefore the above faulted feeder identifying method can be used in an ungrounded system.
Chapter 6

6 Simulation for Identifying the Faulted Phase

6.1 Simulation Procedure
The simulation diagram in Figure 16 (for line parameters, please refer to Table 1) is used for identifying the faulted phase in the system. First, the A-phase (line 3 in feeder1) positive sequence voltage ($V_{1A}$) (A-phase source voltage) is obtained. Then the Trigger switch is activated to create a ground fault with three phases, one at a time. The zero-sequence current waveform is recorded each time. The zero-sequence current waveform is obtained using elements V4, V5 and V6 in the simulation diagram. The angle between zero-sequence current and positive sequence voltage is checked with diagram in Figure 13 to find the faulted phase.

![Simulation Diagram](image)

Figure 16: Simulation diagram for identifying the faulted phase
6.1.1 Simulation Procedure (A-phase to ground fault in feeder1)
The ground fault activator is connected to the A-phase (line 3 in feeder1) to create a
ground fault. Then ICAP simulation is conducted and obtained the zero-sequence
current waveform is obtained. Then the phase difference between positive sequence
voltage \( (V_{1A}) \) and zero-sequence current is calculated. After the simulation, the result is
mapped onto Figure 13 to find the faulted phase.

For A-phase fault the angle difference should lie - between -5 degrees and 95 degrees

6.1.2 Simulation Procedure (B-phase to ground fault in feeder1)
The ground fault activator (Trigger switch) is connected to the B-phase (line 2 in the
circuit diagram) to create a ground fault. Then ICAP simulation is conducted and
obtained the zero-sequence current waveform. Then calculate the phase different
between positive sequence voltage \( (V_{1A}) \) and zero-sequence current. After that the result
is tested with Figure 13 to detect the faulted phase.

For B-phase fault the angle difference should lie-between -25 degrees and -125 degrees

6.1.3 Simulation Procedure(C-phase to ground fault in feeder1)
The ground fault activator (Trigger switch) is connected to the B-phase (line 3 in the
circuit diagram) to create a ground fault. Then ICAP simulation is conducted and
obtained the zero-sequence current waveform. Then calculate the phase different
between positive sequence voltage \( (V_{1A}) \) and zero-sequence current. After that the result
is checked with Figure 13 to detect the faulted phase.

C-phase fault sector: - between 125 degree and -145 degree

6.2 Assumptions

- The single lines to ground faults are not effected by the loads in an ungrounded
  power system. This is because the system loads are connected phase to phase.
  Therefore the loads are not included in this ICAP simulation.
- Fault resistance is equal to zero.
6.3 Simulation results (The faulted phase identification)

Volts

Figure 17: Resultant waveforms of phase selection analysis

6.3.1 Introduction of the results
The waveforms in the result can be represented as follows

[1] The Black waveform: - Positive sequence voltage (V_{1a})
[4] The Red waveform: - zero-sequence current waveform (the B-phase to ground fault)
[2] The Blue waveform: - zero-sequence current waveform (the C-phase to ground fault)

6.3.2 General overview of the results
The overview of the simulation results are represented in Figure 17. The vertical line [1] represents the fault position (The trigger switch activation point). The zero-sequence current generated after each and every phase fault.
6.4 Calculated results
Table 4 shows the calculated data of the angle between positive sequence voltage ($V_{1A}$) and zero-sequence current in each phase when the ground fault is present.

<table>
<thead>
<tr>
<th>Faulted Phase</th>
<th>$V_{1a}$ and $I_0$ angle difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-phase</td>
<td>+69.1 degrees (zero-sequence current lead $V_{1A}$ by 69.1 degrees)</td>
</tr>
<tr>
<td>B-phase</td>
<td>-59.1 degrees (zero-sequence current lag $V_{1A}$ by 59.1 degrees)</td>
</tr>
<tr>
<td>C-phase</td>
<td>-171 degrees (zero-sequence current lag $V_{1A}$ by 171.1 degrees)</td>
</tr>
</tbody>
</table>

Table 4: Angle different between $V_{1A}$ and zero-sequence current

In the table,

$V_{1A}$ is the positive sequence voltage (A-phase source voltage) which is used as reference

$I_0$ is the zero-sequence current when there is the A-phase to ground fault in feeder 1.

