DEVELOPMENT OF AN ALGORITHM FOR THE STUDY OF POWER SYSTEM GROUNDING

by

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ABSTRACT

SONA RAJKUMAR: Development of an algorithm for the study of power system grounding. (Under the direction of DR. V.P. LUKIC)

It is commonly known that when using electronic equipment, both personnel and equipment need to be protected from high power transients. In order to ensure safety and prevent equipment damage, a grounding system must be used to provide a low resistance path to ground. The grounding system is essential to complete an electrical path to ground if there is non-designed or unanticipated above-normal potential current or voltage surges during operating conditions. The goal of the thesis involves obtaining the short circuit current from a given large scale system and attaching the subsystem with a desired type of grounding method according to the user's choice. The first part of the thesis is on developing programs that consists of 4 types of grounding protection: High-resistance neutral grounding, High-resistance grounding with three distribution transformers, Low-impedance grounding, and Solid grounding. To protect the system from the fault, the user has 4 options of grounding protection systems available for analysis and can make a required selection. The second part of the thesis is on large scale analysis i.e., short circuit analysis as final needed results for the subsystem grounding. This is technically, the base of the thesis which is used to calculate the short circuit currents on the large scale system at the location of the fault. The Z-bus calculation has been automated and used to calculate the Thevenin's equivalent circuit and fault currents. Large scale system at the point of short circuit is connected to our system and is analyzed from the grounding point of view. These above obtained short circuit and Thevenin's equivalent values are used in the subsystems by the user to select the required type of grounding system method.

ACKNOWLEDGMENTS

I would like to thank my advisor Dr. V.P. Lukic, for his guidance and motivation, without which, this thesis would not have been possible. His teachings have always been useful and gave encouragement. It would be my duty to extend my gratitude to the committee members Dr. Valentina Chechi and Dr.Mehdi Miri for taking time to be on my committee and assess my work. I am thankful to EPIC (Energy Production and Infrastructure Center) for its generous support.

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CHAPTER 1: INTRODUCTION TO THE GROUNDING METHODS

Short circuits may occur in power systems due to system over voltages caused by lightning or switching surges or due to equipment insulation failure or even due to insulator contamination. Sometimes even mechanical causes may create short circuits. Other well-known reasons include line-to-line, line-to-ground, or line-to-line faults on overhead lines. The resultant short circuit has to the interrupted within few cycles by the circuit breaker [10].

Power systems engineers have developed several methods of effective grounding of industrial power distributions systems over the years in order to protect the systems from short circuit currents. Historically, the method of system grounding selected for various electrical system settings, e.g. industrial, commercial, etc., dates back to the early part of this century when only two methods were considered: solid grounded and ungrounded. Solid grounding with its advantage of high fault levels to drive protective devices into tripping had equally significant disadvantages such as dangers posed by arcs in hazardous areas [11]. Also, the issue of service continuity of critical loads pointed away from this grounding method. The perception that ungrounded systems provide service continuity, at least through the first ground fault, strongly suggested ungrounded systems. In more recent times well accepted, if not misapplied grounding techniques utilizing resistance or reactance, have provided the power systems engineer other alternatives [11].

The goal of the thesis involves obtaining the short circuit current from a given large scale system and attaching the subsystem with a desired type of grounding method according to the user's choice. The developed algorithm consists of 4 types of grounding protection: High-resistance neutral grounding, High-resistance grounding with three distribution transformers, Low-impedance grounding, and Solid grounding. The fault occurs in the large scale system and the short circuit current at the fault location is calculated using the procedure developed in the thesis. To protect the system from the fault if occurred, the user has 4 options of grounding protection systems available for analysis and make decision based on which one is the most adequate in the specific case. The user can pick the type of grounding protection that he/she requires for the system. If the user wants to pick more than one type of grounding protection for the analysis, the procedure presented makes it possible, as shown in Fig 2.1.

Resistance Grounding Systems are used in electrical power distribution systems to limit phase-to-ground fault currents, usually for the following reasons [8].

1. To reduce electrical-shock hazards to personnel caused by stray ground fault currents in the ground return path.

2. To reduce the arc blast or flash hazard to personnel who may have accidentally caused or who happen to be in close proximity to the ground fault.

3. To reduce the momentary line-voltage dip occasioned by the occurrence and clearing of a ground fault.

4. To secure control of the transient over-voltages while at the same time avoiding the shutdown of a facility circuit on the occurrence of the first ground fault (high-resistance grounding).

Here we discuss a few methods for grounding:

- High-resistance neutral grounding
- High-resistance grounding with three distribution transformers
- Low-impedance grounding
- Solid (effective) grounding

Most of the older industrial plants were powered by ungrounded, 3-phase, 3-wire, and delta power systems. Many of these systems are still in use today. This system choice was based on two factors. First, it made the most efficient use of conductor copper. Second, no fault current flowed when the first ground-fault occurred, which was, and still is, considered an advantage in some applications, although a shock hazard is introduced [12].

However, multiple motor failures in numerous industrial plants were seen and were due to severe overvoltages caused by arcing or resonant ground faults on the ungrounded systems. To prevent these overvoltages, many power system neutrals were grounded, usually solidly [7]. There were many factors that contributed to the change to solidly grounded systems and these factors are still important today.

