



Faculty of Engineering and Technology
Joint Master in Electrical Engineering (JMEE)

***Adaptive Neutral Grounding of Power Transformers
Using Solid State Power Electronics***

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Abstract

In this thesis, a new grounding method is proposed depending on an adaptive power electronic circuit connected to the neutral point of the secondary windings in a distribution power transformer. During a transient earth fault, the new grounding method will inject the required neutral current to cancel the fault current and maintain a continuous electrical service for customers. For permanent earth faults and after finishing the fault cancellation period, the new grounding method will produce a determined earth fault current in different stages to enable secondary distribution circuit breakers to interrupt the fault and isolate the faulty section. If the fault doesn't vanish in an early stage, the system will proceed to the next stage and increase the earth fault current according to a preprogramed fault levels, that will force the upstream circuit breakers to trip and isolate the fault. By employing this method, a full current base discrimination of earth fault protection will be achieved in the same distribution voltage level. The proposed method and other traditional methods have been simulated using Matlab Simulink to verify the goals.

المستخلص

في هذه الرسالة، تم اقتراح طريقة جديدة لتأريض نقطة التعادل على الملفات الثانوية لمحولات الطاقة الكهربائية في نظام التوزيع. تعتمد هذه الطريقة على توصيل نقطة التعادل في المحول مع الارض من خلال دائرة الكترولونات القوى. عند حدوث قصر ارضي على شبكة التوزيع يعمل نظام التأريض المقترح على ضخ تيار معين في نقطة التعادل للمحول بحيث يؤدي الى الغاء تيار الخلل وبالتالي التمكن من الاستمرار في تغذية الخدمة للمشتركين حتى انتهاء هذا الخلل المرحلي. اما في حال استمرار الخلل، فان النظام ينتقل تلقائيا الى مرحلة اخرى وهي توليد تيار خلل معين يؤدي الى استجابة القواطع الالية الفرعية وفصل المقطع المعطوب. وفي حال كون الخلل الارضي غير انتقالي (دائم) يقوم النظام الجديد بزيادة تيار الخلل بناءا على قيم مبرمجة والتأكد من فصل القواطع الاقرب للمصدر وبالتالي يتم الحصول على الانتقائية المبنية على تيار القصر الارضي عند نفس جهد التوزيع. تم عمل محاكاة للنظام الجديد والانظمة التقليدية للتأريض باستخدام برنامج ماتلاب للتأكد من النتائج المتوقعة.

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List of Abbreviations:

| | |
|------|--------------------------------------|
| APC | Active Power Compensator |
| BFCL | Bridge Fault Current Limiter |
| VSI | Voltage Source Inverter |
| EHPC | Electromagnetic Hybrid Petersen Coil |
| FCL | Fault Current Limiter |
| IGBT | Insulated Gate Bipolar Transistor |
| MCR | Magnetically Controlled Reactor |
| MOV | Metal Oxide Varistor |
| MV | Medium Voltage |
| SCR | Silicon Controlled Rectifier |
| PLL | Phase Locked Loop |
| CB | Circuit Breaker |
| BF | Breaker Failure |

Chapter 1: Introduction

1.1 Introduction:

Various kinds of power transformer neutral grounding methods are used in distribution companies all over the world [1]. Solid, resistive, isolated and compensated grounding methods are commonly used in MV distribution systems [2]. There are many constraints to consider when selecting the earthing technique, which involves technical considerations (fault currents, overvoltage, discrimination,...etc.), continuity of supply, safety issues, capital and running costs, experience [3], [4]. Besides, there are several goals for grounding the neutral point of a power transformer such as: limiting the influence of overvoltages caused by lightning, stabilizing the voltage under normal operating conditions which maintains the voltage at one level relative to ground. Thus, any equipment connected to the system will be subject only to that potential difference, and facilitating the operation of overcurrent devices, such as fuses, circuit breakers, or relays under a ground fault condition. Ground faults statistically makeup 95% of all faults on electrical systems [5]. The most common type of ground faults is of the arcing type. Neutral system grounding is the single most effective method of controlling system upsets, personnel and component hazards associated with ground faults [5]. When selecting a grounding method, one should focus on the following aspects:

- Limiting voltage sags
- Limiting destructive fault energy levels
- Protection discrimination
- Facilitating protective devices operation
- Personnel and equipment safety
- Continuity of supply

The traditional neutral grounding methods have many advantages and drawbacks. With the revolution of power electronics technology, the various advantages of traditional methods can be

achieved with limited drawbacks. In this thesis, a new adaptive grounding method, based on solid state devices, will be introduced to achieve a better system performance during transient and permanent ground fault. The proposed system will be simulated on a model of a real medium voltage network to demonstrate the achievement of the required goals.

1.2 Problem Statement:

The adaptive neutral grounding method of power transformers significantly contributes to medium voltage distribution reliability by cancellation of transient earth fault occurring in overhead transmission line networks and provides the required minimum fault current for permanent earth faults, which fits to the protective functions and settings already installed in the distribution system. To achieve that, employment of power switching devices is required to perform a variable virtual impedance that provides the required fault current stages according to protection devices settings.

1.3 Objectives:

The main objectives and expected outcomes of the thesis are:

- 1) To reduce the medium voltage supply interruption and to increase the system's continuity of service by cancelation of transient earth faults occurring in the overhead distribution networks
- 2) To provide relatively low ground fault currents for permanent earth faults that fit the protective relays' settings and do not harm the distribution system components
- 3) To reduce the voltage sags occurring in the healthy feeders due to earth faults on other feeders
- 4) To facilitate the protection discrimination in the medium voltage distribution networks using the time base discrimination
- 5) To model an adaptive transformer neutral grounding method employing solid state switches to achieve the required fault current behavior, that fits the protection settings and does not harm the distribution system components

1.4 Thesis Layout:

This thesis is organized in eight chapters. Chapter 2 provides a through literature review about grounding systems. Chapter 3 presents simulation of faults in traditional grounding systems. Chapter 4 presents theory of single line to ground faults and subsequent equivalent circuits and fault current equations. In Chapter 5, two types of single-phase full bridge voltage source inverter are described where bipolar sinusoidal pulse width modulation is used for the first type and unipolar SPWM is used for the second. The proposed grounding system is presented in chapter 6 with relevant flow charts and block diagrams that describes the system performance and requirements. In chapter 7, the simulation of new grounding system is presented. The Simulink model is described and the required results and waveforms is presented and analyzed. In chapter 8, conclusions are drawn and future work is suggested.

Chapter 2: Literature Review

2.1 Traditional Grounding Systems Overview:

In medium voltage distribution systems, a power transformer neutral grounding technique has a great influence on system protection scheme and reliability. There are four traditional methods of a transformer neutral grounding; solid grounding method, resistive grounding method, isolated neutral grounding method and compensated grounding method.

2.1.1 Solid Grounding Method:

In solid grounding method, shown in Figure 2.1, the neutral point of transformer secondary winding is connected directly to ground. This will result in high single phase to ground fault currents. Consequently, simple protective functions can be used to disconnect the feeder at which earth fault occurs. This system is considered ideal for cancelling overvoltages. Also, equipment with line to neutral rated insulation can be used [6]. There are several disadvantages of this system such as: damaging of system components due to high fault currents, discontinuity of service for the faulty feeder, and risk of personnel electric shock due to high touch and step voltages during earth faults (on humans present near the electric poles) [7].

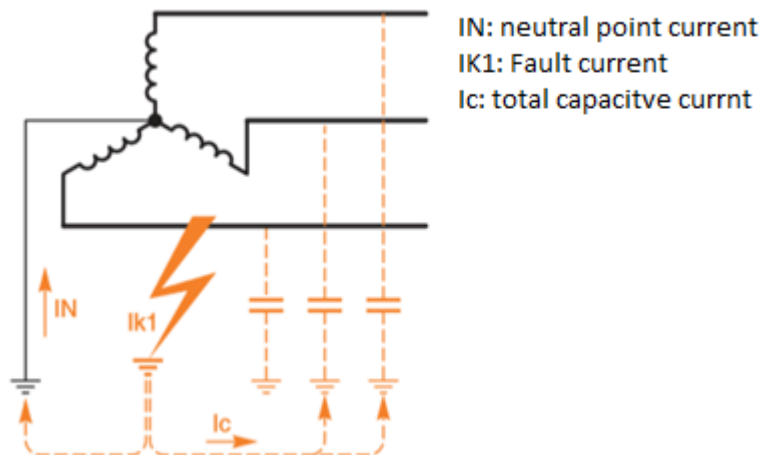


Figure 2. 1 Earth fault in solidly grounded system [8]

2.1.2 Resistive Grounding Method:

In resistive grounding method, a resistive impedance is connected between the neutral point and the ground to limit the earth fault currents [9]. In this system, the first earth fault must be automatically cleared by the protective functions. In this method, the higher the voltage and the current limits are, the higher the cost is, which represents drawbacks of the system.

2.1.3 Isolated Neutral Grounding Method:

In the Isolated Neutral Grounding method, the single phase to ground fault produces a low capacitive current flowing through the capacitance between the phases and the ground as shown in Figure 2.2.

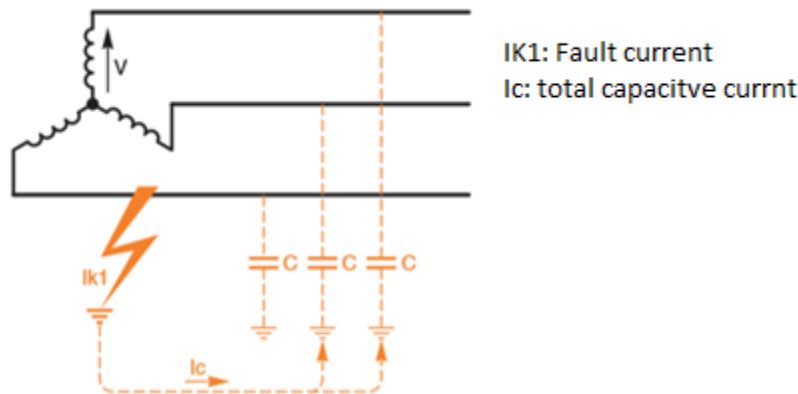


Figure 2. 2 Earth fault in isolated system [8]

One of the main advantages of this system is the continuity of supply during the first earth fault due to low fault current. However, the system doesn't eliminate overvoltage due to the floating neutral point. Also, advanced earth fault protective functions must be used for earth fault detection and isolation, rather than simple functions used in other methods [10].

2.1.4 Compensated Grounding Method:

In a compensated grounding system, shown in Figure 2.3, a reactor is connected between the neutral point and the ground. The inductance of the reactor is tuned to the total phase to earth capacitance of the distribution system, resulting in almost a zero fault current, which eliminates the transient earth faults occurring in the system, without the need of disconnecting the faulty

feeder [11], [12]. Since the fault current is very low, advanced earth fault protective functions should be used to isolate the faulty feeder, and achieve discrimination [13].

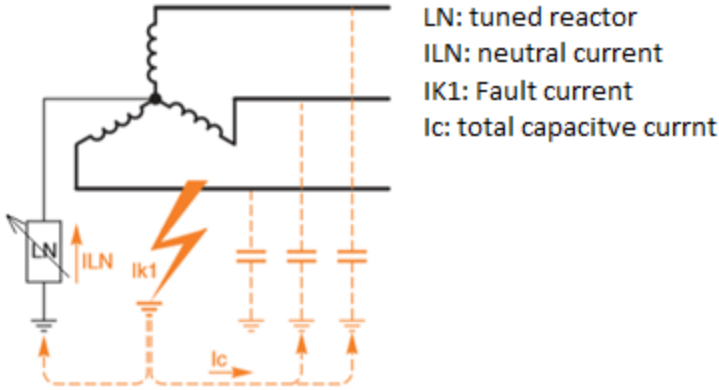


Figure 2. 3 Earth fault in compensated grounding system [8]

In this thesis, an Adaptive Grounding system employing solid state switching devices will be proposed, modeled and simulated. The idea is to merge between the advantages of different classical grounding methods, especially elimination of transient earth faults occurring in the power system and activating the already installed simple earth fault protective relays. This can be achieved by controlling the earth fault current using the solid state switching devices in a pre-set form compatible with the protection criteria of the upstream and downstream protective relays. The proposed earthing system is illustrated in Figure 2.4.

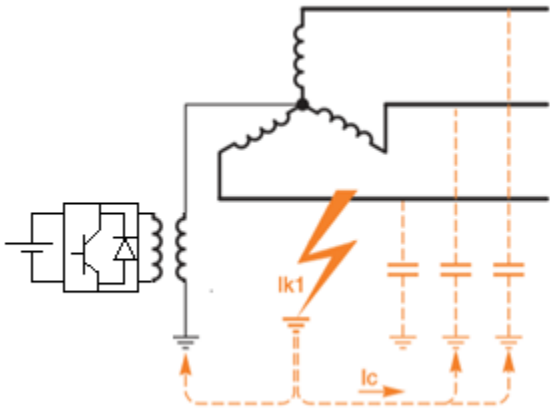


Figure 2. 4 Earth fault in adaptive grounded system

The traditional Grounding methods advantages and drawbacks can be summarized in the table 2.1.

table 2. 1 List of advantages and drawbacks of traditional grounding methods

| Grounding Method | Advantages | Drawbacks |
|----------------------------|--|--|
| Solid Grounding | <ul style="list-style-type: none"> - Damping of transient overvoltages - Simple protection functions | <ul style="list-style-type: none"> - High earth fault currents - Less service continuity - Less personal safety |
| Resistive Grounding | <ul style="list-style-type: none"> - Low detectable earth fault currents - Simple protection functions | <ul style="list-style-type: none"> - Less service continuity - Cost and maintenance of earthing resistance |
| Isolated Neutral Grounding | <ul style="list-style-type: none"> - More service continuity | <ul style="list-style-type: none"> - Failure to eliminate transient overvoltages - Complex protection functions |
| Compensated Grounding | <ul style="list-style-type: none"> - Elimination of transient faults - More continuity of service | <ul style="list-style-type: none"> - Failure to eliminate transient overvoltages - Complex protection functions - Cost and maintenance of Petersen coil |

2.2 Topologies of Fault Current Limiter and Earth Fault Current Control:

Many researches proposed various topologies for fault current limitation using solid state switching devices [14], [15], [16]. The idea of the Fault Current Limiter (FCL) is to limit the fault current in the feeder to a maximum allowed value in order to prevent damaging of system components [17], [18], [19].

- A Bridge Fault Current Limiter (BFCL) topology introduced in [20]. This BFCL contains several parts: Full bridge rectifier, two IGBTs, two limiting resistors, an inductor and Metal Oxide Varistor (MOV), as shown in Figure 2.5

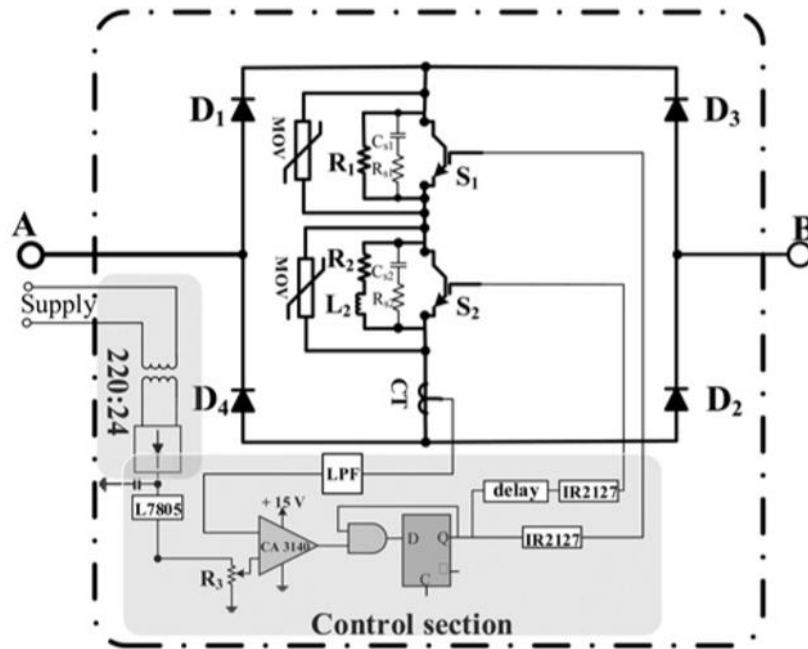


Figure 2. 5 Bridge Fault Current Limiter [15]

The points A and B shown in Figure 2.5 are connected in series with the power line. When a fault occurs, the BFCL operates in two steps. Normally the two switches S_1 and S_2 are closed. At the moment of a fault occurrence, switch S_1 opened inserting a low resistance in the fault path. Thus, the fault current will be high enough to be detected by simple protective relays. After the fault detection, the second stage of limiting of fault current begins by opening switch S_2 , and hence inserting a higher impedance R_2+jX_2 which dramatically limits the current, as shown in Figure 2.6. In Figure 2.6, the BFCL is connected in series with the power line. R_f and L_f represent the fault impedance. The main drawback of this method is the high conduction losses since the four switches are on at any time.