Note: For the Calculation of the angle difference please refer to Appendix B

6.5 Analysis of Simulation results (The Faulted Phase Identification)

6.5.1 General analysis
According to above results, all zero-sequence sinusoidal waveforms are created after the fault. The oscillation in the A-phase and C-phase zero-sequence current sinusoidal waveforms can be observed. The A-phase zero-sequence current waveform has a pure sine shape as expected.

6.5.2 Analysis the results with the relay element function
According to the results in Table 5, it is clear that when the single phase to ground fault is present, the angle differences between the zero-sequence current and positive sequence voltage (A-phase source voltage, $V_{1A}$) are in the expected detection range. This result has proved that the faulted phase can be identified by the phase selection method discussed in the section 4.2.
Chapter 7

7 Simulation for estimating the fault distance

7.1 Procedure

The circuit diagram in Figure 16 is used to validate the ground fault distance algorithm. The A-phase in the first feeder is considered for this analysis. The trigger switch is used to create single line to ground fault.

Step 1:

The simulation is conducted and zero-sequence current waveform is obtained then the magnitude of the zero-sequence current is calculated.

Step 2:

To check the different fault distances of the line, the resistor value, line inductor and line capacitance values are increased by the same amount and the zero-sequence current magnitude is captured for each value.

Step 3:

Magnitude of the zero-sequence current is substituted in to the equation 23 and the fault distance is calculated as the zero-sequence current varies with the fault distance

\[ d = \frac{(V_o + V_1 + V_2)}{(R + jwL)I_o} \]  \hspace{1cm} (23)

\[ K = \frac{(V_o + V_1 + V_2)}{(R + jwL)} \]  \hspace{1cm} (24)

\[ d = \frac{K}{I_o} \]  \hspace{1cm} (25)

- \( d \)- Fault distance
- \( K \)-constant
- \( I_o \)-zero-sequence current
7.2 Required Data

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>1.1028 Ω/km</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>3.8295 mH/km</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>0.0040 µF/km</td>
<td></td>
</tr>
</tbody>
</table>

Table 5: line parameters for simulation

7.3 The fault distance estimation result

<table>
<thead>
<tr>
<th>Distance in KM</th>
<th>Zero-sequence current Io</th>
</tr>
</thead>
<tbody>
<tr>
<td>1km</td>
<td>18.0014</td>
</tr>
<tr>
<td>50km</td>
<td>4.8958</td>
</tr>
<tr>
<td>80km</td>
<td>1.1138</td>
</tr>
</tbody>
</table>

Table 6: zero sequence current variation with the fault distance

Note: Please refer Appendix C for calculation

7.4 Analyse of the fault distance results

According to Table 6, the zero-sequence current decreases when the fault distance increases. Therefore the denominator of the equation 24 decreases when the fault distance increases. In this analysis the following recommendation can be made.

- Equation 23 can be used to calculate the fault distance
- In an ungrounded system, the fault value of the zero-sequence current depends on the fault distance.
Chapter 8

8 Analysis of the Fault resistance

8.1 Introduction to the fault resistance
The fault resistance analysis is important in an ungrounded power system. This is because the fault current depends upon the fault resistance and that requires the relay element to be set accordingly.

For this analysis the fault resistance is increased for an A-phase single-line-to-ground fault in front of the relay measuring point and the resulting characteristic is investigated.

➢ The fault resistance is increased and checked the angle between the zero-sequence current and the positive-sequence voltage (V1a) is measured.
8.2 Simulation procedure
The circuit diagram in Figure 18 is used for this analysis. The trigger switch is connected to a variable resistance (R13). The line parameters and voltage sources are the same as used in Figure 16. The angle difference between zero-sequence current and positive sequence voltage (A-phase sources voltage) is measured by changing the resistor values.