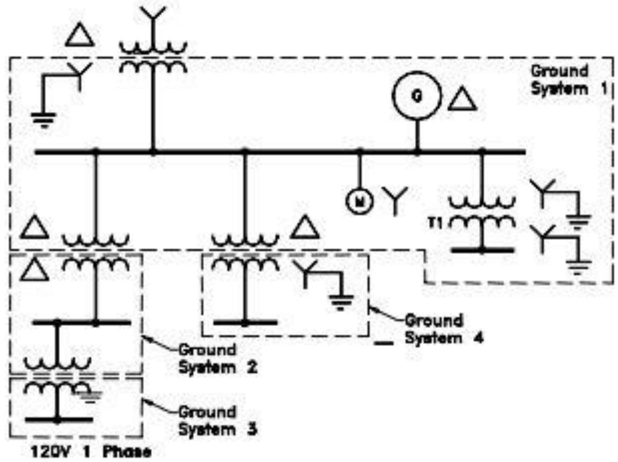


Figure 1.1 Grounding systems

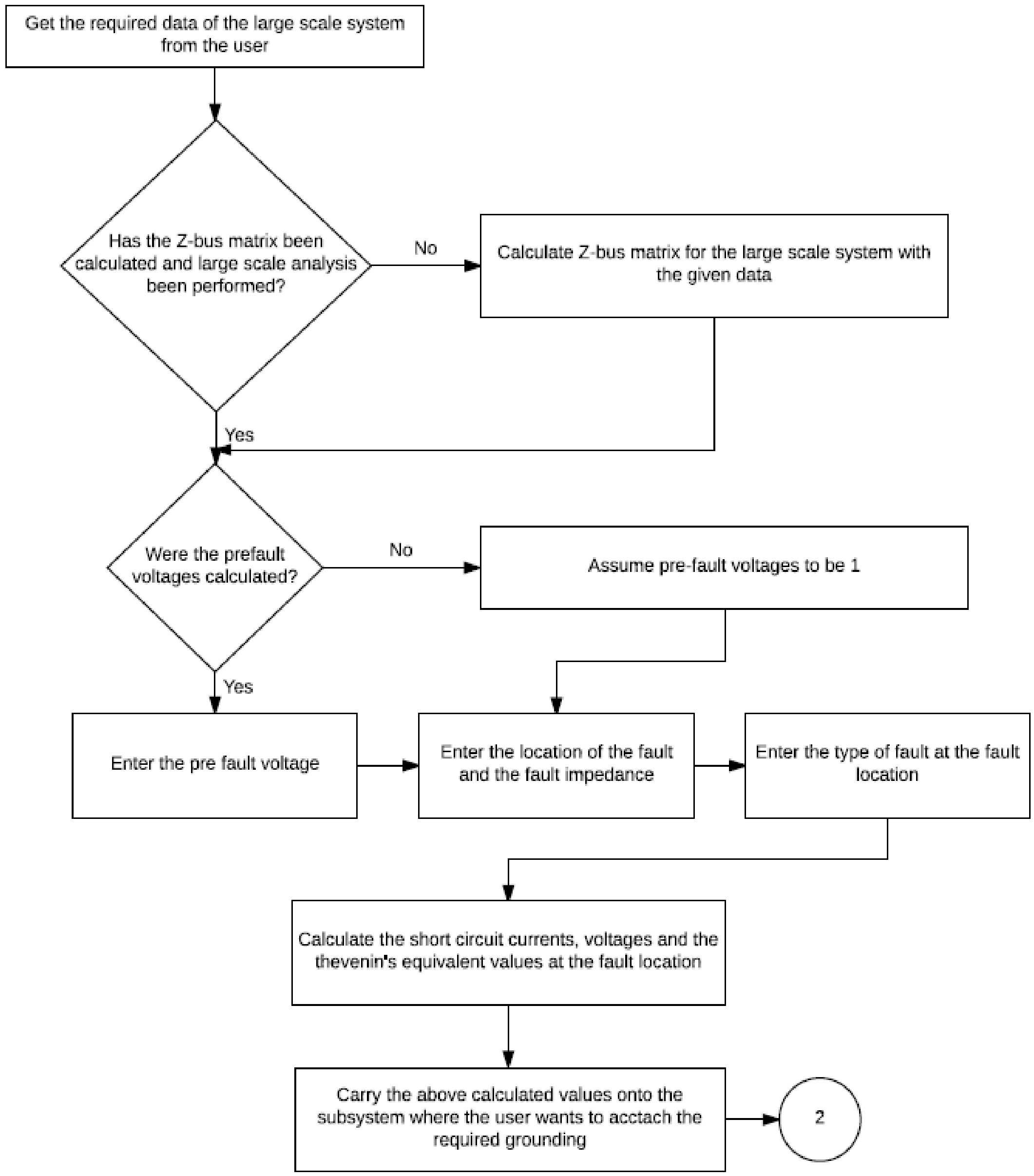
A grounding system is isolated from other grounding systems by delta windings in three-phase systems. It only takes one delta winding to accomplish isolation; not both primary and secondary windings. Beginning at the main transformer secondary, there are four separate grounding systems illustrated in Fig. 1.1. System 1 includes all of the 480 volt system including the source generator through all the primary delta windings of the loads [9]. The wye ungrounded motor and wye-wye solidly grounded transformer secondary is also a part of the 480 volt system. Any grounding problem in the secondary of transformer T1 will affect the 480 volt system. In contrast, any grounding problem in grounding systems 2, 3 or 4 will not affect its respective primary grounding system due to its primary delta windings [11].

The grounding scheme to be used must be given careful consideration for the resulting system to provide the required level of reliability [7]. If designed properly, either a solidly-grounded or high resistance grounding system arrangement can provide stable systems which fulfill the expectations of high reliability and maintainability. A good grounding system requires a high current capacity path with relatively low impedance at the fundamental frequency so that voltages developed under high fault current conditions are not hazardous [6].

CHAPTER 2: SYSTEM GROUNDING

To add grounding for a subsystem, we have to have the connection between our large scale system and the industrial subsystem. The large scale system analysis resulted in Z-bus matrix calculation and based on the z-bus we calculate the short circuit values for any bus, depending on where our subsystem is connected. In the below flowchart we explain the connection between the large scale system and selection of grounding methods chosen in this thesis for the grounding analysis.

The below flowchart also shows that the user can select one or more number of grounding protection methods. If the user initially wants to use low-impedance grounding for his system, then he would select the case 3. But the program allows him to go back and review his/her options. The user can add another grounding method again, and can continue till they use all of the grounding methods. Once the user has used all of the methods, he has arrived at the maximum possible options to be selected and the program ends.