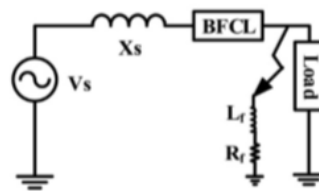


Figure 2. 6 Circuit for analysis of BFCL [15]

- A Single-phase SCR- Based Bridge type FCL introduced in [21] is shown in Figure 2.7. This FCL consists of a rectifier bridge, a DC limiting reactor (L_1) and a by-pass reactor (L_2). In normal

conditions, the switches are ON and the equivalent impedance of the FCL is very low. When a fault occurs, the DC reactor limits the increment speed of the fault current, then the switches are turned OFF and so the DC inductor exits from the circuit and the fault current is limited by the bypass inductor (L_2). Besides the conduction losses in this type, the SCR response time is long.

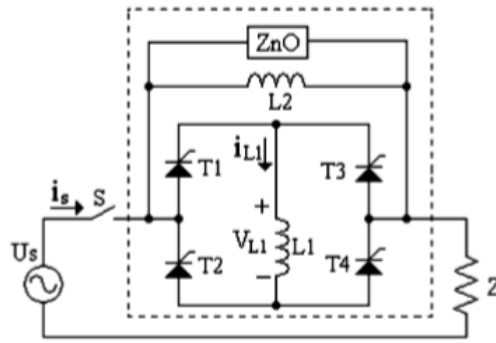


Figure 2. 7 Single phase SCR based bridge FCL [21]

- A Variable Impedance Controlled circuit is shown in Figure 2.8. The neutral and ground points are connected to the diode bridge points A and B. and the equivalent impedance can be controlled by changing the duty cycle of the gating signal of switch T_r .

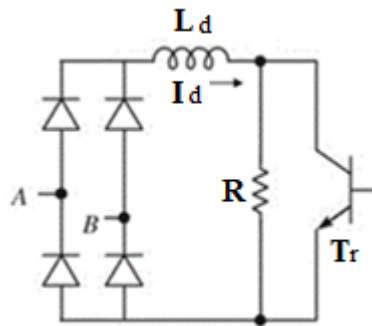


Figure 2. 8 A variable impedance neutral grounding

- An active inverter can be used to inject a zero-sequence current into a system's neutral point, to control zero-sequence voltage flexibly and finally to make the recovery voltage of faulty phase equal to zero, which indicates that the ground-fault current decreases to zero [22].

- A flexible neutral grounding method based on an Electromagnetic Hybrid Petersen Coil (EHPC), which consists of a Magnetically Controlled Reactor (MCR) and an Active Power Compensator (APC) is proposed in [23]. MCR is a controllable reactor, the reactance of which can be adjusted

continuously by adjusting a DC exciting current [24], [25]. Furthermore, APC can be equivalent to a negative resistance connected in parallel and a negative harmonic impedance. The proposed system is shown in Figure 2.9.

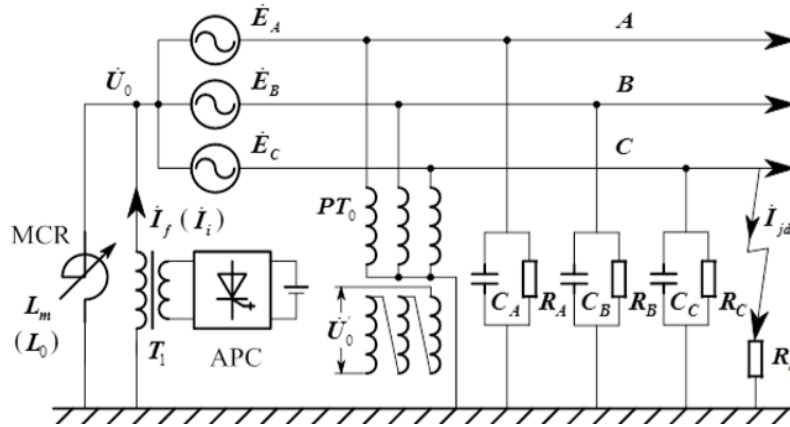


Figure 2. 9 Circuit configuration of an electromagnetic hybrid Petersen Coil flexible grounding system when a single line-to-earth fault occurs [23]

When a power system operates normally, its neutral point grounds through MCR, running in a no-load state, and the EHPC measures the insulation parameters of the system and presets open-loop control parameters. When a single line-to-earth fault occurs, the system's neutral point grounds via the equivalent impedance of EHPC. The EHPC takes first open-loop and then closed-loop control strategy to suppress the recovery voltage of faulty phase and to compensate all the ground-fault current instantly. To shorten the arc suppression time and to improve the compensating characteristics of EHPC, a complex control method of neutral-to-earth impedance based on neutral point displacement voltage and compensating method for the harmonic component of the ground-fault current is used [23]. The control system required for the MCR to adjust the DC exciting current is very complicated and the MCR for a medium voltage power transformer is expensive.

- In [26] an active ground-fault arc suppression device for full compensation of ground current was used. The fault current can be cancelled by producing an output voltage from the inverter which equals $-U_x$. Where U_x is the phase to neutral voltage of the faulty phase. The system is illustrated in Figure. A drawback of this grounding system is that there is no control of the fault current but the control is dedicated for cancellation of the fault current only.

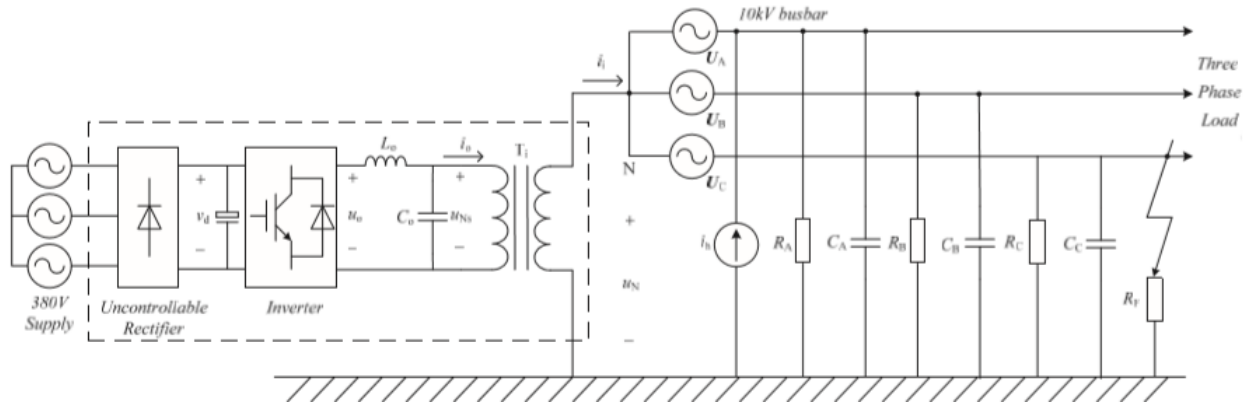


Figure 2. 10 Topology of the distribution network with the arc suppression device [26]

In the Adaptive neutral grounding method, proposed in this thesis, instead of limiting the fault current, the current injected through the neutral must equal the capacitive fault current during the instant of fault occurrence in order to eliminate the transient faults and then the total fault current should be increased to a value that is predictable by simple earth fault protective relays installed in the distribution network.

2.3 Faulty Feeder Identification

Depending on the type of transformer neutral grounding, the identification methods of the faulty feeder varies [27]. In systems with relatively high earth fault currents like solid and resistive grounding, the identification of ground fault in the feeder can be directly decided by measuring the residual current. While due to the low earth fault current in isolated and compensated systems, detecting the faulty feeder becomes more complex [28]. Many methods are proposed by researchers to detect the faulty feeder in the case of Petersen or isolated neutral grounding; these methods can be classified into two main categories; steady state detection method and transient state detection method [29].

2.3.1 Steady State Detection Method:

The method depends on the residual voltage and current readings during the steady state, and contains of the following:

2.3.1.1 Residual Incremental Method:

The method uses the residual current component variation based on changing the compensation level by controlling the arc suppression coil size. The healthy feeder will not encounter any changes with respect to coil size variation, unlike the faulty feeder which will have changes in the residual current value and phase. This method doesn't work with isolated systems [30].

2.3.1.2 Injection Method:

In this method a current signal with a frequency between n and $n+1$ times the rated frequency of the line is injected by an instrument to the earth fault path. The signal can be detected and traced in the faulty feeder and so it can be identified. The capacity of the voltage transformer limits the intensity of the injected current and if the system has a large grounding impedance value, the result accuracy will be decreased due to the capacitance of lines [31].

2.3.1.3 Comparing Amplitude and Phase of Zero Sequence Current Method:

In this method the zero sequence components of the feeders are compared to each other. The one that has opposite direction represents the faulty feeder. The draw backs of this method are the complexity of application and the mis operation in the case of short circuits.

2.3.1.4 Harmonic Method:

In a system with Petersen coil grounding, the zero-sequence current has a lot of harmonics especially the fifth component [32]. The coil suppresses the zero-sequence current and has a high effect on it unlike the fifth harmonic component, so the method compares the fifth harmonic in the residual current of different feeders and the one that opposes the other has the earth fault.

2.3.2 Transient State Detection Methods:

The method depends on the momentary readings of currents and voltages. The most common method of this type is the wavelet method.

2.3.2.1 Wavelet Method:

The wavelet analysis has a good multi solution features in the time and frequency domain of the signal [33]. The wavelet transformation of residual current can localize the fault through

determination of amplitude and phase of the signal in addition to the relationship of frequency content and time domain.

2.3.2.2 First Half Wave Method:

The basic assumption of this method is that the single line to ground fault occurs at the maximum of fault phase voltage [34]. It considers that the capacitance of faulty phase discharges through the transmission line into the fault point. The first half wave of faulty line short circuit current has opposite direction with reference to healthy lines. The method requires high data sampling rates and it is highly influenced by transmission line parameters and fault initial angle

2.3.2.3 Transient Energy of Zero Sequence Current Method:

The amplitude of the transient energy in the faulty feeder is the biggest and the polarity is reversed compared with other feeders. The faulty feeder can be localized based on this method principal but the drawback transient energy of zero sequence current is a poor proportion of active component in transient current.

Chapter 3: Single Line to Earth Fault Analysis

In order to calculate the earth fault current, it is necessary to derive a relationship between voltages and currents in the three phases according to fault condition, then the symmetrical component method is applied to calculate the fault current and determine the interconnection between the different sequence networks to satisfy this condition. A simple single line to earth fault in distribution system is depicted in Figure 3.1.

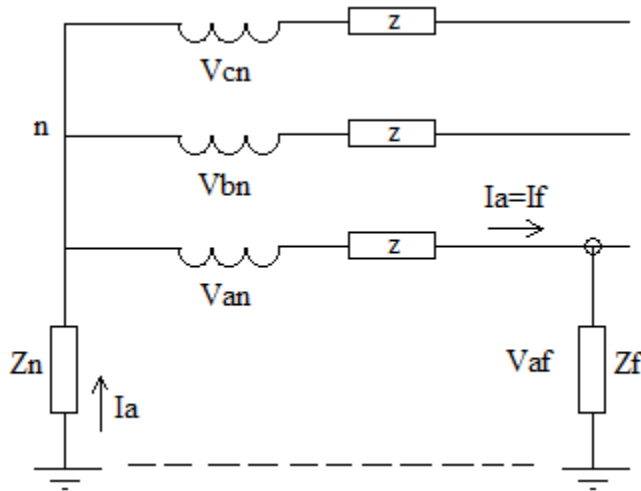


Figure 3. 1 Single Line to Earth Fault in Distribution System

Referring to Figure 3.1, it can be shown that:

$$V_{af} = Z_f I_a, \dots\dots\dots (3.1)$$

$$I_b = 0, \dots\dots\dots (3.2)$$

$$I_c = 0, \dots\dots\dots (3.3)$$

Using the symmetrical components representation, equations (3.1 – 3.3) can be rewritten as;

$$V_{a1} + V_{a2} + V_{a0} = Z_f (I_{a1} + I_{a2} + I_{a0}) \dots\dots\dots (3.4)$$

$$a^2 I_{a1} + a I_{a2} + I_{a0} = 0, \dots\dots\dots (3.5)$$

$$a I_{a1} + a^2 I_{a2} + I_{a0} = 0, \dots\dots\dots (3.6)$$

where, V_{a1} , V_{a2} , and V_{a0} are the positive, negative and zero sequence components of the voltage of phase a. and I_{a1} , I_{a2} , and I_{a0} are the positive, negative and zero sequence components of the fault current.

subtracting equation 3.6 from equation 3.5 gives;

$$(a^2-a) I_{a1} + (a-a^2) I_{a2} = 0, \Rightarrow I_{a1} = I_{a2}$$

Substituting in equation 3.5 yields,

$$(a^2-a) I_{a1} + I_{a0} = 0, \Rightarrow I_{a1} = I_{a0}$$

So,

$$I_{a1} = I_{a2} = I_{a0} = I_a/3 \dots\dots\dots(3.7)$$

Equation 3.4 can be replaced by

$$[V_{an} - I_{a1}Z_1] + [-I_{a2}Z_2] + [-I_{a0}(Z_0 + 3Z_N)] = 3Z_f I_{a1},$$

$$V_{an} = I_{a1}(Z_1 + Z_2 + Z_0 + 3Z_N + 3Z_f),$$

and

$$I_f = I_a = 3I_{a1} = \frac{3V_n}{Z_1 + Z_2 + Z_0 + 3Z_N + 3Z_f} \dots\dots\dots(3.8)$$

where, $V_{an} = V_{bn} = V_{cn} = V_n$ (balanced system).

Equations 3.7 and 3.8 can be represented as an interconnection between three sequence networks as shown in Figure 3.2.

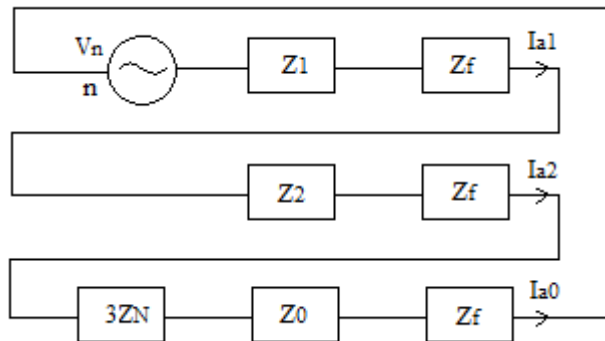


Figure 3. 2 Three Sequence Network

It is shown that, the earth fault current depends on the type of earthing system and the neutral impedance. For a solidly grounding system this value will be zero, whilst for an isolated system, this value will be infinite. The fault current is also affected by the value of the network impedance between healthy phases and the ground, as depicted in Figure 3.3.

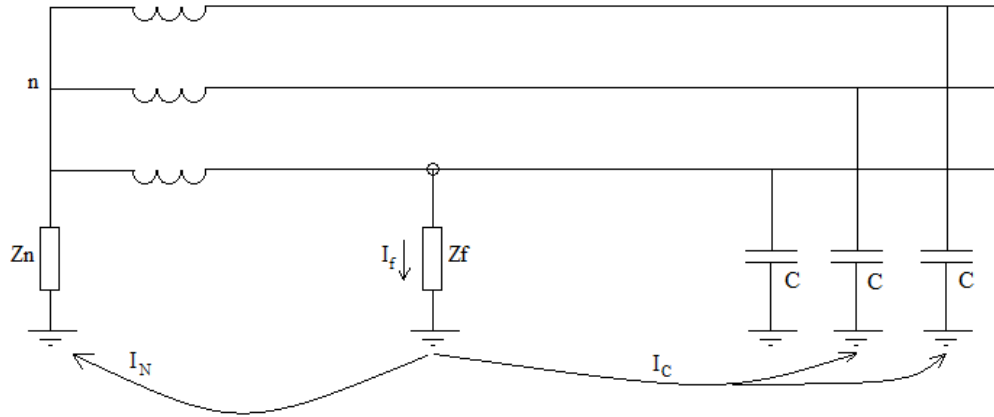


Figure 3.3 Earth Fault Current Path

Therefore, the fault current has two components; one passes through the neutral point of the secondary circuit of the transformer I_N , and the other passes through the capacitance of healthy phases I_c . That is:

$$I_F = I_N + I_c$$

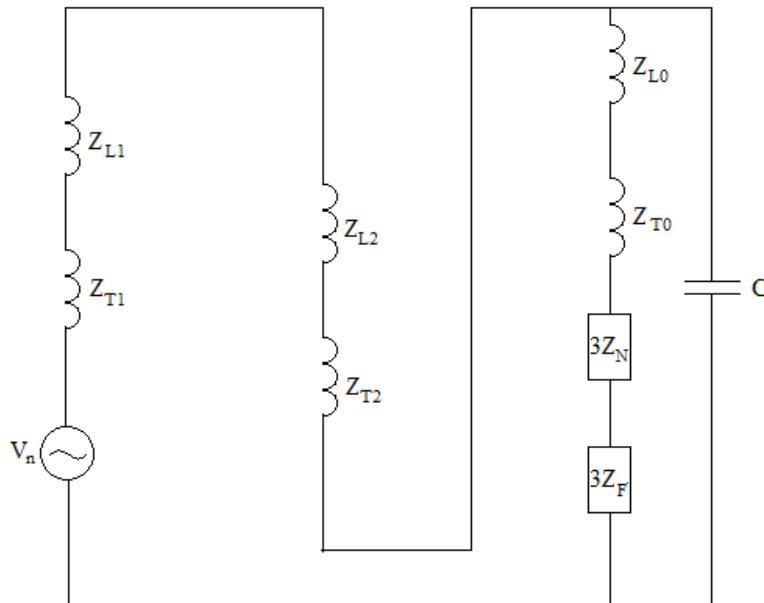


Figure 3.4 Sequence Network representation of an earth fault

The sequence network can be represented as shown in Figure 3.4.