Figure 18: Simulation diagram for fault resistance analysis
8.3 Results of the fault resistance analysis

<table>
<thead>
<tr>
<th>Fault resistance value(Ω)</th>
<th>Phase difference(between $V_{a1}$ and zero-sequence current)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>57.60°</td>
</tr>
<tr>
<td>50</td>
<td>54.85°</td>
</tr>
<tr>
<td>100</td>
<td>37.35°</td>
</tr>
</tbody>
</table>

Table 7: fault resistance result

8.4 Analyse the results of the fault analysis

According to the above results it can be observed when the fault resistance increases, phase difference between positive sequence voltage (A-phase source voltage $V_{a1}$) and zero-sequence current decrease. Therefore this analysis is important for the faulted phasor selection element. It can be seem that the ground fault resistance is effect to the relay sensitivity of an ungrounded power system.
Chapter 9

9 Fault Detection sensitivity discussion

9.1 Imbalance of the system
The imbalance of the system is one of the main factors in setting fault detection sensitivity. The imbalance of the system is present because line-to-ground capacitance per phase is not always equal. This imbalance is applied to the system and all other equipment connected to the grid. The load dynamics can also affect the balance of the system. Therefore due to the imbalance of the power line and load the maximum sensitivity of the detection element is required [2].

9.2 The current transformer sensitivity
The current transformer used in the system for measuring zero-sequence current also impacts on the sensitivity of the fault detection relay. The higher the current ratio the lower the fault sensitivity and lower current ratio gives higher fault sensitivity. Therefore the current transformer should have the lowest error when operating in the linear region [2].

9.3 Ground sensitivity
The ground sensitivity depends on the type of soil on the ground. Experiments proved that different soils can have different fault resistance.

The fault sensitivity is different in areas with vegetation.

Different weather conditions leads to different fault resistances. Rain and thunderstorms cause varying single line to ground sensitivities [2].
Chapter 10

10 Conclusion

The Advanced Relay Element introduced in this thesis project is a very useful element. This is because it is able to identify the faulted feeder at faulted phase, and measure the fault distance. Previously, ungrounded fault detecting methods have limitations because of very small ground fault current. Therefore the advance relay element would be a good contribution to industry.

According to the results of this project, it is clear that analysing the zero-sequence current and zero-sequence voltage lead to good methods for detecting faults in an ungrounded system.

The faulted feeder identification results have proven that analysing the angle between the zero-sequence current and zero-sequence voltage is a good method for detecting faults. The result values are close to expected values.

An algorithm is used to identify the faulted phase and is more suitable method for identifying the faulted phase in an ungrounded system than traditional methods. The positive sequence voltage is a more reliable quantity to identify the fault. The simulation gives results very close to the expected values.

The analysis for calculating the fault distance was very successful. It proves that zero-sequence current changes with the fault distance and that this can be used to calculate the fault distance from the relay.

The fault resistance analysis is conducted to investigate the sensitivity of the relay element. It is observed that increasing in fault resistance decreases in the angle difference between the zero-sequence current and the positive-sequence voltage ($V_{1A}$).

The fault detection sensitivity is discussed to understand the practical use and limitations of the relay element.
10.1 Limitation of the relay element

In the phase selection algorithm there are gaps between each phase fault sector. If the phase different (between positive sequence voltage $V_{1a}$ and zero-sequence current) is within the gap it is harder to identify the faulted phase.

This system is more suitable for short distance between the fault and the relay. This is because zero-sequence current decreases with fault distance, which decrease relay sensitivity.

10.2 Future Recommendation

1) This relay can analyse only single line to ground faults. It can not detect other faults such as two phase to ground and three phases to ground. Therefore this relay can be used in conjunction with other fault detection systems. This relay will be able to identify the other ground faults.