Get the required data of the large scale system from the user
Has the Z-bus matrix been calculated and large scale analysis been performed?
No
Calculate Z-bus matrix for the large scale system with the given data
Yes
Were the prefault voltages calculated?
No
Assume pre-fault voltages to be 1
Yes
Enter the pre fault voltage
Enter the location of the fault and the fault impedance
Enter the type of fault at the fault location
Calculate the short circuit currents, voltages and the thevenin's equivalent values at the fault location
Carry the above calculated values onto the subsystem where the user wants to acctach the required grounding
2

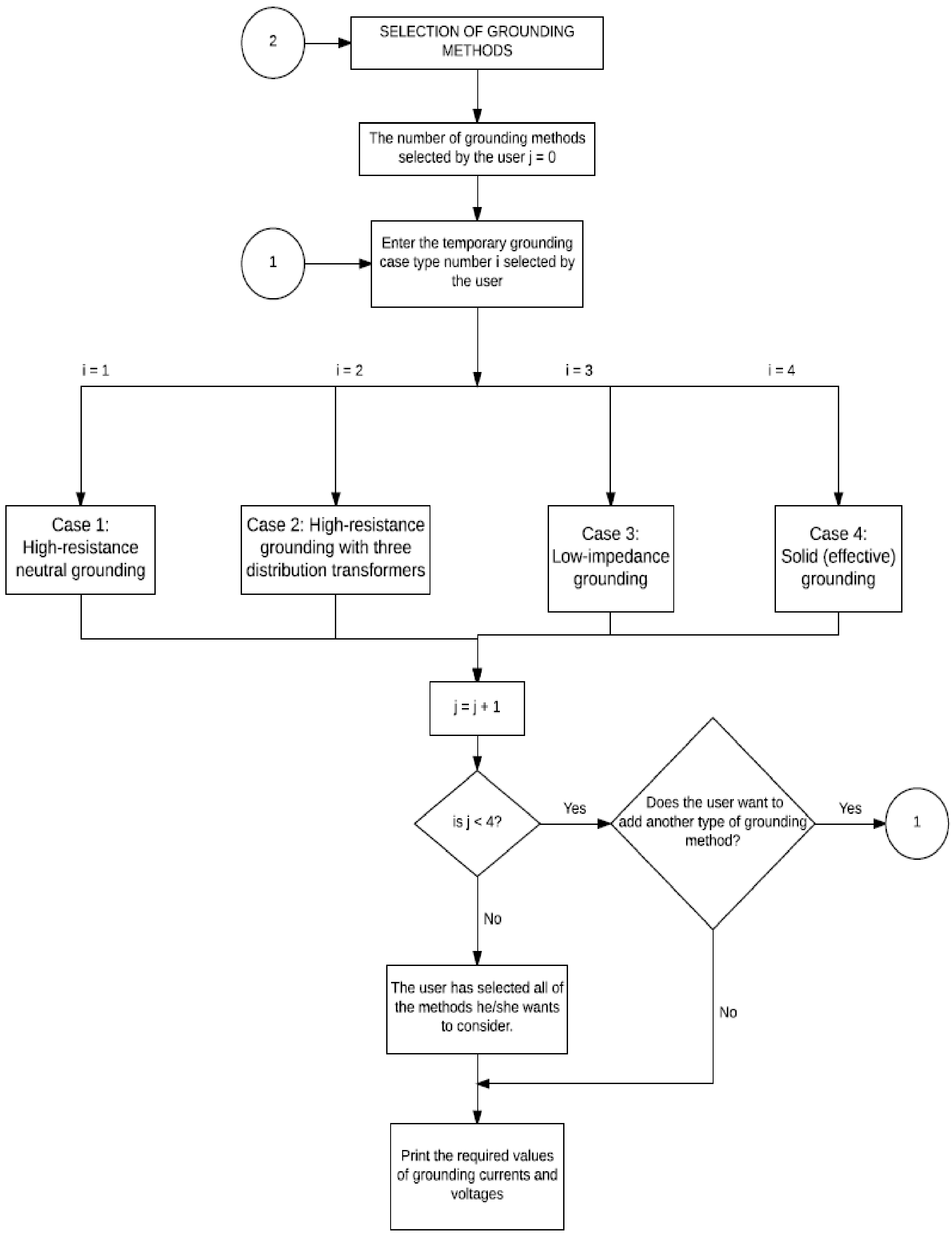


Figure 2.1 Flowchart on system grounding

In order to guide the user through as to which grounding system would suit their system best, we have listed a few advantages and disadvantages of each method below [9]:

- High-Resistance Grounding

Advantages:

- No transient over-voltages
- Easy fault location method
- No Arc Flash Hazards (with ground faults)

Disadvantages:

- No directly connected line-to-neutral loads
- Requires different arrester ratings
- Requires higher cable insulation ratings

- Low Impedance Grounding:

Advantages:

- Eliminates high transient overvoltages
- Limits damage to faulted equipment
- Reduces shock hazard to personnel

Disadvantages:

- Some equipment damage can still occur
- Faulted circuit must be de-energized
- Line-to-neutral loads cannot be used

- Solid Grounding:

Advantages:

- Eliminated transient over-voltage problem
- Permit line-to-neutral loads (lighting, heating cables)
- Ground faults easy to locate

Disadvantages:

- Cause unscheduled service interruption
- Danger from low-level arcing ground faults
- Strong shock hazard to personnel
- Coordination Issues
- Arc-flash issues

In the upcoming chapters, we are going to analyze about every grounding method, develop and program for the methods and verify those programs using manually calculated examples for the methods.

CHAPTER 3: HIGH-RESISTANCE NEUTRAL GROUNDING

High resistance grounding of the neutral limits the ground fault current to a very low level (typically from 1 to 10 amps) and this is achieved by connecting a current limiting resistor between the neutral of the transformer secondary and the earth ground and is used on low voltage systems of 600 volts or less, under 3000 amp. By limiting the ground fault current, the fault can be tolerated on the system until it can be located, and then isolated or removed at a convenient time [5]. To avoid transient over-voltages, a high resistor must be sized so that the amount of ground fault current that the unit with allow to flow exceeds the electrical system's charging current [5].