Positive sequence impedance $Z_1 = Z_{L1} + Z_{T1}$

Negative sequence impedance $Z_2 = Z_{L2} + Z_{T2}$

Zero sequence impedance $Z_0 = (Z_{L0} + Z_{T0} + 3Z_N + 3Z_F) \parallel Z_C$

Let $Z_{net0} = (Z_{L0} + Z_{T0} + 3Z_N + 3Z_F) \rightarrow Z_0 = Z_{net0} \parallel Z_C = \frac{Z_{net0} \frac{1}{j\omega C}}{Z_{net0} + \frac{1}{j\omega C}} = \frac{1}{\frac{1}{Z_{net0}} + j\omega C}$.

where,

Z_{Li} : line impedance of sequence i, where i takes the values of 0,1 and 2

Z_{Ti} : transformer impedance of sequence i, where i takes the values of 0,1 and 2

Z_C : healthy phases zero sequence capacitive reactance

Z_{net0} : sum of zero sequence impedances

C: healthy phases zero sequence capacitance

So, the fault current can be represented as:

$$I_f = \frac{3V_n}{Z_1 + Z_2 + Z_0} , \text{ since } Z_1 = Z_2 \text{ hence, } I_f = \frac{3V_n}{2Z_1 + Z_0}$$

If the neutral is grounded using Z_N , normally its value is much higher than the value of Z_1 . Therefore, the value of $2Z_1$ can be neglected compared to Z_0 and the fault current becomes:

$$I_f = \frac{3V_n}{Z_0}$$

Depending on the fault current equation, the effect of normal neutral grounding techniques on the earth fault current can be illustrated as follows:

- For an isolated system (i.e. Z_N is very high),

$$Z_0 = 1/j\omega C$$

Thus,

$$I_f = 3j\omega C V_n$$

- If $Z_N \gg (Z_{net0} - Z_N)$, then the zero sequence impedance and fault current are given by:

$$Z_0 = \frac{1}{\frac{1}{3Z_n} + j\omega C}$$

$$I_f = 3V_n \left[\frac{1}{3Z_n} + j\omega C \right] = \frac{V_n}{Z_n} + 3j\omega C V_n = I_n + I_C \dots\dots\dots(3.9)$$

where,

$$I_n = \frac{V_n}{Z_n}$$

$$I_c = 3j\omega CV_n$$

If Z_n is an inductor with inductance L_n , the fault current value is:

$$I_f = V_n \left[\frac{1}{j\omega L_n} + 3j\omega C \right] = V_n \left[3j\omega C - j \frac{1}{\omega L_n} \right]$$

If $3\omega C = \frac{1}{j\omega L_n}$ then the earth fault current value will be zero, and that is the case of Peterson coil grounding in which a variable inductor is used between neutral point and earth to limit the earth fault current to zero.

For a solid grounding, the value of $Z_n=0$, and the other components of the zero-sequence impedance are not negligible. The earth fault current can be represented as:

$$I_f = \frac{3V_n}{2Z_1 + Z_{net0}} = \frac{3V_n}{2Z_1 + Z_{L0} + Z_{T0} + 3Z_f}$$

where the capacitive fault current is neglected.

If $Z_{L0} + Z_{T0}$ is close to Z_1 which is the case of DY transformer, then:

$$I_f = \frac{3V_n}{3Z_1 + 3Z_f} = \frac{V_n}{Z_1 + Z_f} \dots\dots\dots (3.10)$$

It is shown from equation 3.10 that, the earth fault current in the case of solid grounding is very high and close to three phase short circuit.

In the case of medium voltage distribution, the power transformer's secondary circuit is connected to several outgoing feeders as shown in Figure 3.5. A residual current measuring device is installed at each feeder. The residual current must be accurately measured on each feeder in order to determine the faulty one.

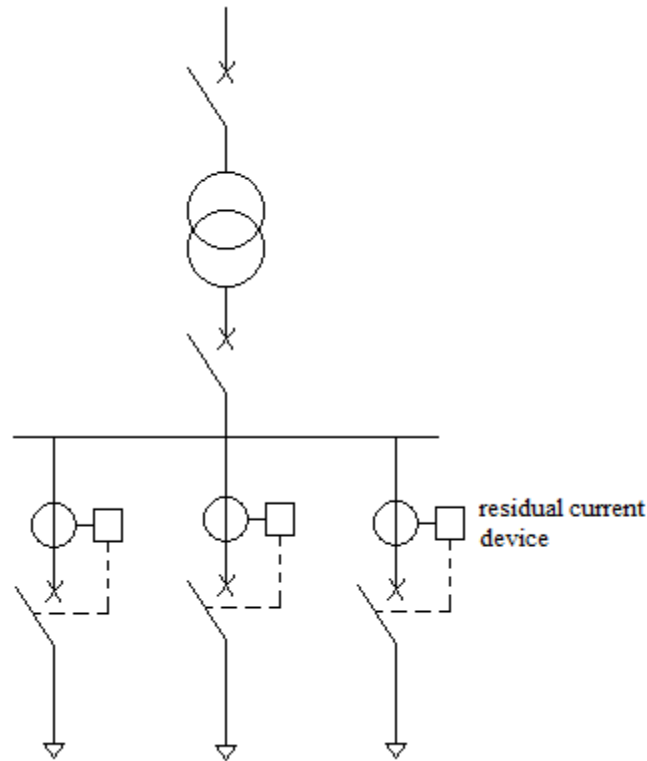


Figure 3. 5 Single Line Diagram (SLD) for medium voltage Substation

Assuming a single line to earth fault on feeder 1. The current measured by residual devices represents the capacitive current flowing to earth through capacitance. Figure 3.6 shows the three-phase diagram of this case.

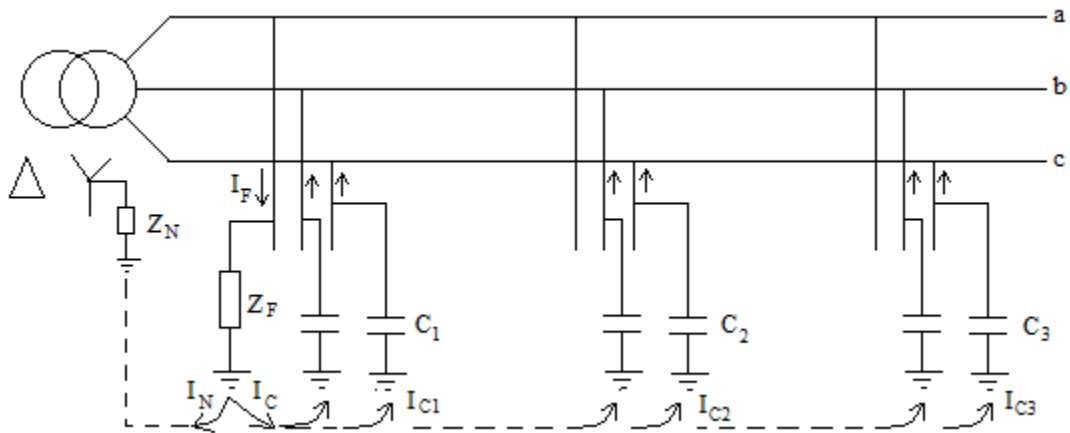


Figure 3. 6 Earth Fault current components

Because phase “a” is short circuited to ground, no current will flow in this phase for all feeders. The fault current will be divided into two parts. One flows through the earthing impedance and

the other one flows through the capacitance of all feeders. Applying equation 3.9 by substituting C as the equivalent phase capacitance for all network yields,

$$I_f = \frac{V_n}{Z_N} + 3j\omega CV_n$$

where,

$C = C_1 + C_2 + C_3$ and C_1 is the capacitance per phase of faulty feeder

The residual current will be measured by residual current devices installed at the beginning of each feeder. The current measured by a residual device for the faulty feeder equals the vectorial summation of the fault current and the capacitive current in the healthy phases (in this case phase b and c).

$$I_{res1} = \frac{V_N}{Z_N} + 3j\omega(C - C_f)V_n$$

On the other hand, the residual current devices on the healthy feeders will detect the following current:

$$I_{res2,3} = 3j\omega C_i V_n, i = 2,3$$

Since all residual devices on the outgoing feeder will detect a residual current at the time of earth fault, the protection settings' threshold should be carefully calibrated to distinguish the faulty feeder and avoid tripping of healthy ones.

Chapter 4: Proposed Grounding System Design

4.1 Full Bridge VSI:

The topology of single-phase voltage source inverter is shown in Figure 4.1. For the switches shown in the VSI topology, it should be noticed that two switches in the same leg can't be switched ON at the same time because the DC link will be short circuited. The switches could have 4 defined states as shown in table 4.1

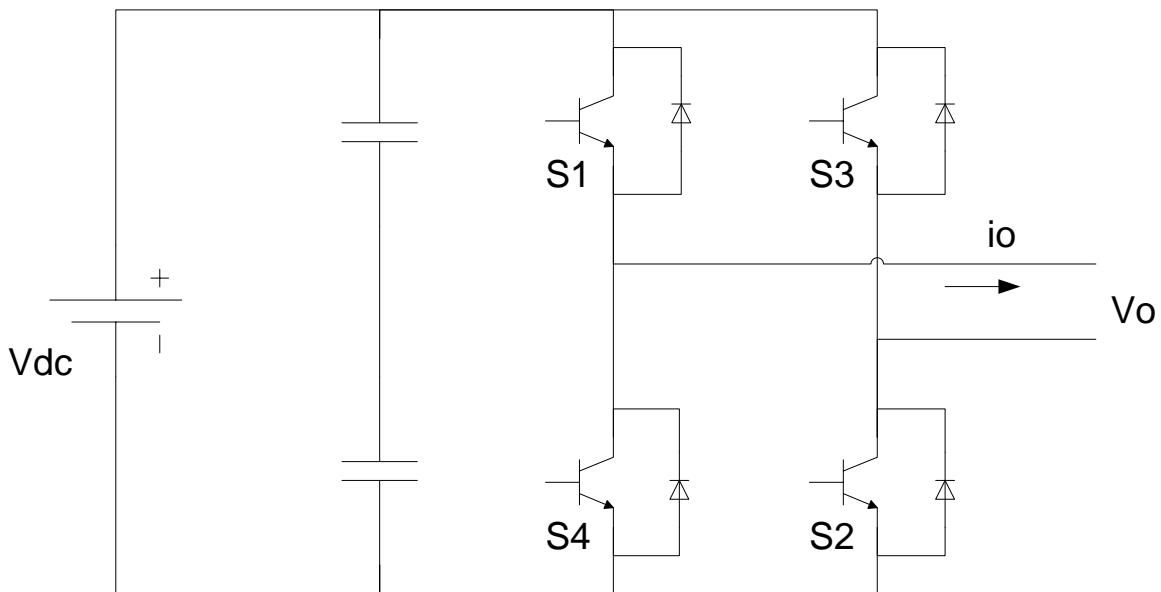


Figure 4. 1 A single phase Full Bridge VSI

table 4. 1 Defined Status of VSI switches

| Switches Status | | | | Vo |
|-----------------|-----|-----|-----|-------------|
| S1 | S2 | S3 | S4 | |
| ON | ON | OFF | OFF | Vdc |
| OFF | OFF | ON | ON | -Vdc |
| ON | OFF | ON | OFF | 0 |
| OFF | ON | OFF | ON | 0 |

In order to avoid a short circuit on the DC link, a dead time is added to the control voltages of the switches in the same leg, where the two switches in the same leg are off. Many control techniques exist for the full bridge VSI. The PWM (Bipolar and Unipolar) are a well-known one.

A) Bipolar PWM for Full bridge VSI Control:

In this method only the first two states in table 4.1 are used, so the output voltage V_o features two values which are V_{dc} and $-V_{dc}$.

To generate the states, a carrier-based technique can be used as shown in Figure 4.2

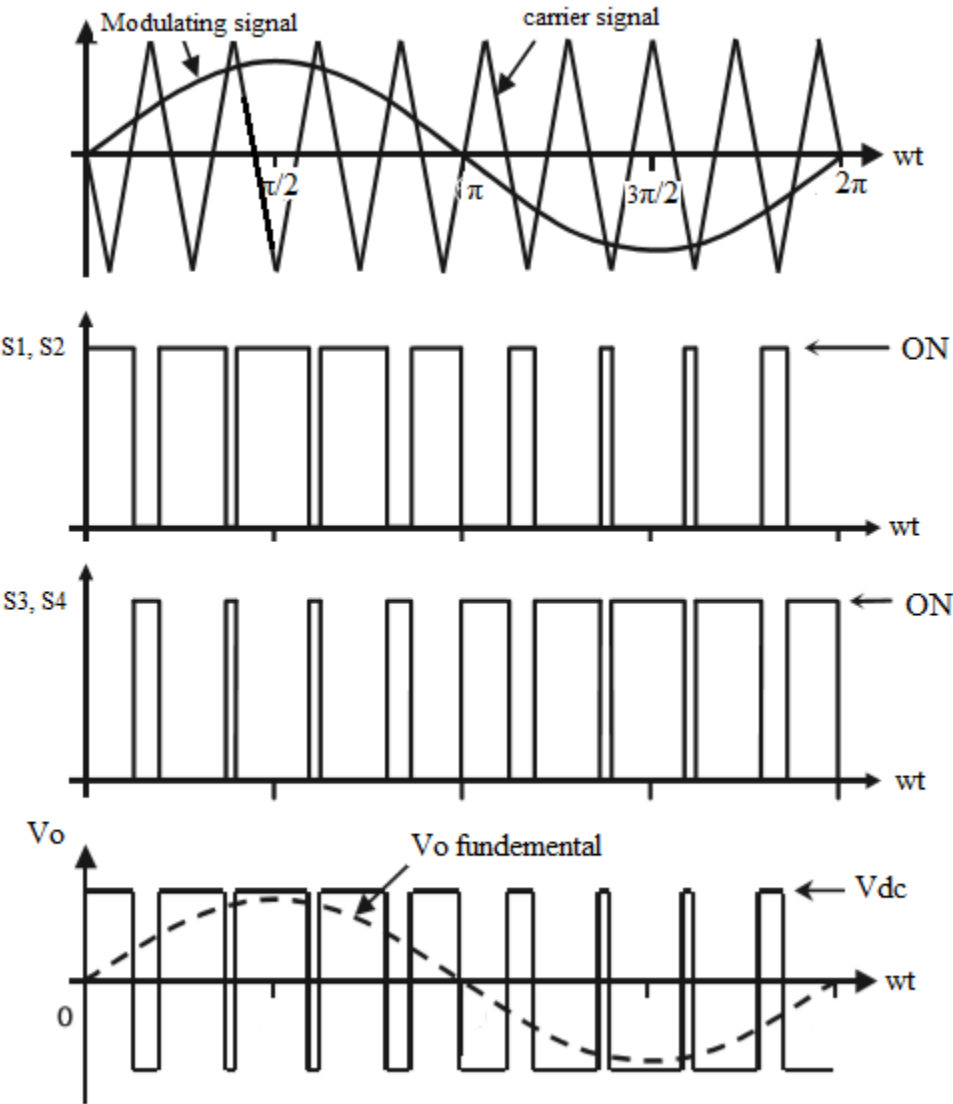


Figure 4. 2 SPWM Bipolar

When the modulating signal (V_m) is greater than the carrier one (V_c), S1 and S2 will be ON and S3, S4 will be OFF. So, the output signal will be V_{dc} . On the contrary, when $V_c > V_m$, S3 and S4 will be ON and S1 and S2 will be OFF. So the output voltage will be $-V_{dc}$. The output voltage waveform is shown at the lowest plot of Figure 4.2.