2) Ground fault detection relays can be connected with other relays through a SCADA system. This system would be more useful to an operator in analysing the whole system from a central location.
References


[13] Soon-Ryul and San-Hee, Ground-fault location algorithm for ungrounded radial distribution system, Department of Electrical Engineering, Myongji University, South Korea, Original Paper, Code DOI 10.1007/s00202-006-0027-1


Appendices

Appendix A

Feeder identification

For this calculation to obtain clear data, the simulation is conducted for each feeder and measuring phase difference and of the zero-sequence voltage and zero-sequence current.

Feeder 1 (A-phase to ground fault in feeder 1)

![Figure 19: 3Io and 3Vo waveform at feeder 1(A-phase to ground fault in feeder 1)](image)

Frequency of the system is 50Hz

\[ T = \frac{1}{f} = \frac{1}{50} = 20ms \]

\[ \Delta_t = 4.952ms \]

\[ \theta = \frac{\Delta_t}{T} \times 360^\circ = \frac{4.762}{20} \times 360^\circ = 86.3^\circ \]

A-Phase to grounded fault Io lag \( V_o \) by 86.4\(^\circ\) degrees

\[ V_o = V_{m1} < \theta \]

\[ I_o = I_{m1} < 0 - 86.4^\circ \]
\[ \frac{V_o}{I_o} = \frac{V_{m1} \angle \theta}{I_{m1} \angle \theta - 86.4^\circ} \]

\[ \frac{V_o}{I_o} = \frac{V_{m1} \angle \theta - (\theta - 86.4^\circ)}{I_{m1}} \]

\[ \frac{V_o}{I_o} = Z_{m1} \angle (86.4^\circ \approx 90^\circ) \]

\[ \frac{V_o}{I_o} = Z_{m1} \angle 90^\circ \]

\[ \frac{V_o}{I_o} = +Z_{m1}j \]

Feeder 2(A-phase to ground fault in feeder 1)

Frequency of the system is 50Hz

\[ T = \frac{1}{f} = \frac{1}{50} = 20\text{ms} \]

\[ \Delta t = 4.952\text{ms} \]

\[ \Theta = \frac{\Delta t \times 360^\circ}{T} = \frac{4.952 \times 360^\circ}{20} = 89.2^\circ \]

A-Phase to grounded fault Io lead \( V_o \) by 89.2° degrees
\[ V_o = V_{m2} < 0 \]

\[ I_o = I_{m2} < 0 + 89.2^\circ \]

\[
\frac{V_o}{I_o} = \frac{V_{m2} \angle \theta}{I_{m2} \angle (\theta + 89.2^\circ)}
\]

\[
\frac{V_o}{I_o} = \frac{V_{m2} \angle \theta}{I_{m2}} \approx (\theta + 89.20^\circ)
\]

\[
\frac{V_o}{I_o} = Z_{m2} \angle (-89.20^\circ \approx -90^\circ)
\]

\[
\frac{V_o}{I_o} = Z_{m2} \angle -90^\circ
\]

\[
\frac{V_o}{I_o} = -Z_{m2} \angle 90^\circ
\]
Feeder 3 (A-phase to ground fault in feeder 1)

Figure 21: 3Io and 3Vo waveform at feeder 3 (A-phase to ground fault in feeder 1)

Frequency of the system is 50Hz

\[ T = \frac{1}{f} = \frac{1}{50} = 20\, ms \]

\[ \Delta_t = 4.79\, ms \]

\[ \Theta = \frac{\Delta_t}{T} \times 360^\circ = \frac{4.79}{20} \times 360^\circ = 86.22^\circ \]