The grounding resistor may be connected in the neutral of a power transformer or across the broken delta secondary of three phase-to-ground connected distribution transformers. These systems are mainly used in such Medium Voltage and Low Voltage industrial networks, where the continuity of service is important because a single fault does not cause a system outage [4]. If the grounding resistor is selected so that its current is higher than the system capacitive earth fault, then the potential transient overvoltages are limited to 2.5 times the normal crest voltage. The limiting factor for the resistance is also the thermal rating of the wining of the transformer [4].

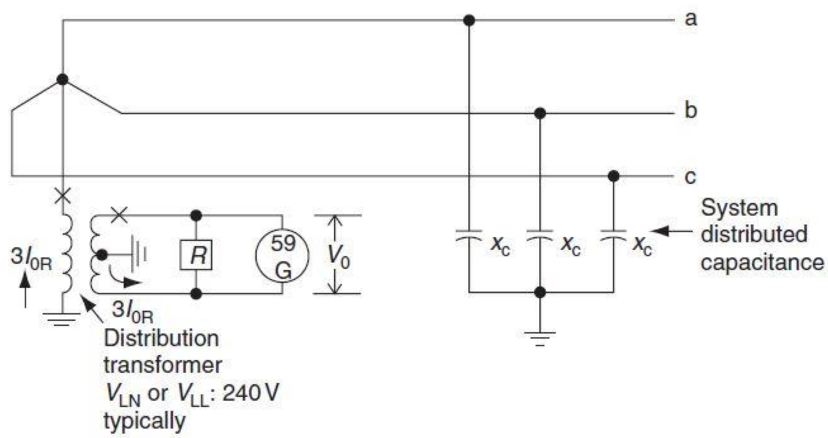


Figure 3.1: High resistance grounding with resistor in neutral of distribution transformer

The grounding resistor may be connected in the neutral of a generator or power transformer, as shown in Fig 3.1, or across the broken delta of line-to-ground connected distribution transformers. With the resistor in the neutral, as in Fig 3.1, a solid ground fault can produce a maximum V_o equivalent to the phase-to-neutral voltage. Thus a line-to-neutral rated distribution transformer is normally used, although line-to-line ratings have also been used [3]. For the grounding system, a solid ground fault can raise the voltage on two of the distribution transformers to line-to-line equivalent. Thus, line-to-line ratings are suggested for this application, especially if the protection system is used for alarm, rather than direct trip. The neutral connection, as shown in Fig 3.11, is used for unit generator applications and in industrial systems with a single power transformer supply [3].

3.1: Design of the grounding with the resistor in neutral:

Consider a distribution system with unit generator as shown in Fig 3.2, with grounding applied through a resistor connected to the secondary of the distribution transformer. The area of ground protection is the generator to the low-voltage winding transformer and to the high-voltage winding of the unit auxiliary transformer [3].

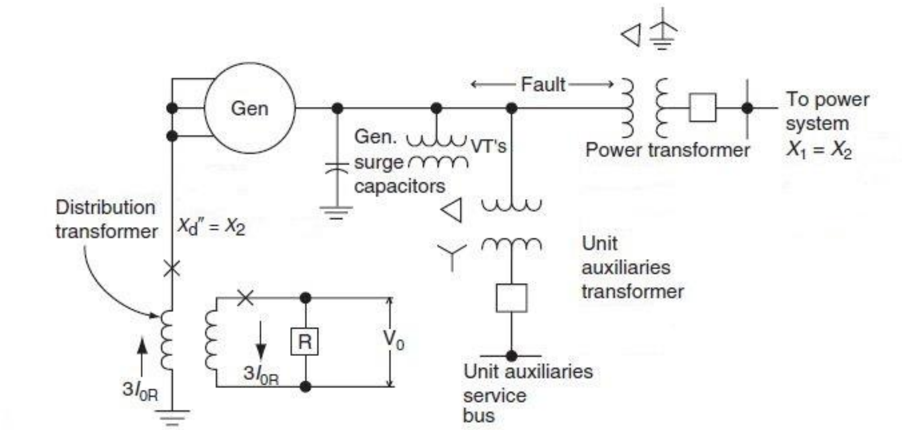


Figure 3.2: Unit generator system showing high resistance grounding with neutral resistor

The following capacitances to the ground must be considered to calculate the required grounding resistance: Capacitance of the generator windings (C_{GW}) , capacitance of the generator surge capacitor (C_{GS}), capacitance of the generator-to-transformer leads (C_{GT}), capacitance of the power transformer low-voltage winding (C_{LT}), capacitance of the station service transformer high-voltage winding (C_{TH}) and capacitance of the voltage transformer windings (C_{VT}).

The total capacitance (C) to ground is obtained by the sum of all the above capacitances.

$$C = C_{GW} + C_{GS} + C_{GT} + C_{LT} + C_{TH} + C_{VT}$$

The capacitive reactance X_c is found using

$$X_C = \frac{-j*10^6}{2\pi f C}$$

The pu value of the capacitive reactance is:

$$X_{C(pu)} = \frac{S_{Base}X_C}{V_{Base}^2}$$

Design method considers the approach when the grounding resistor is equal in the magnitude to the capacitive reactance. We assume the base value to some convenient number we in this study, will take the base as 100 MVA. Since the total system capacitance reactance X_c is in parallel to the resistor in grounding path, the total impedance of this parallel combination is,

$$Z_0 = \frac{R\angle 0° * X_C\angle -90°}{R\angle 0° + X_C\angle -90°}$$

This total impedance is assumed to be zero sequence impedance since positive and negative sequence impedances are negligible.

In this study, we will consider single phase short circuit. The currents calculated based on short circuit analysis with symmetrical components are with regard to equivalent circuit for this type of short circuit.

$$I_{1pu} = I_{2pu} = I_{0pu} = \frac{Vs}{Zo}$$, where usually V_s is 1 pu

The actual fault currents are calculated as

$$I_1 = I_2 = I_0 = (I_{1pu})*I_B$$, where I_B is the base current

Distribution transformer is receiving the current on its primary windings. Turn ratio of the transformer is V_{prim}/V_{sec}. For the primary transformer windings, zero sequence current from the neutral to the ground is equal to $3I_0$. For each phase, one zero current is drawn. The other two total zero sequence current from neutral to the ground is $3I_0$. This is the current that we have in the primary of the distribution transformer. On the secondary side of distribution transformer, we have the current

$$I_s = \frac{3I_{OR}}{\left(\frac{V_{\text{prim}}}{V_{\text{sec}}}\right)}$$

As assumed before, we will place resistance equal in magnitude to the total system natural capacitances or $3R = X_C$.