The amplitude of the output sinusoidal signal is equal to mV_{dc} where m is the modulation index.

B) Unipolar PWM for Full Bridge VSI:

In unipolar technique, the two legs are controlled independently with two modulating signals as shown in Figure 4.3, and so all the states indicated in Table 4.1 are used. In this case, the output value can feature $+V_{dc}$, $-V_{dc}$ and 0. The amplitude of the output signal is equal to mV_{dc} where m is the modulating index.

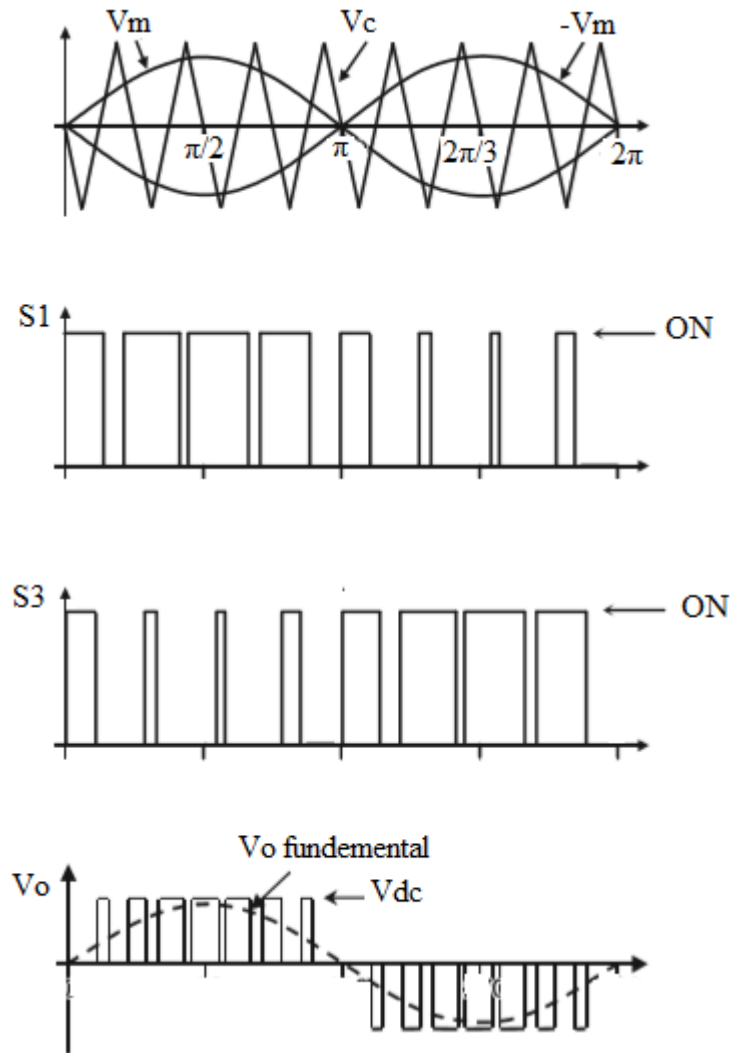


Figure 4. 3 SPWM Unipolar

In unipolar technique, the output voltage doesn't have even harmonics like the bipolar one, and thus if the normalized carrier frequency ($m_f = \text{carrier frequency}/\text{modulating frequency}$) is even, then the harmonics in the output voltage will appear at normalized odd frequencies f_h centered around twice the normalized carrier frequency m_f and its multiples. This is considered an important advantage of unipolar technique compared with bipolar, because smaller filter components could be used to get less distorted voltage output.

4.2 Proposed Grounding System Flow Chart:

The proposed neutral grounding method, consists of a power electronic converter, aiming to change the fault current in a way that guarantees the best protection practice. This can be accomplished by firstly detecting the earth fault, then cancelling the fault current to enable transient faults to vanish. If the fault still exists (a permanent fault), the converter increases the fault current gradually from zero to 40A (this value is chosen by the electrical distributor), letting the medium voltage customers and secondary circuit breakers to trip and isolating the faulty section. Figure 4.4 shows the proposed system scheme summarized in a Flow Chart.

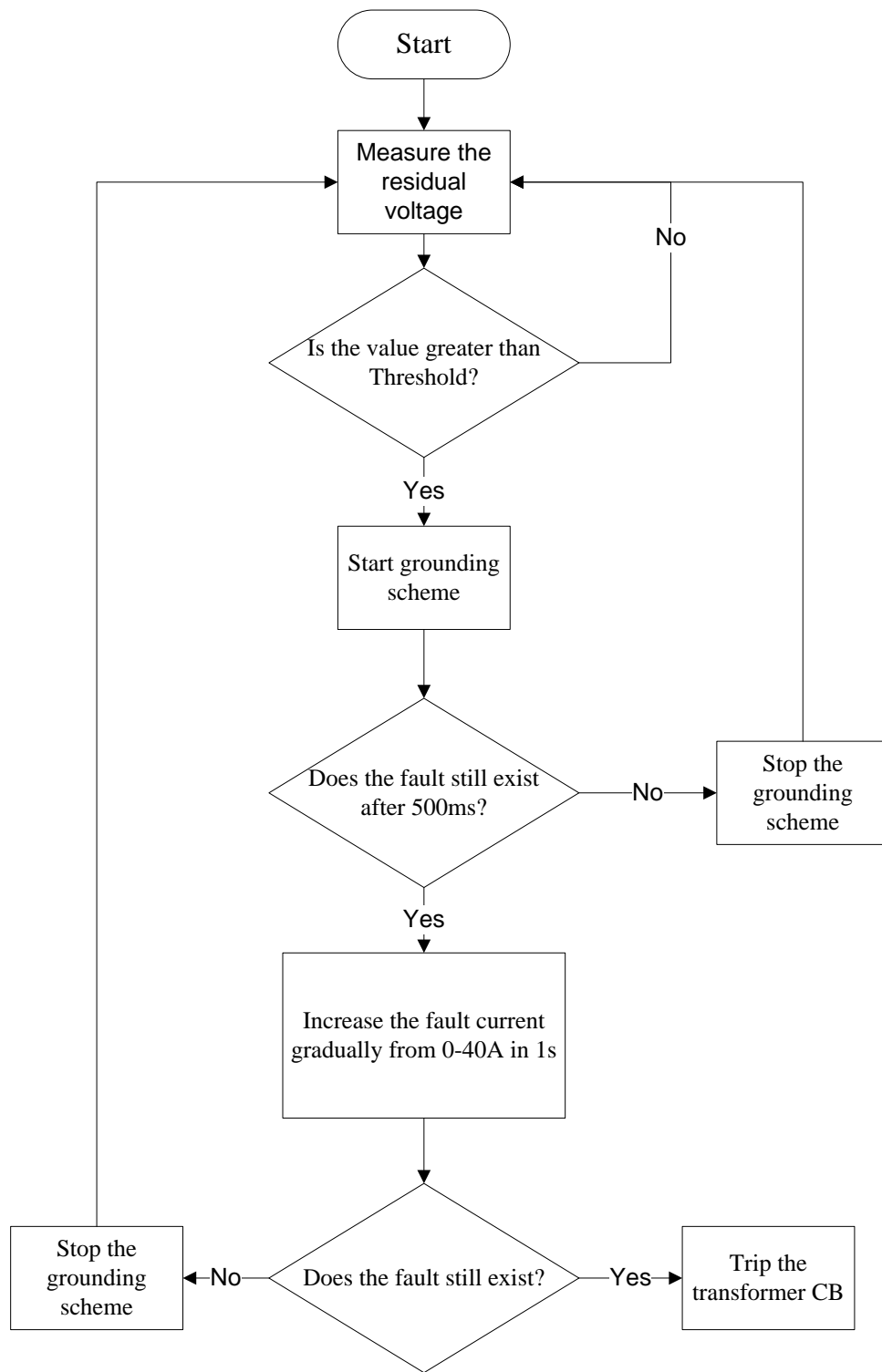


Figure 4. 4 The proposed grounding Scheme summarized in a flow chart

4.3 Proposed Grounding System Block Diagram:

In order to compensate the earth fault current, a Voltage Source Inverter (VSI) is presented between the neutral point of the power transformer and the ground. The Voltage Source Inverter operation depends on the faulty phase, the residual voltage and the residual current readings, as illustrated in the block diagram of the proposed grounding system shown in Figure 4.5.

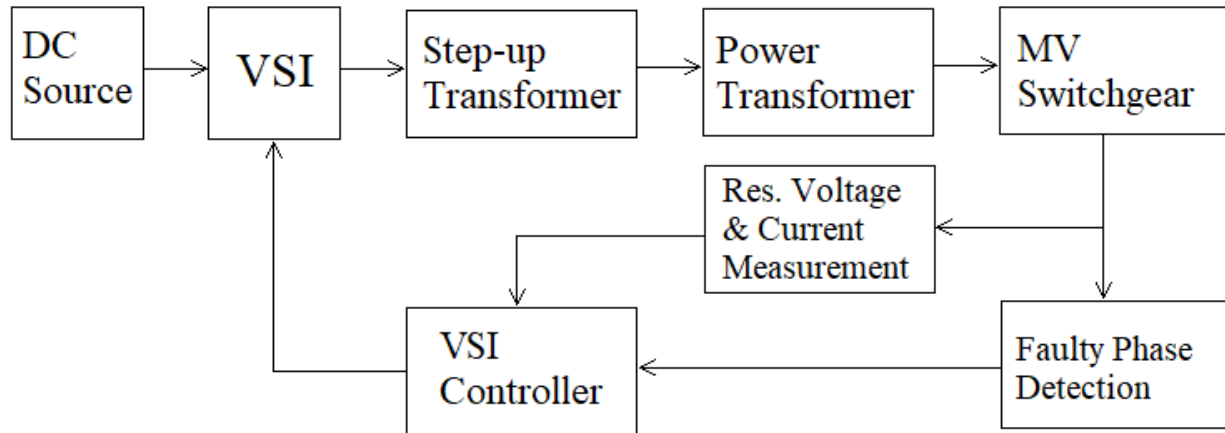


Figure 4. 5 The proposed grounding system block diagram

4.4 The Proposed Grounding System Topology:

The power network can be modeled in the presence of an earth fault and a VSI between the neutral point and ground, as shown in Figure 4.6. According to [35] and [36], the VSI is used as a voltage source to generate a voltage that negatively equal the line to ground voltage of the faulty phase at the moment of fault. The proposed system in this thesis will use the VSI as a current source with special control to achieve the required goals.

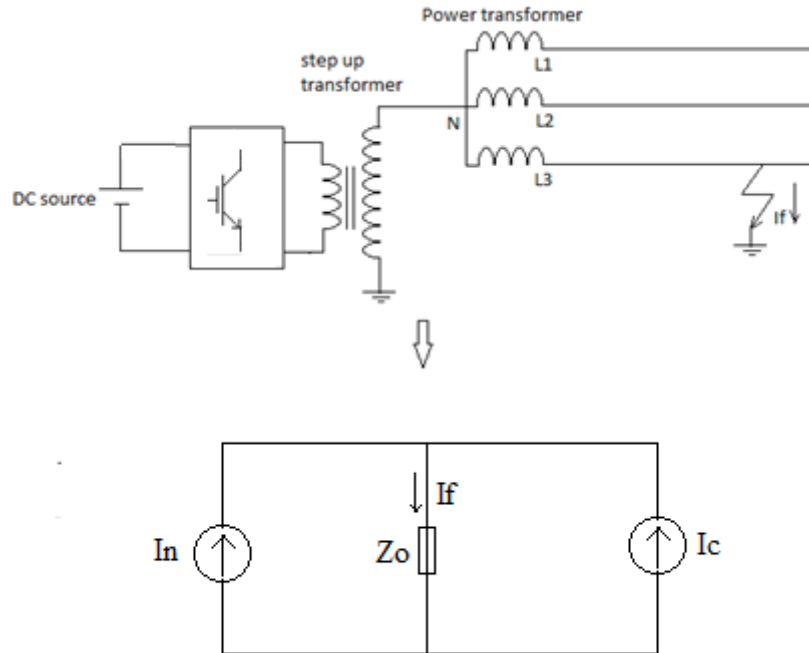


Figure 4. 6 Modeling of a power network during an earth fault on one phase

where,

I_n : Injected neutral current

I_c : network capacitive current

I_f : Fault current

Z_o : Zero sequence impedance

From Figure 4.6, it can be shown that the total fault current I_f equals:

$$I_f = I_n + I_c \dots\dots\dots(4.1)$$

Thus, the total fault current can be cancelled by setting the neutral current to the inverse of network capacitive current.

The proposed system topology depends on a current controlled voltage source inverter (VSI). The inverter is supposed to cancel the earth fault current by injecting a current to the neutral point that equals the inverse of capacitive fault current. If the fault is permanent, the VSI begins operation

after a specified time to increase the earth fault current gradually until the faulty feeder trips. The system topology is shown in Figure 4.7.

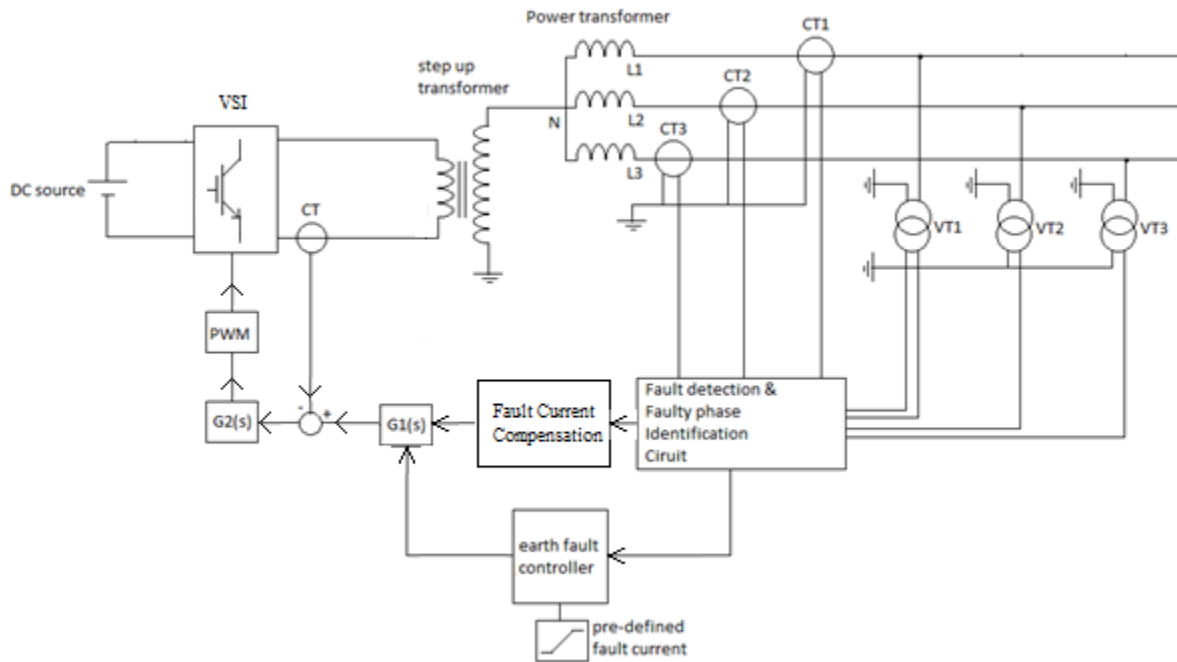


Figure 4. 7 The proposed grounding method topology

The fault is detected and identified in the fault detection and faulty phase identification block. Then, the fault current compensation block generates the phase and amplitude of the reference current to compensate the fault. The reference current is compared with the injected current using a CT at the output of the VSI. After that, the earth fault controller takes over the control and start to increase the fault current according to pre-defined scheme.

Chapter 5: Simulation Results and Analysis

To simulate ground fault in different grounding systems, Matlab/Simulink program was used.