A-Phase to grounded fault Io leads Vo by 86.22° degrees

\[ V_o = V_{m3} < 0 \]

\[ I_o = I_{m3} < 0 + 86.22^\circ \]

\[ \frac{V_o}{I_o} = \frac{V_{m3} \angle \theta}{I_{m3} \angle (\theta + 86.22^\circ)} \]

\[ \frac{V_o}{I_o} = \frac{V_{m3}}{I_{m3}} \angle \theta - (\theta + 86.22^\circ) \]

\[ \frac{V_o}{I_o} = Z_{m3} \angle (-86.22^\circ \approx -90^\circ) \]

\[ \frac{V_o}{I_o} = Z_{m3} \angle -90^\circ \]

\[ \frac{V_o}{I_o} = -Z_{m3} I \]
Appendix B
Phase selection results

A-phase to ground fault in feeder 1

Figure 22: resulting waveform zero-sequence current and V_{1a}

Frequency of the system is 50Hz

\[
T = \frac{1}{f} = \frac{1}{50} = 20ms
\]

\[
\Delta_t = 3.61905ms
\]

\[
\theta = \frac{\Delta_t}{T} \times 360^\circ = \frac{3.61905}{20} \times 360^\circ = 65.2^\circ
\]

A-Phase to grounded zero-sequence current lead V_{1A} by 65.2 degrees
B-phase to ground fault in feeder 1

Figure 23: resulting waveform zero-sequence current and V\textsubscript{1a}

Frequency = 50Hz

\[ T = \frac{1}{f} = \frac{1}{50} = 20ms \]

\[ \Delta t = 3.23810ms \]

\[ \Theta = \frac{\Delta t \times 360^\circ}{T} = \frac{3.23810 \times 360^\circ}{20} = 58.28^\circ \]

B-Phase - zero-sequence current lag V\textsubscript{1A} by 58.28 degrees
C-phase to ground fault in feeder 1

Figure 24: resulting waveform Io and V1a

Frequency of the system is 50Hz

\[ T = \frac{1}{f} = \frac{1}{50} = 20\text{ms} \]

\[ \Delta_t = 9.5238\text{ms} \]

\[ \theta = \frac{\Delta_t \times 360^\circ}{T} = \frac{9.5238 \times 360^\circ}{20} = 171.14^\circ \]

C-Phase - zero-sequence current lag V1a by 171.14 degrees
Appendix C

1. Results of the distance measuring element (1km length)

Figure 25: zero-sequence current waveform of fault distance measuring simulation

Amplitude = 36.0082/2 = 18.0014
2. Results of the distance measuring element (50km length)

Figure 26: zero-sequence current waveform of fault distance measuring simulation
Amplitude=9.79161/2=4.895805

3. Result of the distance measuring element (80km length)

Figure 27: zero-sequence current waveform of fault distance measuring simulation
Amplitude=2.227/2=1.1138
Distance measuring element system summary

<table>
<thead>
<tr>
<th>Distance in KM</th>
<th>Zero-sequence current measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1km</td>
<td>18.0014</td>
</tr>
<tr>
<td>50km</td>
<td>4.8958</td>
</tr>
<tr>
<td>80km</td>
<td>1.1138</td>
</tr>
</tbody>
</table>

Table 8: Distance measuring element results
Appendix D
Fault resistance calculation

\[ R(\text{fault resistance}) = 1 \Omega \]

Figure 28: Resulting waveform zero-sequence current and \( V_{1a} \) (for fault resistance simulation)

3.2381 = 57.6

\[ R = 50 \Omega \]

Figure 29: Resulting waveform zero-sequence current and \( V_{1a} \) (for fault resistance simulation)

3.04762 = 54.846

\[ R = 100 \Omega \]
Figure 30: Resulting waveform zero-sequence current and $V_{1a}$ (for fault resistance simulation)

2.0965 = 37.35

<table>
<thead>
<tr>
<th>Fault resistance value (Ω)</th>
<th>Phase difference (between $V_{a1}$ and $I_o$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>57.6°</td>
</tr>
<tr>
<td>50</td>
<td>54.846°</td>
</tr>
<tr>
<td>100</td>
<td>37.35°</td>
</tr>
</tbody>
</table>

Table 9: Phase difference (between $V_{a1}$ and zero-sequence current) vs fault resistance