Each R is for one phase current. Resistance placed in the neutral of the generator will be seen on the secondary side of the distribution.

$$R_S = \frac{R}{\left(\frac{V_{\text{prim}}}{V_{\text{sec}}}\right)^2}$$

In terms of total system neutral capacitances resistance on the secondary side of distribution transformer will be

$$R_S = \frac{X_C}{3}\left(\frac{V_{\text{prim}}}{V_{\text{sec}}}\right)^2$$

Voltage across the secondary side of distribution transformer will be,

$$V_0 = R_s I_s$$

The power on the secondary side dissipated in the form of heat is,

$$S = \frac{V_{LL}}{\sqrt{3}} * 3I_{OR}$$

When this grounding is used for generator units, tripping the units is recommended, so that these rating could be short time ratings rather than continuous ratings.

The normal charging current for this system would be

$$I_c = \frac{V_{LL}}{\sqrt{3} * X_C}$$

The use of a distribution transformer and a secondary resistor, rather than a resistor directly connected in the neutral, is an economic consideration. With high-resistance grounding it is generally less expensive to use the resistor in the secondary, as shown. The flow of current through the system for a ground fault is sometimes hard to visualize from the zero-sequence quantities [3]. Although positive and negative sequence impedances are quite negligible in high resistance grounded system, the three-sequence currents are equal at the fault and flow through the system. Since there is a positive-sequence source at either end, the positive and negative sequence currents divide by 0.51 and 0.49 distribution factors in the positive and negative sequence networks [3].

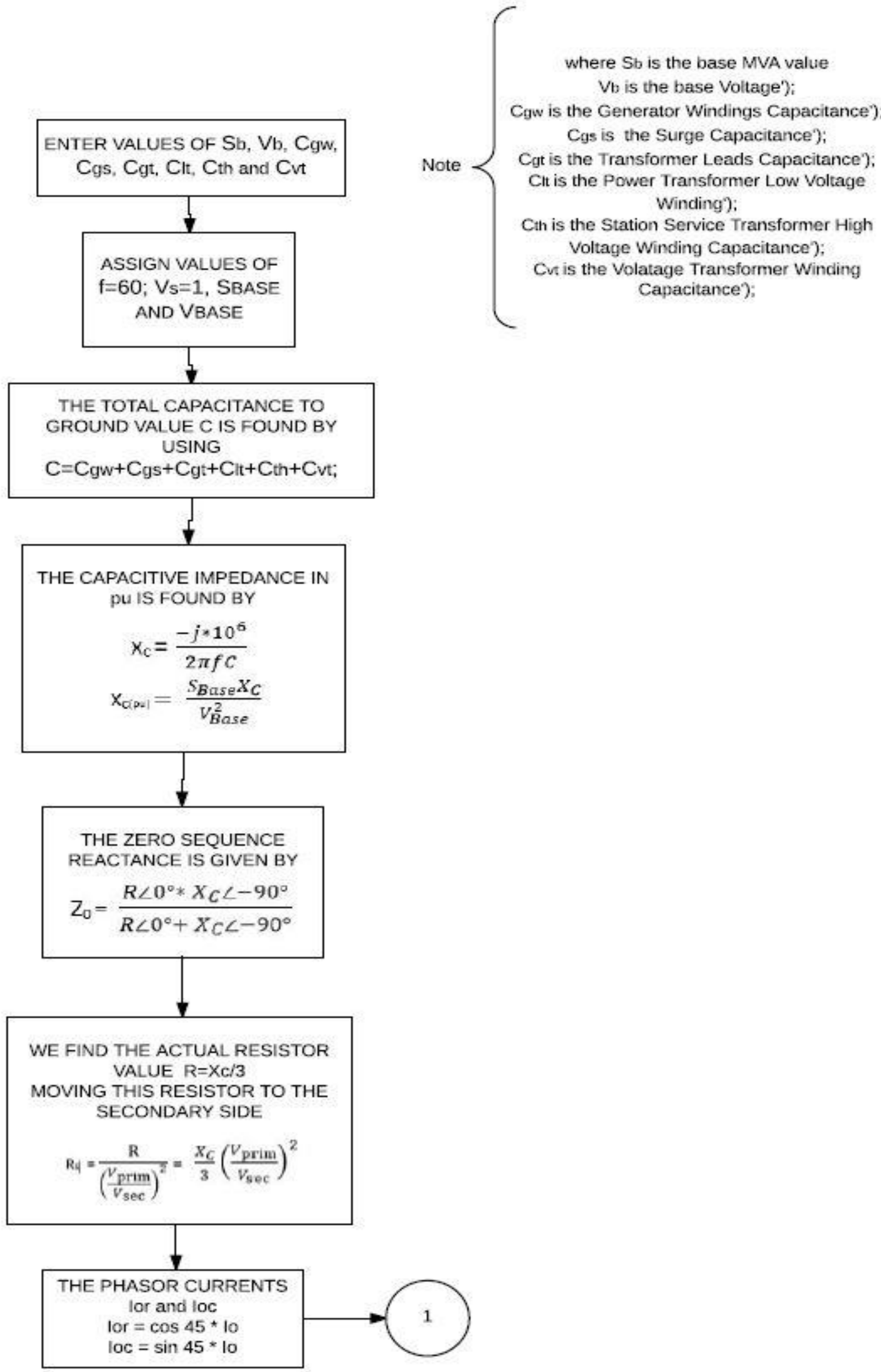
The currents flowing through the system are approximate, for the capacitance normally distributed is shown as lumped. Before the fault, a charging current flows symmetrically in the three phases. Because this is the same order of magnitude as the fault currents, Thevenin's theorem and superposition must be used to determine the currents flowing during the ground fault. Thus in phase a, from the generator to the lumped capacitance, I_{a1} is the sum of the prefault charging current and the fault component [3].