The medium voltage substation under study shown in Figure 5.1 is simulated by 33kV three phase source with a short circuit level of 250MVA, which represents the same short circuit level of the supplying company at medium voltage connection point. The main transformer is represented by 10MVA 33kV/11kV transformer, then three 11kV feeders are simulated by distributed parameter line (feeder 1 is a cable network, while feeder 2&3 are overhead lines) and the load is represented by a distribution transformer with 400kVA capacity and a three phase series RLC load. The simulation parameters are shown in Table 5.1. These parameters are obtained from GIS department in JDECo for an actual network

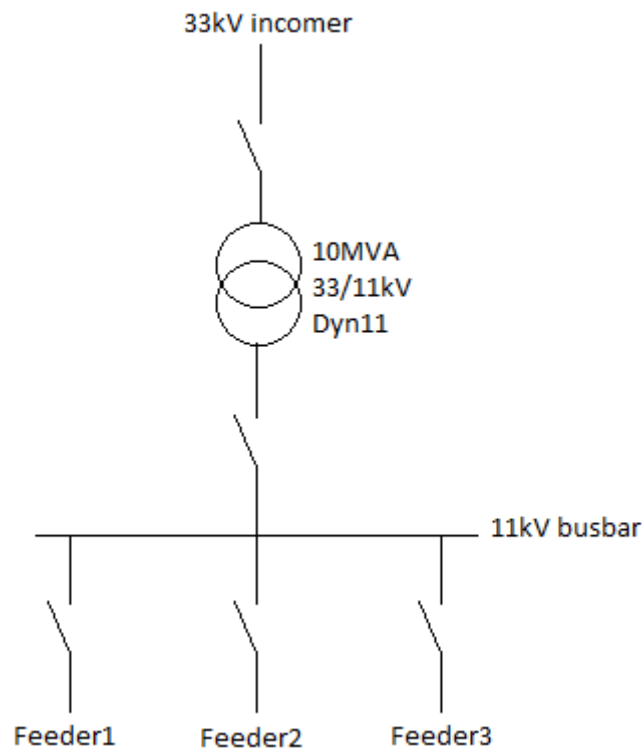


Figure 5. 1 Medium voltage substation under study

Table 5. 1 Simulation Parameters of the network under study

| | Parameters | Value |
|------------------------------|--------------------------------------|---------------|
| 3 Phase Source | Phase-phase voltage | 33kV |
| | Phase angle of phase A | 0 |
| | Frequency | 50 Hz |
| | Three phase short circuit level | 250 MVA |
| | X/R ratio | 7 |
| | Configuration | Yg |
| Power transformer parameters | Connection | Dyn11 |
| | Nominal power | 10 MVA |
| | Frequency | 50 Hz |
| | Primary windings' voltage | 33 kV |
| | Primary windings' R (p.u) | 0.002 |
| | Primary windings' L (p.u) | 0.08 |
| | Secondary windings' voltage | 11kV |
| | Secondary windings' R (p.u) | 0.002 |
| | Secondary windings' L (p.u) | 0.08 |
| | Magnetizing resistance Rm (p.u) | 500 |
| | Magnetizing inductance Lm (p.u) | 500 |
| Feeder 1 parameters | Frequency | 50 Hz |
| | Positive sequence resistance per km | 0.0127 ohm |
| | Zero sequence resistance per km | 0.386 ohm |
| | Positive sequence inductance per km | 0.93 mH |
| | Zero sequence inductance per km | 4.13mH |
| | Positive sequence capacitance per km | 1.27 μ F |
| | Zero sequence capacitance per km | 0.775 μ F |
| | Length | 12 km |
| Feeder 2 parameters | Frequency | 50 Hz |
| | Positive sequence resistance per km | 0.0127 ohm |
| | Zero sequence resistance per km | 0.386 ohm |
| | Positive sequence inductance per km | 0.93 mH |
| | Zero sequence inductance per km | 4.13mH |

| | | |
|---------------------|--------------------------------------|------------|
| | Positive sequence capacitance per km | 12.7 nF |
| | Zero sequence capacitance per km | 7.75 nF |
| | Length | 12 km |
| Feeder 3 parameters | Frequency | 50 Hz |
| | Positive sequence resistance per km | 0.0127 ohm |
| | Zero sequence resistance per km | 0.386 ohm |
| | Positive sequence inductance per km | 0.93 mH |
| | Zero sequence inductance per km | 4.13mH |
| | Positive sequence capacitance per km | 12.7 nF |
| | Zero sequence capacitance per km | 7.75 nF |
| | Length | 12 km |

5.1 Isolated neutral simulation:

Figure 5.2 shows the simulation circuit of the network under study during an earth fault occurring in feeder 3. The simulation results of Figure 5.3 show an increment in the faulty line current at feeder 3. The current raised from its nominal value to 70A rms at the moment of fault (100 ms) due to the equivalent capacitance between the other phases in the healthy feeders and the faulty one as well.

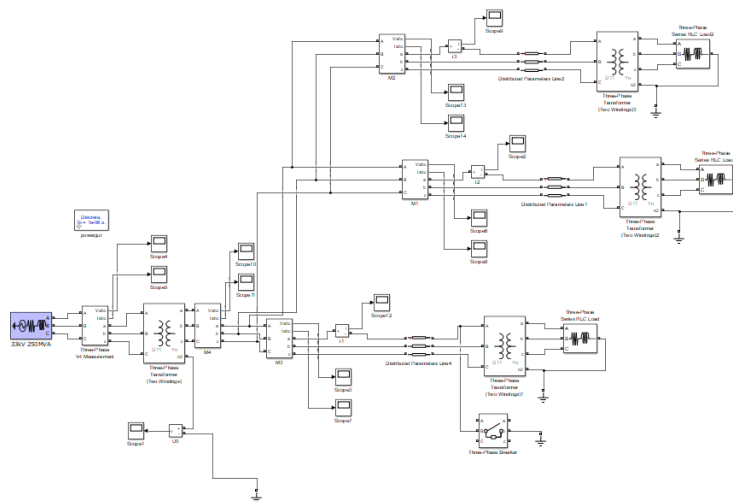


Figure 5. 2 An Isolated neutral system simulation circuit

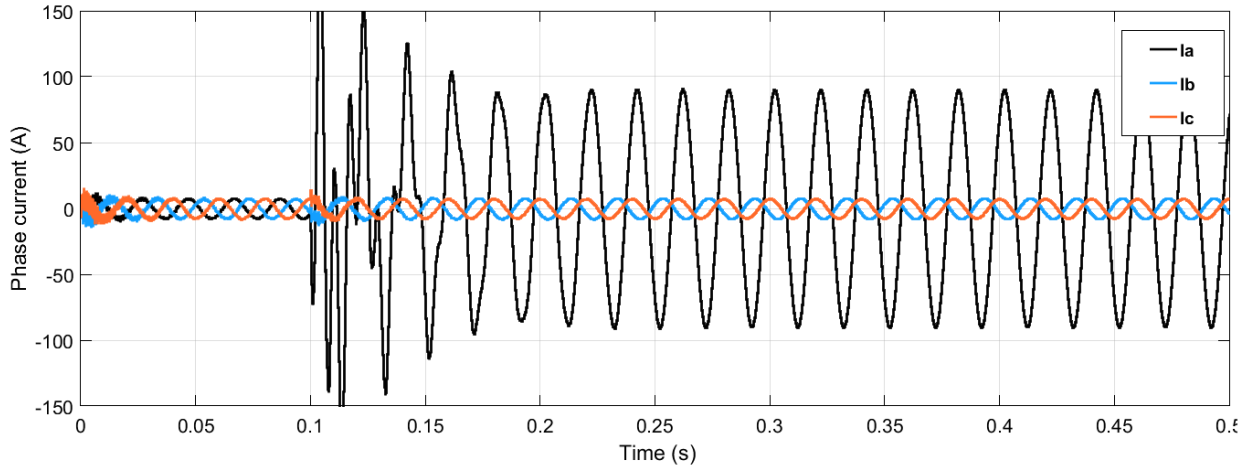


Figure 5.3 Faulty feeder three phase currents waveforms

The fault current value depends on the overall equivalent capacitance between the faulty phase and the healthy ones, and the fault current distributed in the healthy feeders depending on their equivalent capacitance value.

Figure 5.4 shows the three phase current waveforms in feeder 2. It shows that feeder 2 does not undergo changes in the current waveforms after the fault. This is because of the low capacitance of feeder 2 compared to feeder 1, due to the fact that feeder 2 and 3 consist of overhead lines while feeder 1 consists of underground cables.

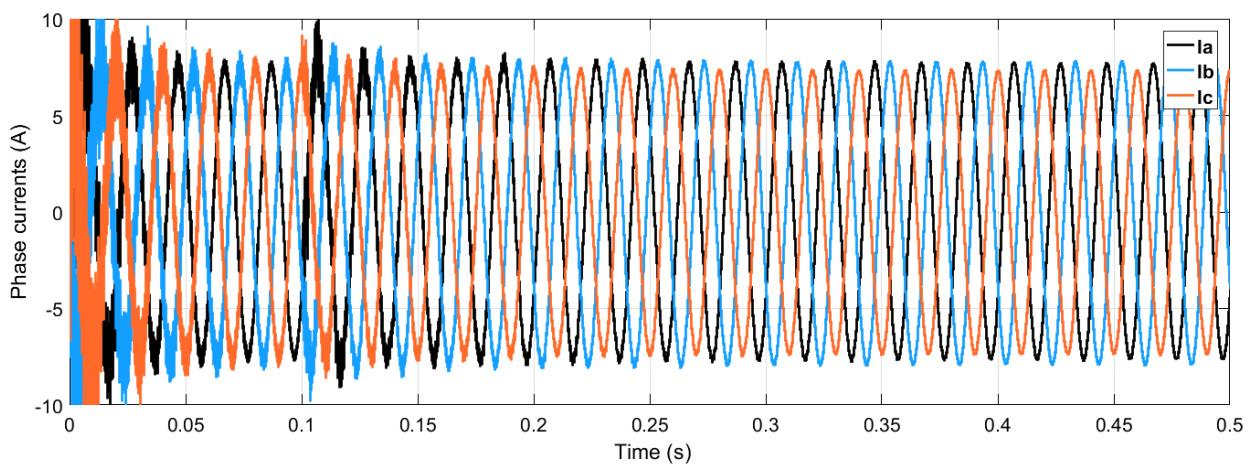


Figure 5.4 Three phase current waveform in feeder 2

The overall currents drawn from the main transformer at 11kV side are shown in Figure 5.5. When the ground fault happened at phase A in feeder 3 after running the simulation by 100 ms,

the current raised in this feeder to 70A rms. The current raised also in the other phases keeping the vector summation of the three phases to be zero. This is because there is no connection between earth and neutral of the main transformer (Isolated neutral system)

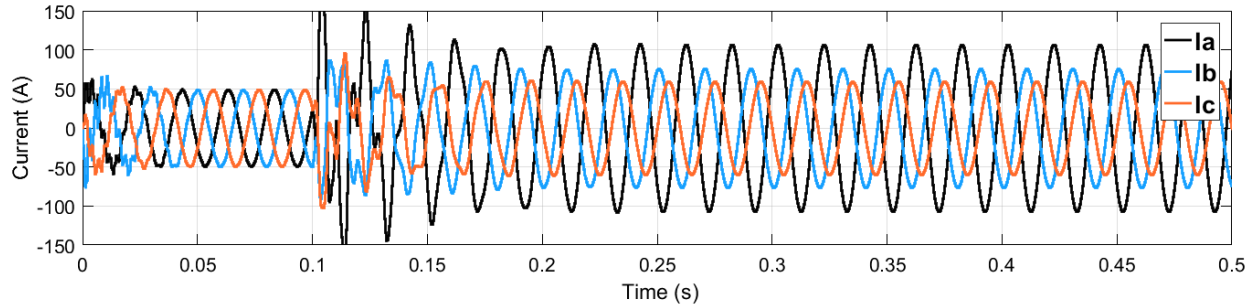


Figure 5. 5 The phase currents at the output of the main transformer

5.2 Solidly Grounded Neutral Simulation:

Figure 5.6 shows the simulation circuit of a solidly grounded neutral in the same network under test. The solidly grounded neutral system is characterized by high earth fault current due to the low impedance of the fault path. Figure 5.7 shows the faulty feeder three phase currents where the high raise in the faulty phase current (about 2900A rms) can be noticed.

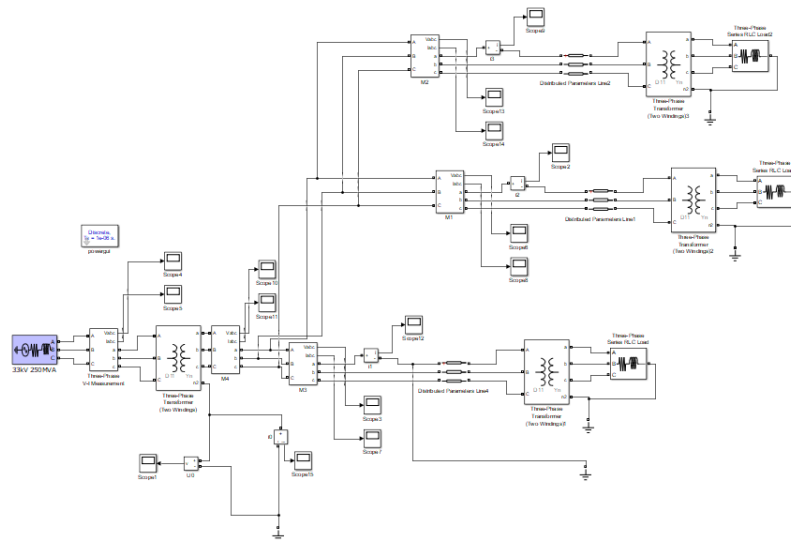


Figure 5. 6 Solidly grounded neutral simulation circuit

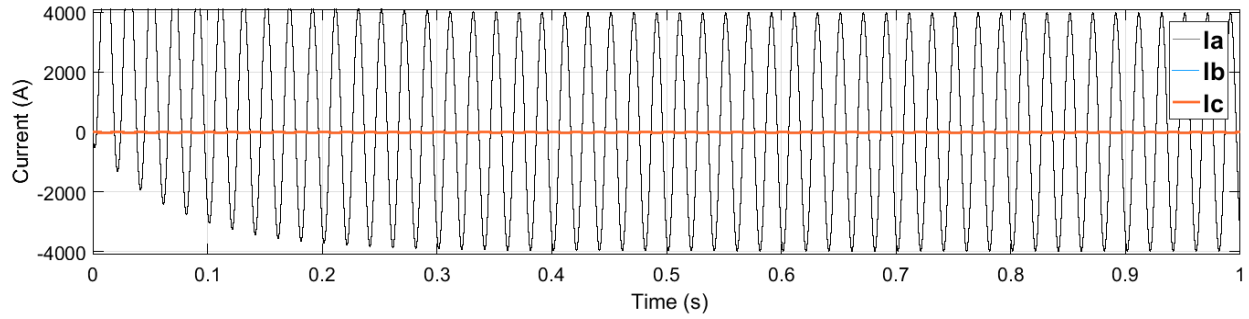


Figure 5.7 Faulty feeder currents in a solidly grounded neutral system

The high current drawn by the faulty phase causes a considerable voltage drop on that phase at main transformer terminal. Figure 5.8 shows the three phase voltages on the output of the main transformer where the voltage drop on the faulty phase A can be noticed (fault position is shifted to the end of feeder).

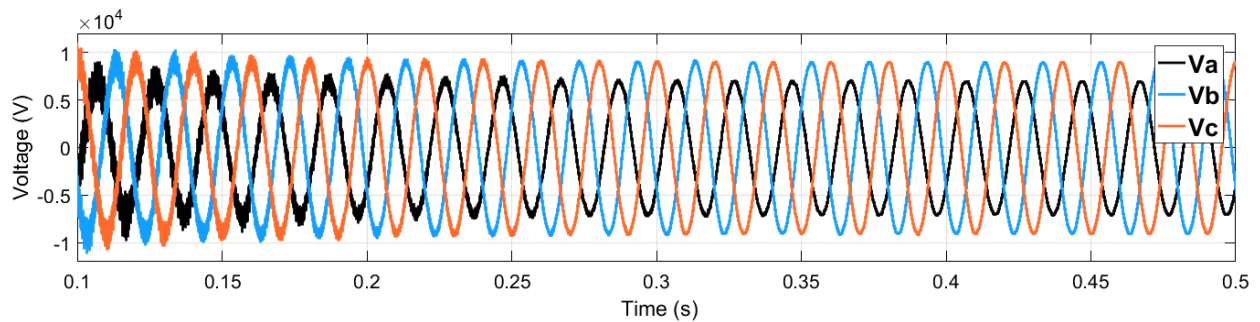


Figure 5.8 Phase voltages at the output of main transformer during earth fault current in a solidly grounded neutral system

Due to the high voltage drop on the faulty phase at the main transformer, a reduction in phase A current is noticed on the healthy feeders 1 and 2, as shown in Figures 5.9 and 5.10, respectively.

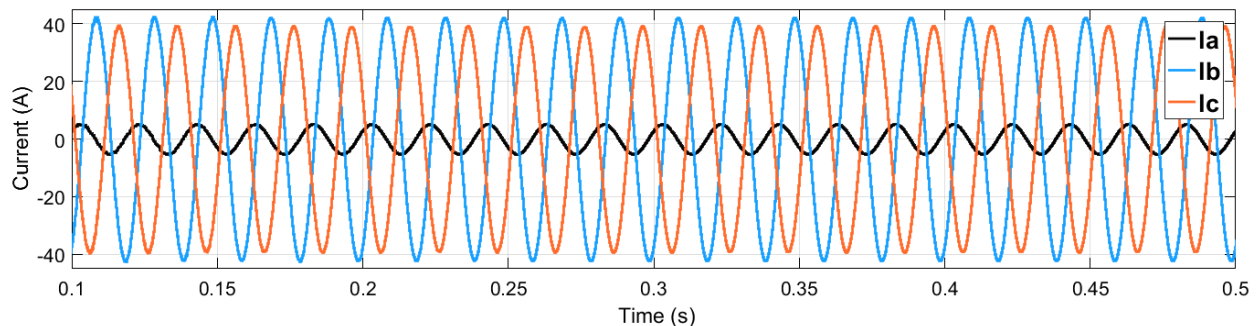


Figure 5.9 Three phase currents in feeder 1 during an earth fault on feeder 3 in a solidly grounded neutral system

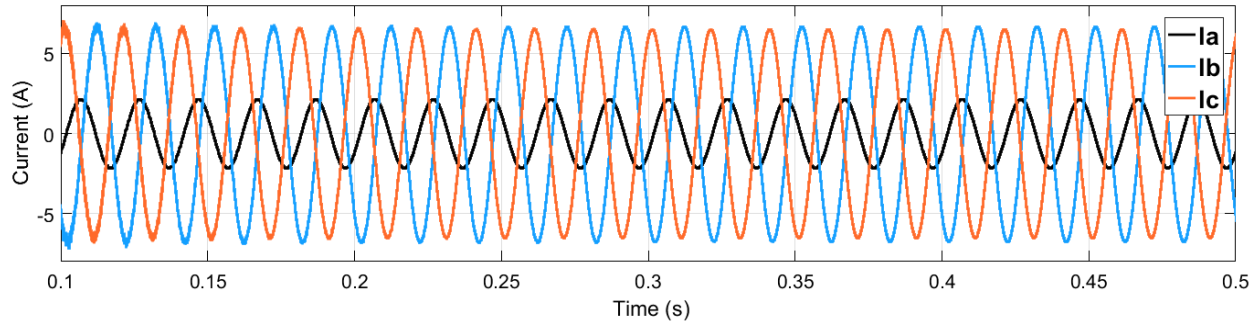


Figure 5. 10 Three phase currents in feeder 2 during an earth fault on feeder 3 in a solidly grounded neutral system

5.3 Resistive Grounded Neutral Simulation:

To simulate the earth fault in a resistive grounded neutral system a resistance of 50 ohm is added between the secondary neutral point of the transformer and earth as shown in Figure 5.11.

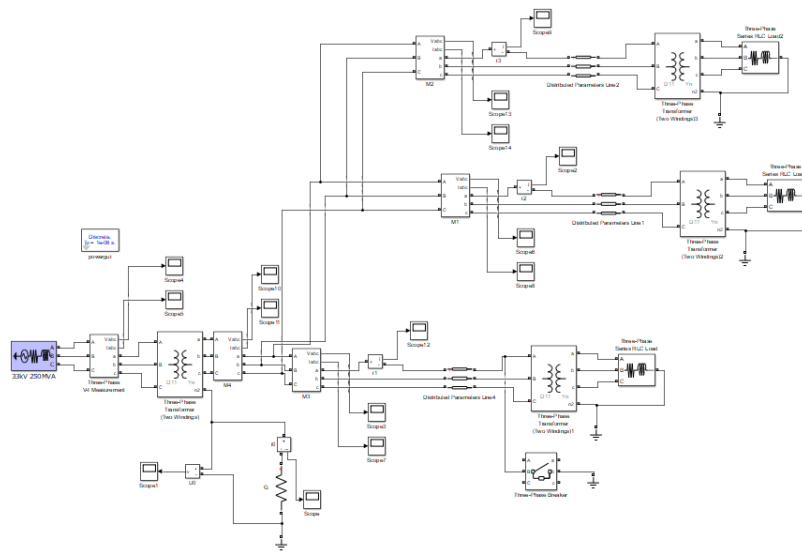


Figure 5. 11 A resistive grounded neutral simulation circuit

The 50-ohm medium voltage resistance which was added in the path of earth fault limited the earth fault current to 200A peak (140A rms) as shown in Figure 5.12. The fault current is limited to a value that is compatible with the simple protection setting of the protection relay. In this case, the threshold current of the protection setting is 100A, so the fault current should exceed this value to be detectable. Moreover, the fault current should be limited to value that can be handled by the network cables to avoid overheating.

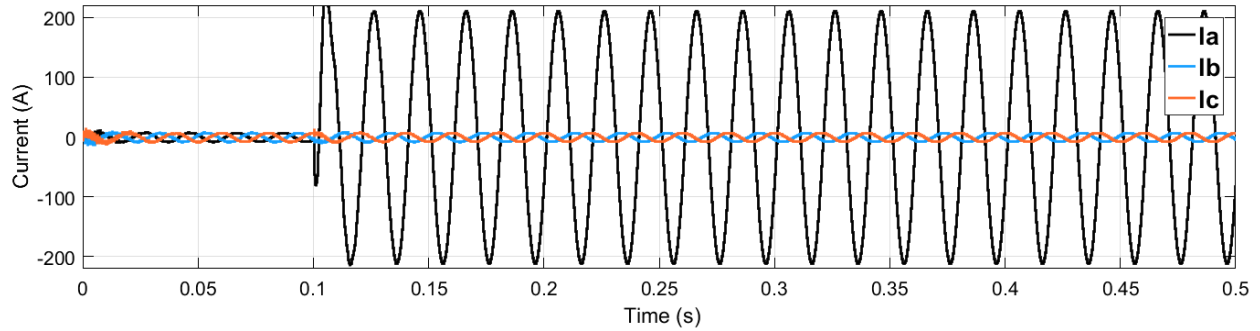


Figure 5.12 Faulty feeder currents in a resistive grounded neutral system

The three phase voltages (phase to phase) voltage haven't been affected by the fault, as shown in Figure 5.13, causing no supply changes to the distribution transformers and hence to the loads. But the neutral point voltage displacement, depicted in Figure 5.14, makes a considerable change in the line to ground voltages, as shown in Figure 5.15. This will affect the line currents in cable networks, such as feeder 1 (see Figure 5.16) because the equivalent capacitance current will be different in the three phases, while the effect on low capacitance networks (overhead line networks) such as feeder 2 will be much less, as indicated in Figure 5.17. One important disadvantage of such system grounding is the phase to ground overvoltage that occurs in healthy phases as shown in Figure 5.15, which has a negative impact on system components' insulation and lightning arrestors.

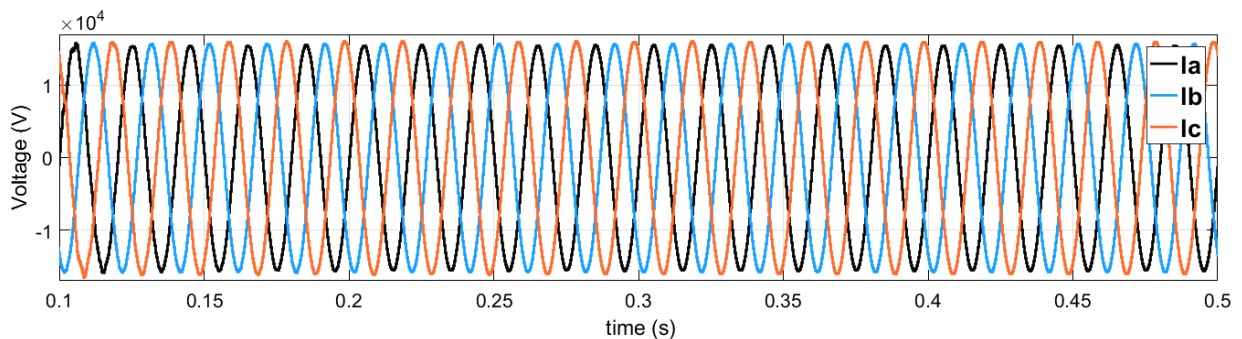


Figure 5.13 Phase to phase voltages of the network measured at the output of the main transformer during an earth fault at phase A in feeder 3

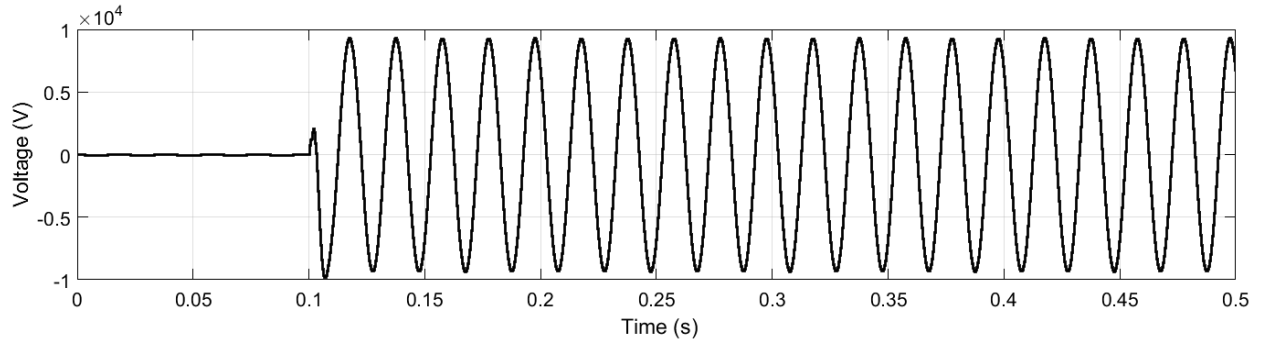


Figure 5. 14 A neutral to ground voltage during an earth fault in a resistive grounded system

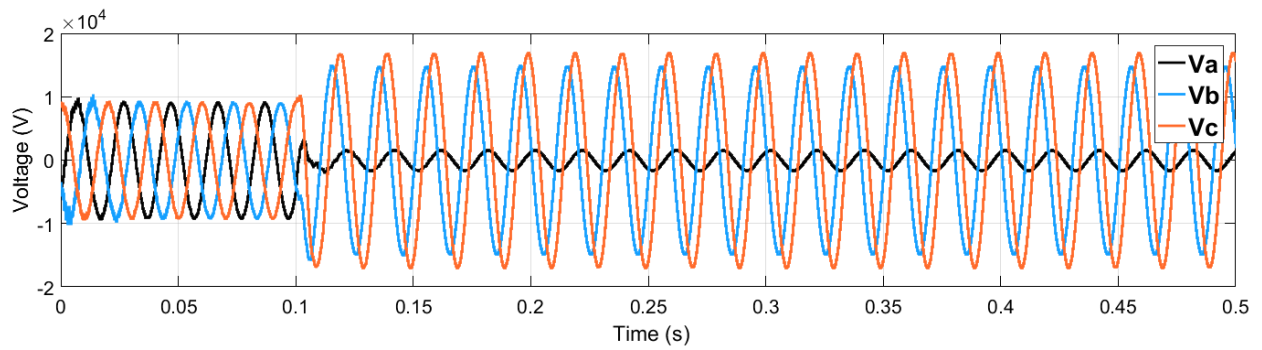


Figure 5. 15 Line to ground voltages during an earth fault in a resistive grounded system

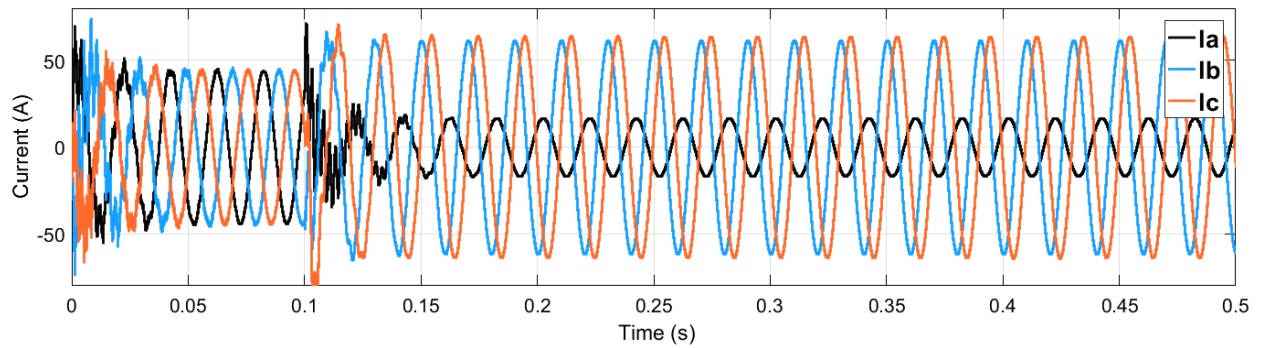


Figure 5. 16 Line currents in feeder 1 during an earth fault at phase A in feeder 3 (a resistive grounded system)

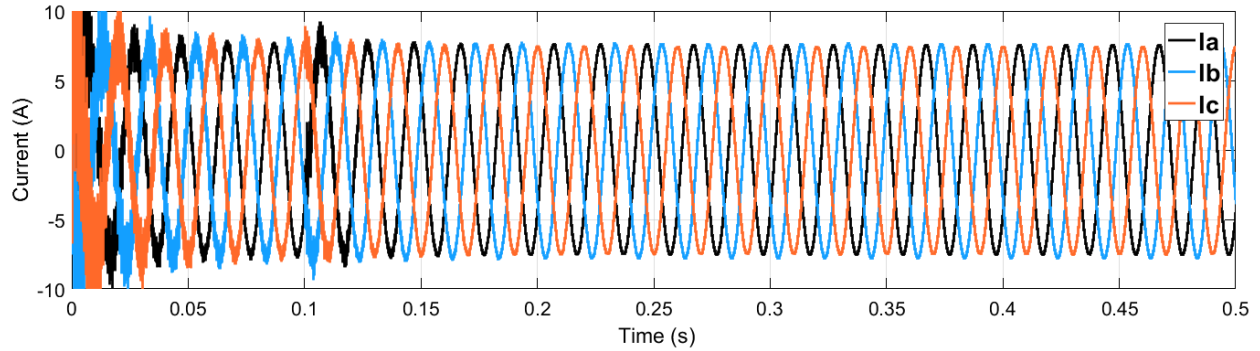


Figure 5. 17 Line currents in feeder 2 during an earth fault at phase A in feeder 3 (a resistive grounded system)

5.4 Compensated Grounded Neutral Simulation:

In order to cancel the earth fault current a coil is added between the secondary neutral point of the transformer and the earth as shown in Figure 5.18. The main purpose of compensated grounded method is to cancel the earth fault originated because of the line capacitance by generation of inductive current in the parallel path through the neutral point as indicated in Figure 5.19. It can be noticed that, a high transient current and DC component are associated with the fault. This may lead to malfunction of the protection relay so more complicated protection functions are employed in this system. On the other hand, the cancellation of fault current gives the flexibility of higher tripping time for the protection relays and thus distinguishing of fault may be facilitated.

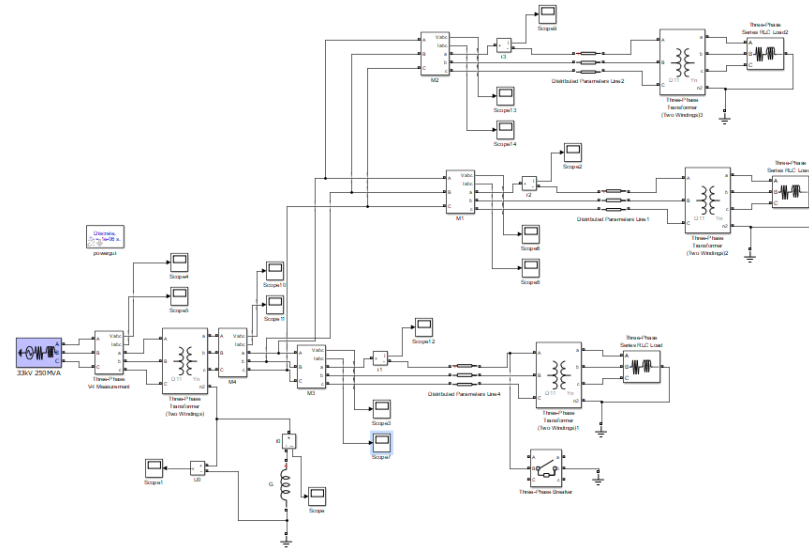


Figure 5. 18 A compensated grounded neutral simulation circuit

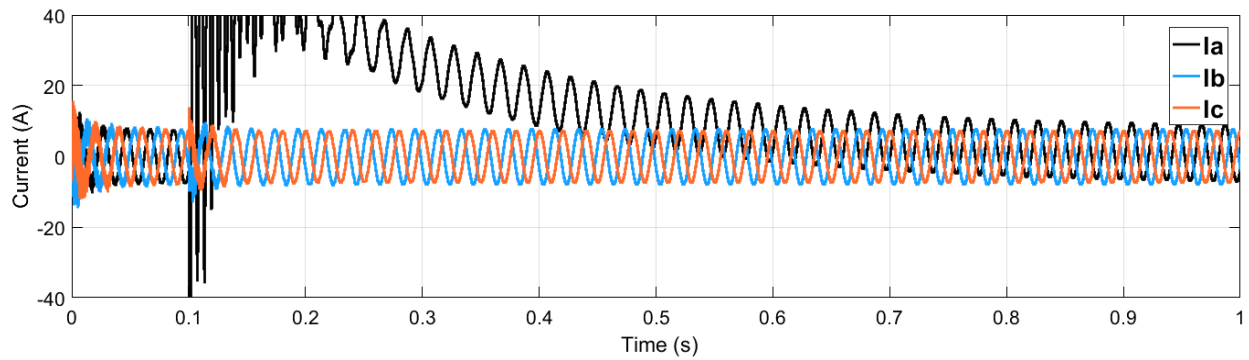


Figure 5. 19 Faulty feeder currents in a compensated grounded neutral system

Similar to the resistive grounded system, a voltage swell occurs in the healthy phases as indicated in Figure 5.20.