The negative and zero-sequence components exist as normally determined by the fault. In the lumped shunt capacitance, the charging current cancels the zero -sequence phase a component to provide zero current, because this branch is essentially shorted out by the solid phase-a-to -ground fault [3]. In the unfaulted phases the charging currents add to the zero-sequence component, providing currents such as I_{a0}, I_{a1}, I_{a2}, I_{b0}, I_{b1}, I_{b2}, I_{c0}, I_{c1} and I_{c2}

.

Again, this assumes that none of the distributed capacitance is in the area to the right of the fault location. As has been indicated, the total fault value would not change for different fault locations; similarly, the distribution will not change basically for no series impedance is considered between the generator and the power transformer [3].

Our goal is to calculate the value of the resistance that we place in the secondary winding of the distribution transformer. The following flow chart gives the logic of the calculation for the high resistance grounding with the resistor of the neutral of distribution transformer.


ENTER VALUES OF Sb, Vb, Cgw, Cgs, Cgt, Clt, Cth and Cvt
ASSIGN VALUES OF f=60; Vs=1, SBASE AND VBASE
THE TOTAL CAPACITANCE TO GROUND VALUE C IS FOUND BY USING
C=Cgw+Cgs+Cgt+Clt+Cth+Cvt;
THE CAPACITIVE IMPEDANCE IN pu IS FOUND BY
$X_C = \frac{-j*10^6}{2\pi f C}$
$X_{C(pu)} = \frac{S_{Base} X_C}{V_{Base}^2}$
THE ZERO SEQUENCE REACTANCE IS GIVEN BY
$Z_0 = \frac{R\angle 0° * X_C\angle -90°}{R\angle 0° + X_C\angle -90°}$
WE FIND THE ACTUAL RESISTOR VALUE R=Xc/3
MOVING THIS RESISTOR TO THE SECONDARY SIDE
$R_{ij} = \frac{R}{\left(\frac{V_{prim}}{V_{sec}}\right)^2} = \frac{X_C}{3}\left(\frac{V_{prim}}{V_{sec}}\right)^2$
THE PHASOR CURRENTS Ior and Ioc
Ior = cos 45 * Io
Ioc = sin 45 * Io
1
Note
where Sb is the base MVA value
Vb is the base Voltage');
Cgw is the Generator Windings Capacitance');
Cgs is the Surge Capacitance');
Cgt is the Transformer Leads Capacitance');
Clt is the Power Transformer Low Voltage Winding');
Cth is the Station Service Transformer High Voltage Winding Capacitance');
Cvt is the Volatage Transformer Winding Capacitance');

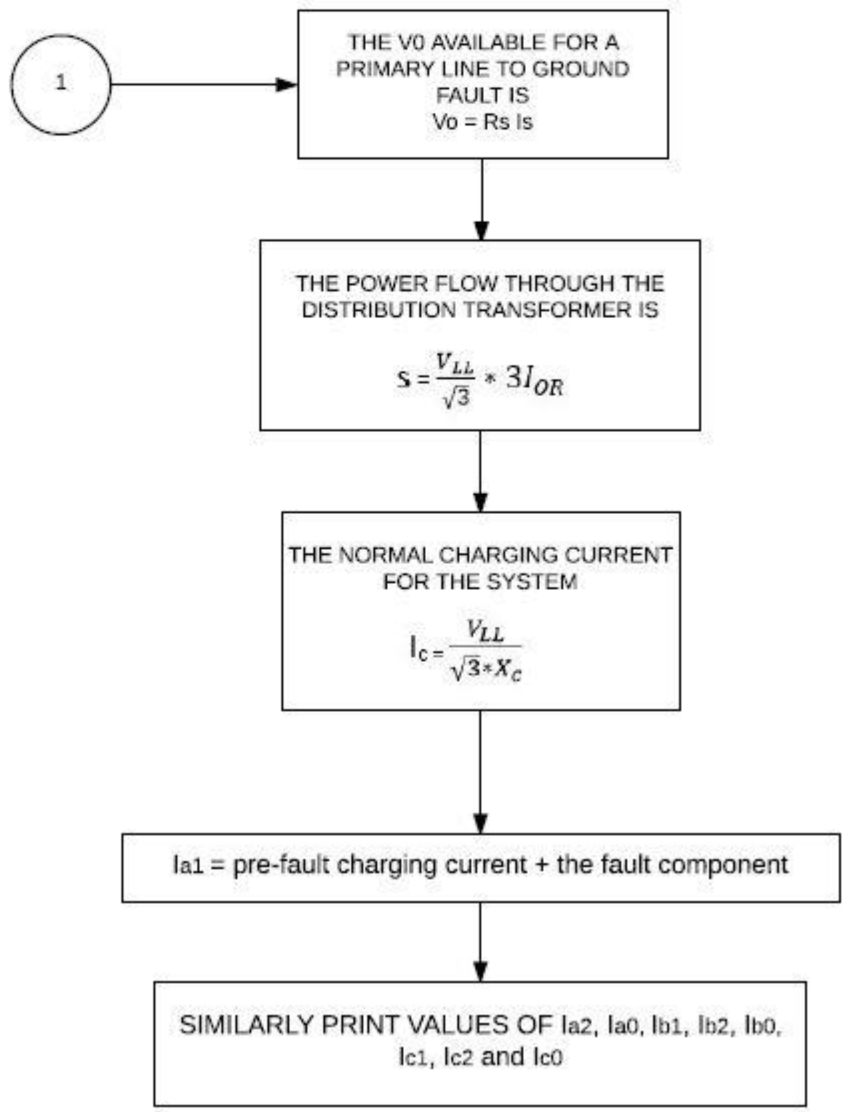


Figure 3.3: Flowchart for high-resistance grounding with a neutral connected resistor at the distribution transformer

3.2: Example for A Typical High-Resistance Neutral Grounding System:

Consider a distribution system with a 160 MVA 18kV unit generator with the resistor connected to the secondary of the distribution transformer. The area of ground protection is the generator to the low-voltage winding transformer and to the high-voltage winding of the unit auxiliary transformer. In this are the following capacitances to the ground (microfarads per phase) must be considered:

Generator windings capacitance (C_{GW})	0.24
Generator surge capacitance (C_{GS})	0.25
The generator-to-transformer leads capacitance (C_{GT})	0.004
Power transformer low-voltage winding capacitance (C_{LT})	0.03
Station service transformer capacitance (C_{TH})	0.004
High-voltage winding voltage transformer windings capacitance (C_{VT})	0.0005
Total capacitance to ground (C)	0.5285

In the following figure 3.4, our example network is given with all system parameters:

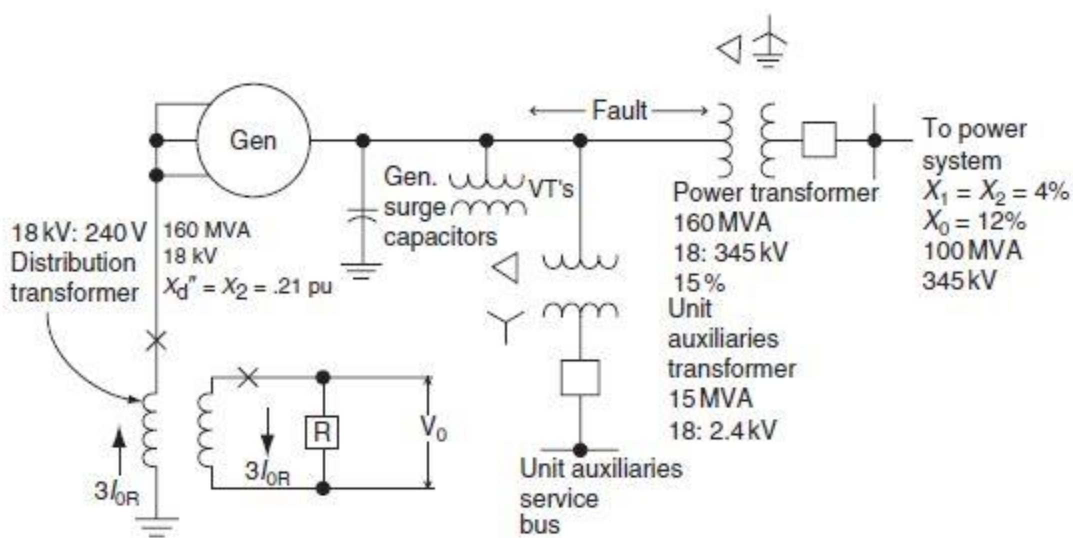


Figure 3.4: Unit generator system of high resistance grounding with neutral resistor connected to distribution transformer

The capacitive reactance X_c is found using

$$X_C = \frac{-j*10^6}{2\pi f C} = 5019.08\ \Omega/\text{phase}$$

The pu value of the capacitive reactance on a 100MVA 18kV base is:

$$X_{C(pu)} = \frac{S_{Base} X_C}{V_{Base}^2} = \frac{100 \quad 5019}{18^2} = 1549.1 \text{ pu}$$

Selecting the grounding resistor to be equal to the capacitive reactance and using the convenient 100 MVA base, 3R in the zero-sequence network would be 1549.1 pu. For a solid fault in this area,

$$Z_0 = \frac{1549.1\angle 0° * 1549.1 \quad \angle -90°}{1549.1\angle 0° + 1549.1 \quad \angle -90°} = 1095.38\angle -45° \text{ pu}$$

The positive and negative sequence reactance Z_1 and Z_2 which are derived from the circuit as j0.066 pu and hence, are negligible. For the single phase short circuit, the currents in each of the equivalent circuit, positive, negative and zero are equal to the zero sequence current.

$$I_{1pu} = I_{2pu} = I_{0pu} = \frac{1}{1095.38\angle -45°} = 0.00091\angle 45° \text{ pu}$$

$$I_B = 3207.5 \text{ A at } 18 \text{ kV}$$

The actual fault currents are found by

$I_1 = I_2 = I_0 = (I_{1pu})*I_B$, where I_B is the base current

$I_1 = I_2 = I_0 = 0.00091(3207.5) = 2.92$ A at 18kV

In the figure 3.5, a simplified circuit of our example considering the distribution of fault currents is given.

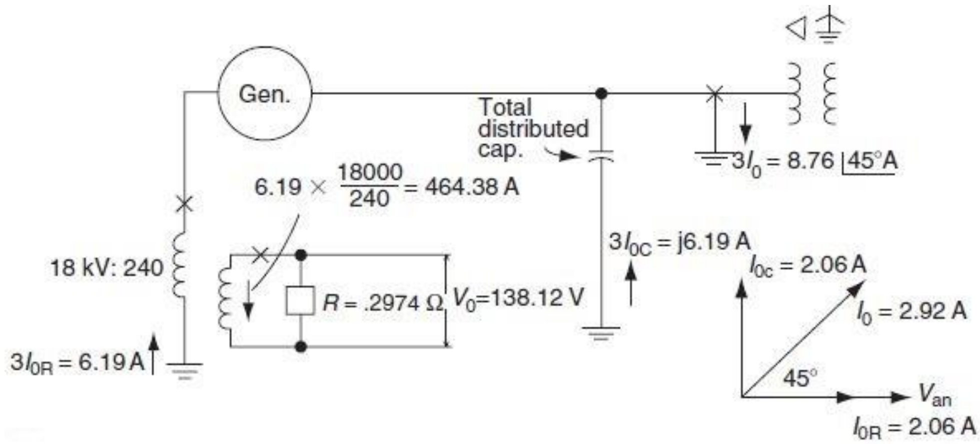


Fig 3.5: Distribution of fault currents in the system

The actual resistor value connected to the secondary of the distribution transformer will be

$$R_S = \frac{R}{\left(\frac{V_{prim}}{V_{sec}}\right)^2} = \frac{X_C}{3}\left(\frac{V_{prim}}{V_{sec}}\right)^2 = \frac{5019.08}{3}\left(\frac{240}{18{,}000}\right)^2 = 0.2974\ \Omega$$