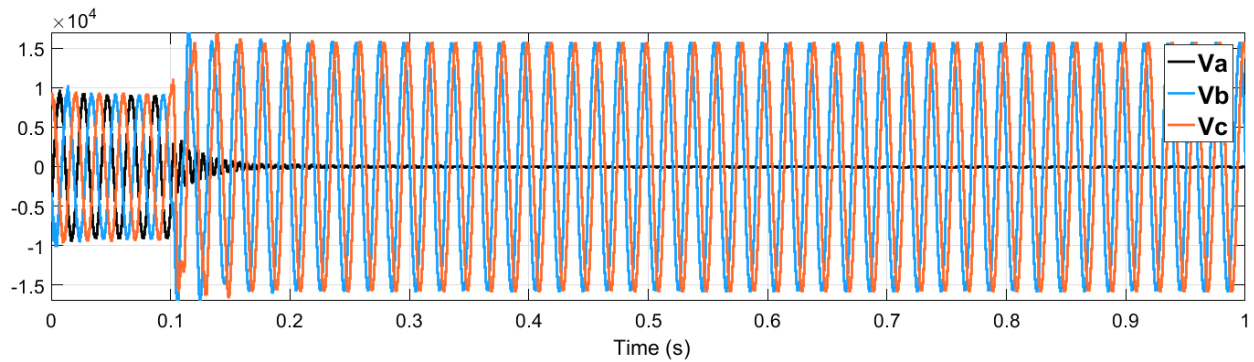


Figure 5. 20 line to ground voltages during earth fault in compensated grounded system

5.5 Model Construction:

The proposed grounding system is also modeled and simulated using Matlab Simulink program.

Figure 5.21 shows the simulated distribution substation, where a 250MVA 33kV generator is used to simulate the connection point with transmission company and 10MVA 33/11kV Dyn11 transformer block is used in the substation. The neutral point of the transformer is left floating (Isolated neutral) to get the system capacitive fault current. Three feeders are connected to the transformer secondary circuit. The feeders are modeled using distributed parameters line block. The load is simulated by a distribution transformer with capacity of 400kVA. A single phase earth fault is made on the third feeder.

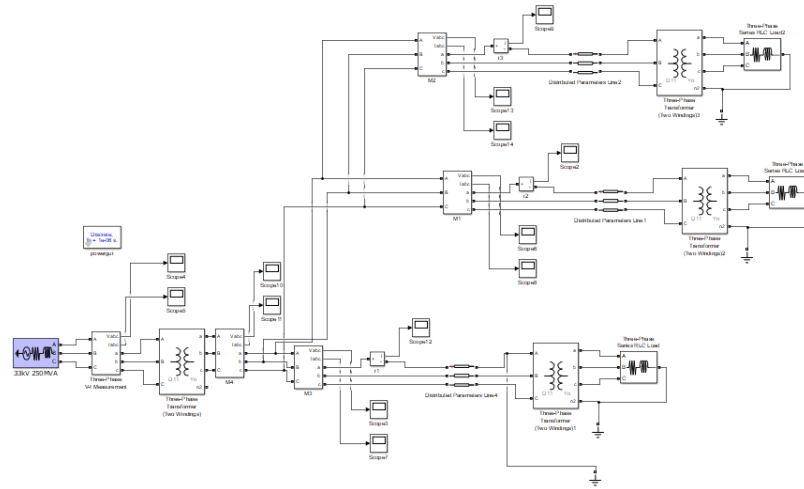


Figure 5. 21 Distribution Substation with Isolated Neutral

Since the neutral point is isolated from ground, the earth fault current at the faulty feeder is expected to equal the network capacitive current as shown in the simulation result of Figure 5.22

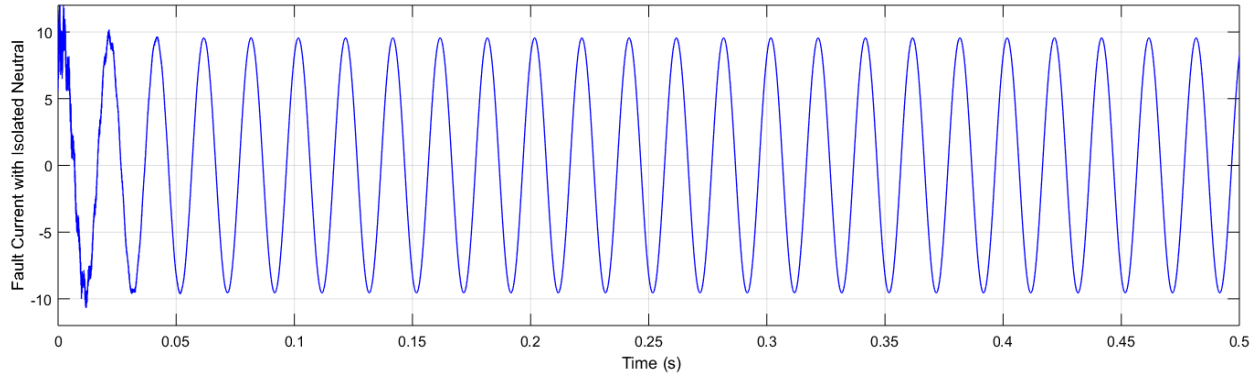


Figure 5.22 Fault Current with Isolated Neutral

This fault current will flow through the line to ground capacitance of all feeders in the substation and hence will be detected as residual current in the feeders. Figure 5.23 shows the residual currents in feeder 1 and 2 at the time of fault in feeder 3.

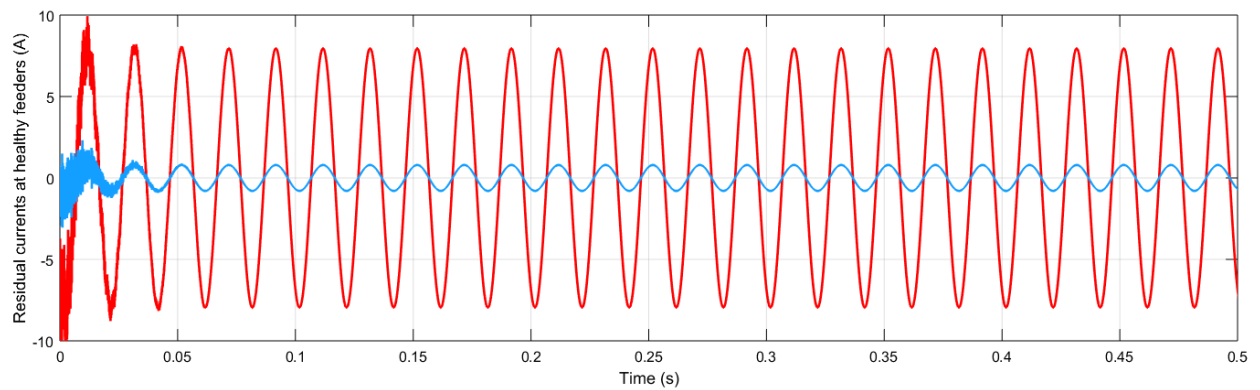


Figure 5.23 Residual Currents in Healthy Feeders

It can be shown that the residual current is higher at the feeder with more cable sections. The reason of that is the higher capacitance of cable feeders with respect to overhead lines. Also, the summation of residual current in healthy feeders is approximately equal the faulty current without the amount of current returned in healthy phases at the faulty feeder.

The current flowing through the neutral point is equal to zero because it is isolated. So, the total residual current at the secondary side of the transformer is equal to zero.

In order to compensate the fault current and bring it to almost zero, a voltage source inverter is introduced between the neutral point and the ground as shown in Figure 5.24. The used PWM modulator is unipolar single-phase full bridge source with carrier frequency of 20kHz.

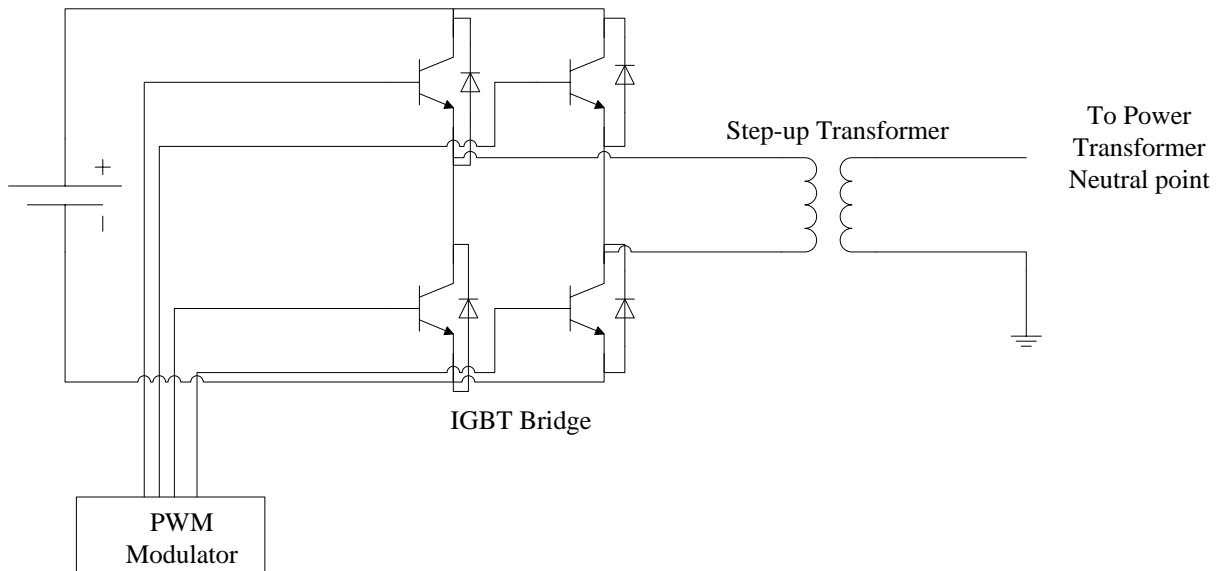


Figure 5. 24 Voltage Source Inverter Connected to Neutral Point

5.6 Controlling the PWM:

In order to achieve the required goals of the new earthing technique, the PWM must have a closed loop control to enable the VSI to generate the required neutral current. Figure 5.25 shows the closed loop control used for PWM generation.

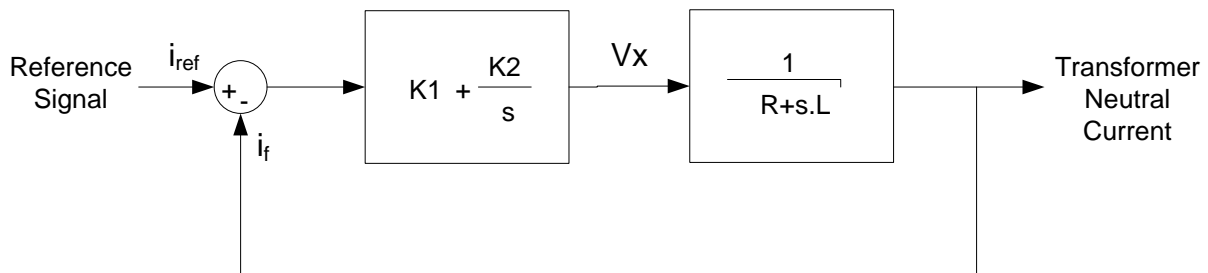


Figure 5. 25 Closed Loop Control for PWM control

The transfer function of the system could be calculated from the control equation of unity feedback system:

$$T(s) = \frac{G(s)}{1 + G(s)}$$

where $G(s)$ is the forward transfer function. From the control system shown in Figure 5.25, $G(s)$ can be written as:

$$G(s) = G1(s) * G2(s)$$

$$G1(s) = K1 + \frac{K2}{s}$$

$$G2(s) = \frac{1}{R + sL}$$

where:

R: zero sequence resistance

L: zero sequence inductance

$$T(s) = \frac{K1.s + K2}{L.s^2 + (K1 + R).s + K2}$$

The transfer function shows that when selecting the value of K1 and K2 it should not exceed the limit which makes the control system overdamped. The reason of that is to prevent overshooting in the response.

The PI controller is not able to follow a sinusoidal reference signal because the steady state error can not be terminated due to the dynamics of the integral term. In such case where the reference signal is sinusoidal, the PR controller is used which has the same functionality of PI controller but with the ability to track sinusoidal reference signal. The PI controller has a gain at a resonant frequency and almost zero gain at other frequencies.

The ideal resonant controller, can be mathematically derived by transforming an ideal synchronous frame PI controller to the stationary frame and achieves infinite gain at the AC frequency of ω_n to force the steady state voltage error to zero and no phase shift and gain at other frequencies. For Kp it is tuned in the same way as for PI controller. [37]

Because the error signal in the PWM control circuit is sinusoidal, the PI controller is substitute by the controller $G(s) = Kp + \frac{Kr.s}{s^2 + \omega_n^2}$

The reference signal is set according to the required function and protection discrimination as follows:

- To get the network capacitive current, the reference signal is set to zero in the range 0-50 ms. This allows the network capacitive current to flow in the fault point. This current

represents the residual current of the faulty feeder without the capacitive current returning in the healthy phase at the same feeder.

- The reference current is set to negative network capacitive current in the range 50-500 ms by getting the exact phase of the capacitive current read by the residual current transformer at the faulty feeder using PLL. This will compensate the fault current and reduce it to almost zero at the fault point. If the fault is transient, it will be vanished without interrupting the power supply.
- If the fault is permanent, the system will start the pre programmed sequence of reference current to allow the fault to increase through different stages. This will let the secondary circuit breakers trip before the primary ones achieving current base discrimination for the earth fault at the same distribution voltage level.

Figure 5.26 shows the earth fault reference sequence starting from 0.5s after the fault occurrence.

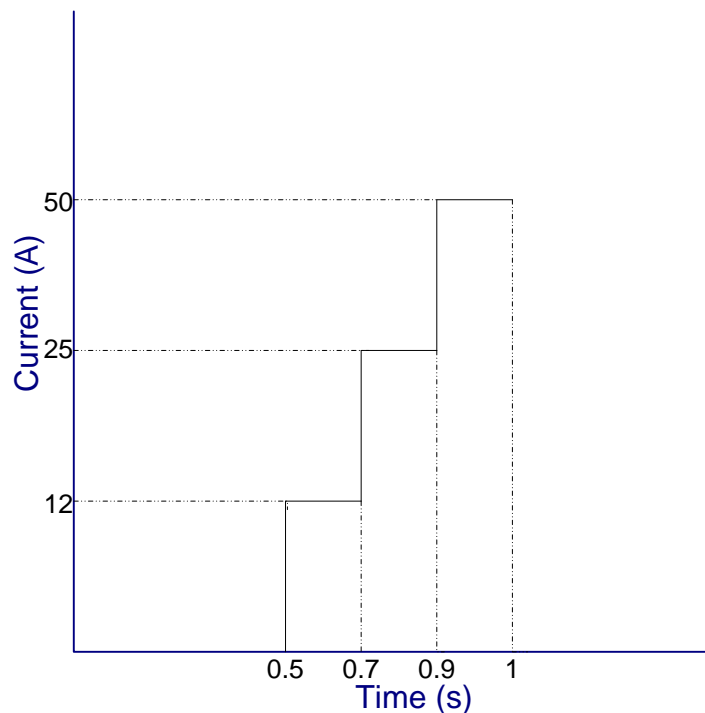


Figure 5. 26 Earth Fault Reference Sequence

Figure 5.27 shows the single line diagram of a medium voltage feeder where the earth fault setting threshold of the protection relays A, B and C are calibrated according to the protection discrimination sequence which fit with the earth fault reference current setting of the VSI.

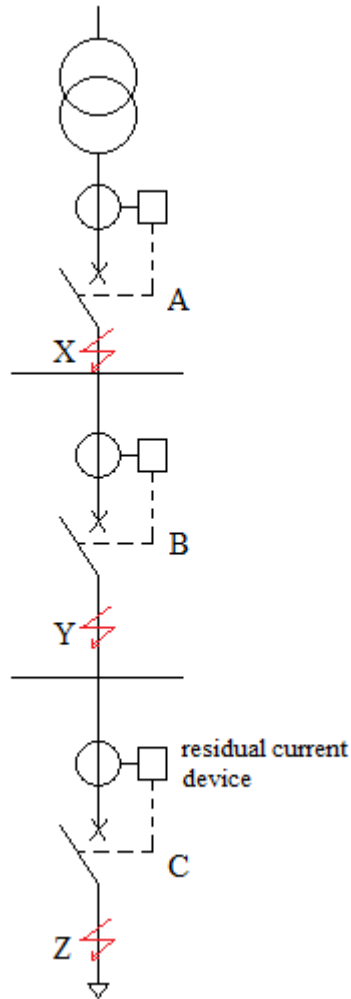


Figure 5. 27 Single Line Diagram of MV Feeder

The A, B, and C protection relays in the medium voltage feeder are calibrated as follows:

Relay C: I_0 Current setting: 10A, Tripping time: 100 ms

Relay B: I_0 Current setting: 20A, Tripping time: 100 ms

Relay A: I_0 Current setting: 40A, Tripping time: 100 ms

These values are chosen according to the CT ratio of the circuit breaker, where the current threshold of the earth fault is set 10% of the rated current of the CT. For upstream breaker (point A in the figure), the normal CT ratio is 400/5. Hence, the threshold earth fault value is set to 40A. The same for downstream circuit breakers and customers' main circuit breakers

If an earth fault happens at point Z, the earth fault controller connected to transformer neutral point will start the sequence after trying to cancellate the fault through 500 ms. After that the earth fault

controller will inject 12A in the neutral point resulting in earth fault more than 10A at point Z. This will activate the earth fault protection of relay C at the downstream and will not reach the threshold value of the other relays in the upstream. This will cause feeder C to trip alone without the other feeders and discrimination will be achieved. In a case of breaker failure at C, the earth fault controller will increase the fault current after 200ms to more than 20A which will activate the earth fault protection at relay B alone without influencing relay A at the upstream. Hence, a protection backup is also achieved.

If the earth fault happens at point Y, the earth fault current will be detected by relays A and B. the earth fault controller will inject 10A at the beginning of the sequence, then it will inject 20A after 200ms. This will activate the earth fault protection in relay B alone and the faulty part will be isolated by circuit breaker B. If circuit breaker B has a BF (Breaker Failure), then the earth fault controller will increase the earth fault current up to 40A after 200ms which will activate the earth fault protection in relay A.

If the fault happens at point A, the controller will complete the sequence up to 40A and the protection relay at A will trip the CB and isolate the fault which happens in the upstream.

5.7 Proposed System Simulation Results:

The VSI is introduced between the neutral point of the transformer and the ground as shown in Figure 5.28.

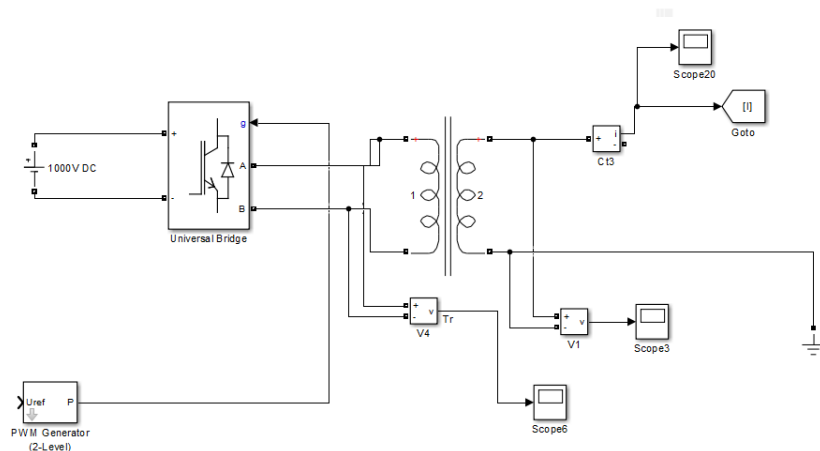


Figure 5. 28 The proposed VSI connected to power transformer neutral point

The VSI model consists of universal bridge supplied by 1000V DC source and a step-up transformer with ratio of 11000/110 connected directly to the output of the bridge. The Dc voltage source was chosen to be compatible with the step-up transformer ratio, the modulating signal and the required voltage range to inject the fault currents. The secondary side of the step-up transformer is connected from one side to the neutral point of the power transformer and to the ground from the other side.

The universal bridge is controlled by PWM generator which is controlled by the control circuit shown in Figure 5.29. Two reference current are used. One from the residual current circuit in which is responsible for fault current compensation, and the other is from the fault current controller. Both signals are compared with the injected current from the VSI and the output error signal is used to control the PWM generator by PI controller.

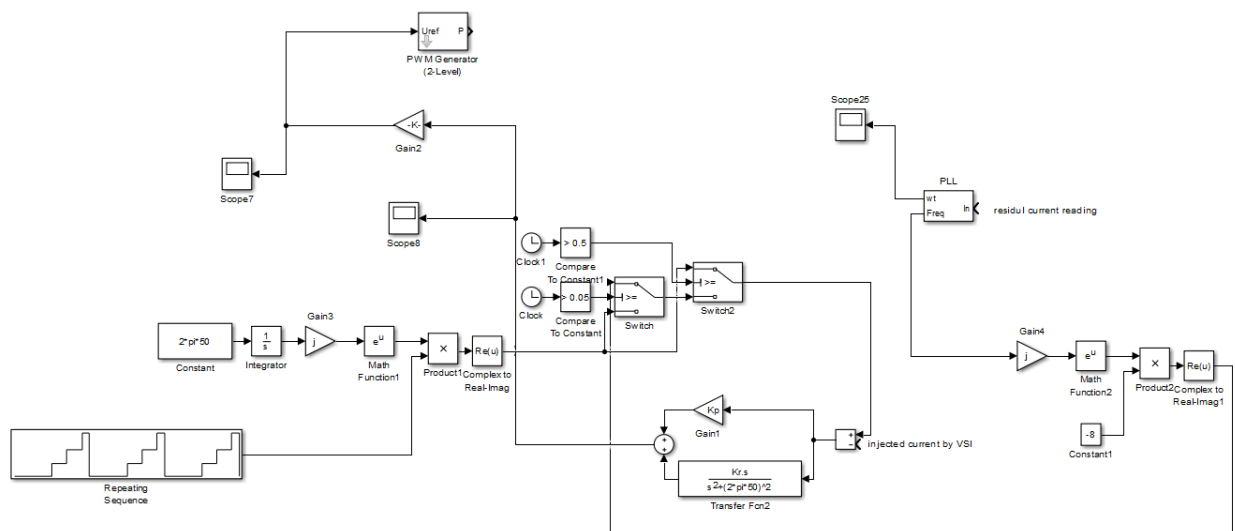


Figure 5.29 Closed Loop Control of PWM Generator

An earth fault is made on one feeder at a single phase, and the corresponding transformer neutral current and fault current are monitored as shown in Figure 5.30

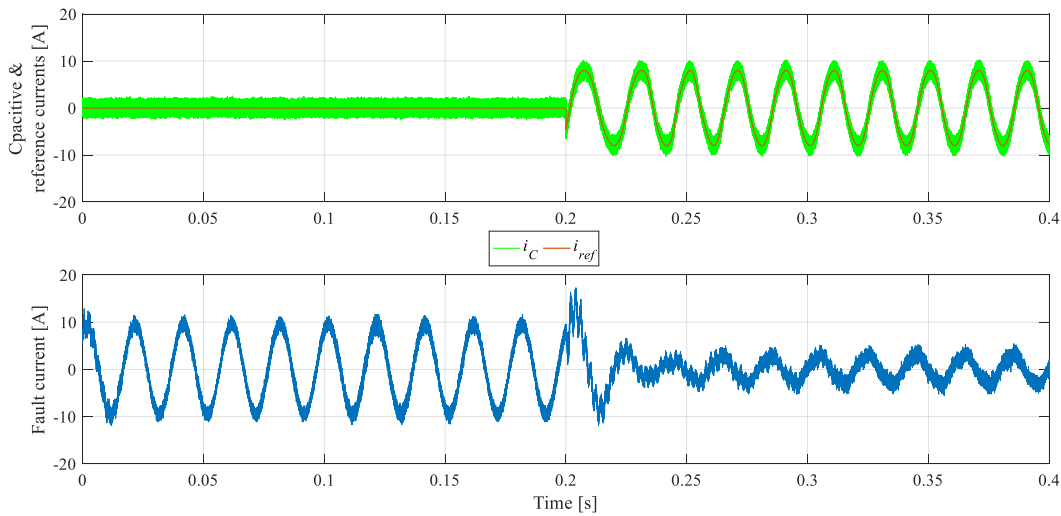


Figure 5. 30 Injected Neutral and Fault Currents

The upper plot of Figure 5.30 shows the reference and injected current of the VSI, where the reference current in the first stage [0-200ms] is set to zero. At the same stage, the fault current shown in the lower plot of Figure 5.30 represents the total capacitive current of the distribution system. At 0.2s the reference signal is set to neutralize the fault current by forcing the VSI to inject negative value of the total capacitive current detected in the first stage. The result of that is almost zero fault current as indicated in the lower plot of Figure 5.30.

Figure 5.30 was obtained by running the simulation on 400ms without starting the earth fault control sequence. The VSI is programmed to operate as an isolated system for 200ms and then to compensate the earth fault current between 200-400 ms.

To achieve fault current discrimination, the system was programmed to operate in 5 stages as shown in Figure 5.31. The five earth fault control stages are:

Stage1: It starts from 0 to 50ms. The system at this stage operates as an isolated system by using zero reference signal for PWM controller. In this stage, the earth fault current value at the fault point is equal to the total network capacitive current. This fault current is measured at the faulty feeder to generate the reference current for the next stage.

Stage2: It starts from 50ms to 500ms. The purpose of this stage is to compensate for the capacitive fault current measured at the first stage. The reference signal is generated in this stage by inverting the capacitive current measured in the first stage.

Stage3: It starts from 500ms to 700ms. If the fault is permanent and doesn't vanished in the second stage, the VSI generates a low current fault signal compatible with the protection scheme to let the downstream circuit breaker to isolate the fault without influencing the upstream ones.

Stage4: It starts from 700ms to 900ms. If the fault does not exist in the protection zone of the last circuit breaker in the distribution feeder (normally MV customer circuit breaker), then no breaker will trip in the third stage because the fault current is less than the threshold of the earth fault protection in the higher-level circuit breakers. Thus, the VSI increases the fault current to a higher value which exceeds the threshold of the circuit breaker in the upstream. Consequently, this breaker will trip and isolate the fault.

Stage5: It starts from 900ms to 1s. This stage is reached by the controller if the earth fault is next to the transformer main breaker. In this stage, the VSI will inject a higher earth fault current to let the main circuit breaker trips and isolate the fault.

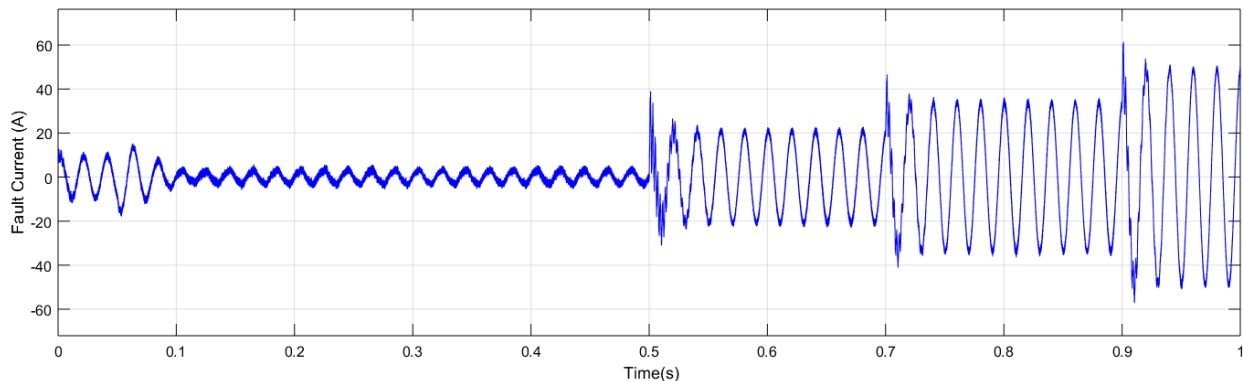


Figure 5. 31 Five Stages Control of Earth Fault Current

A main advantage of the proposed grounding method compared to traditional solid grounding method which is normally used in distribution companies at distribution voltages of 33 & 11kV is the limitation of voltage sags at the healthy feeders. Figure 5.32 shows the three phase voltages of healthy feeders at the moment of earth fault. Comparing this result with voltages of healthy feeders in solid grounding method depicted in Figure 5.8 shows an enhancement of the phase voltage in which the fault occurs. This contributes to a great extent in limiting voltage sags that people will feel on healthy feeders in the case of solid grounding.

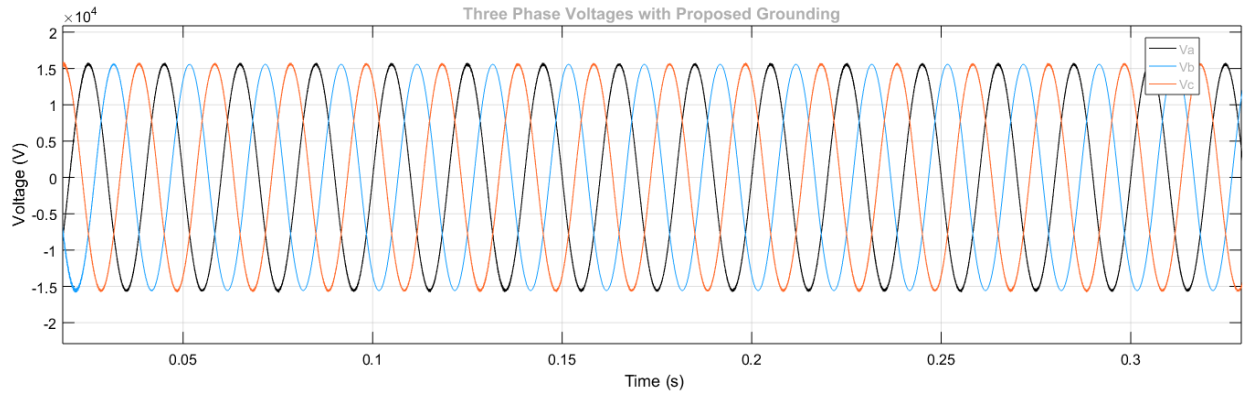


Figure 5. 32 Three Phase Voltages with proposed grounding method

Moreover, the proposed grounding method increases personal safety by minimizing the earth fault current, that results in less touch voltage on the object on which the fault occurs.

Chapter 6: Conclusions and Recommended Future Work

6.1 Conclusions:

In this thesis, various neutral grounding methods are studied. The conventional grounding method; solid, isolated, resistive and compensated neutral grounding methods have been introduced and simulated using Matlab/Simulink software. Solid state techniques of controlling the fault current have been introduced in the literature review. An adaptive neutral grounding technique implementing VSI is introduced in this proposal to achieve required goals which enhance the earth fault protection in medium voltage network, while utilizing the protective relays already installed in the system.

The enhancement of the proposed method focuses on the following issues:

- Reducing the earth fault currents in the system, which protects all network components
- Eliminating transient earth fault in the network, which contributes to a great enhancement of MV distribution reliability
- Achieving a current protection discrimination at the same voltage level by controlling the fault current
- Utilizing already existing protective relays in the MV distribution network
- Limiting voltage sags in healthy feeders
- Increasing personal safety

The proposed adaptive grounding methods consists of inserting a VSI between the neutral point and the ground to inject current into the neutral point of the transformer at the moment of fault occurrence. This current will compensate for the capacitive current at the fault point, resulting in almost zero fault current. Consequently, transient earth fault will be cancelled and the system can continue supplying power without any interruption. If the fault is permanent, the VSI increases the injected current, which will result in a total fault current greater than zero. The inverter increases the fault current until it reaches the threshold value of earth fault protection at the secondary switchgear. If the fault occurs in a secondary branch, the secondary circuit breaker will trip and

isolate the faulty part, otherwise the inverter increases the current until reaching the threshold of the primary switchgear, and so the primary circuit breaker will trip and isolate the feeder.

6.2 Future Work:

The following guidelines are suggested for future work in this field:

- Designing the VSI, and implementing the system as prototype to validate the simulation results by experimental one
- Simulating the proposed system under various fault conditions
- Analyzing the results and drawing up conclusions
- Utilizing impedance converters to control the earth fault currents.
- Decreasing the output harmonics of the VSI by using multi-level inverter

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