With a secondary current of $I_s = \frac{3I_{OR}}{\left(\frac{V_{prim}}{V_{sec}}\right)} = \frac{6.19}{\left(\frac{240}{18{,}000}\right)} = 464.38$ A in the distribution transformer secondary, the voltage(V_0) across the resistance in the secondary winding of the transformer will be

$$V_0 = R_S I_S = (464.38)(0.2974) = 138.12\ \text{V}$$

The power flow through the distribution transformer is given by $S = \frac{V_{LL}}{\sqrt{3}} * 3I_{OR} = \frac{6.19\ (18)}{\sqrt{3}}$ = 64.33kVA

The total current due to system capacitances for our example is $I_c = \frac{V_{LL}}{\sqrt{3} * X_C} = \frac{18{,}000}{\sqrt{3} * 5019} = 2.07$ A/phase at 18 kV

The currents flowing through the system are approximate, for the capacitance normally distributed is shown as lumped. Before the fault, a charging current of 2.07A flows symmetrically in the three phases. Because this is the same order of magnitude as the fault currents, Thevenin's theorem and superposition must be used to determine the currents flowing during the ground fault. Thus in phase a, from the generator to the lumped capacitance, I_{a1} is the sum of the prefault charging current and the fault component, or $2.07\angle 90° + 0.51*2.92\angle 45°$ which is $I_{a1} = 3.29\angle 71.4°$. Similarly,

$I_{b1} = 2.07\angle -30° + 0.51*2.92\angle -75° = 3.29\angle -48.7°$

And $\quad I_{c1} = 2.07\angle 210° + 0.51*2.92\angle 165° = 3.29\angle 191.41°$

The negative and zero-sequence components exist as normally determined by the fault. In the lumped shunt capacitance, the charging current cancels the zero -sequence phase a component to provide zero current, because this branch is essentially shorted out by the solid phase-a-to -ground fault. In the unfaulted phases the charging currents add to the zero-sequence component, providing currents such as I_{a0}, I_{a1}, I_{a2}, I_{b0}, I_{b1}, I_{b2}, I_{c0}, I_{c1} and I_{c2} . Similarly the other phasor currents are calculated and is distributed as shown in Fig 3.6.

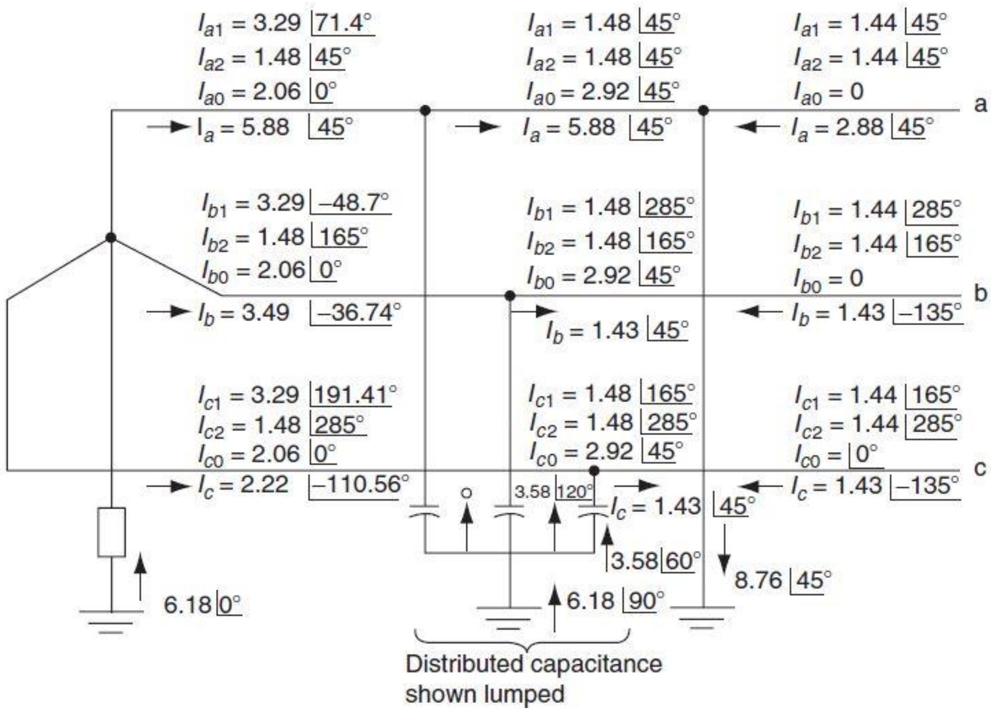


Figure 3.6: Three-phase and sequence current distribution for the system during a solid phase-a-to-ground fault

CHAPTER 4: HIGH-RESISTANCE GROUNDING WITH 3 DISTRIBUTION TRANSFORMERS

High resistance grounding with 3 distribution transformers is typically applied to 480V circuits with limited application to 2400V and 4160V systems. The ground fault current magnitude is sufficiently low such that no appreciable damage is done at the fault point and iron damage to any motors is limited [11]. This means that the faulted circuit need not be tripped off-line when the fault first occurs. It also means that location of the ground fault most likely is unknown. In this respect, it performs just like an ungrounded system [11].

The second point however, is that high resistance grounding can control the transient overvoltage phenomenon if the circuit is designed properly. For high resistance grounding to be effective, the size of the resistor must be carefully selected for each system [11]. Underground fault conditions, the resistance must dominate over the system charging capacitance but not to the point of permitting excessive current to flow and thereby excluding continuous operation [11].

The advantages of a high resistance grounded system are as follows [11]:

- Provides maximum service continuity.
- Relatively inexpensive.
- Controls transient overvoltages due to arcing ground faults on ungrounded systems.

• Ground fault detection scheme makes it easy to locate the fault.

• Limit iron damage to motors and generators.

The disadvantages of high resistance grounding are:

• Can detect ground faults easily but difficult to find ground fault unless a ground fault detection scheme is employed.

• Not practicable above 5 kV unless tripping is provided. C.

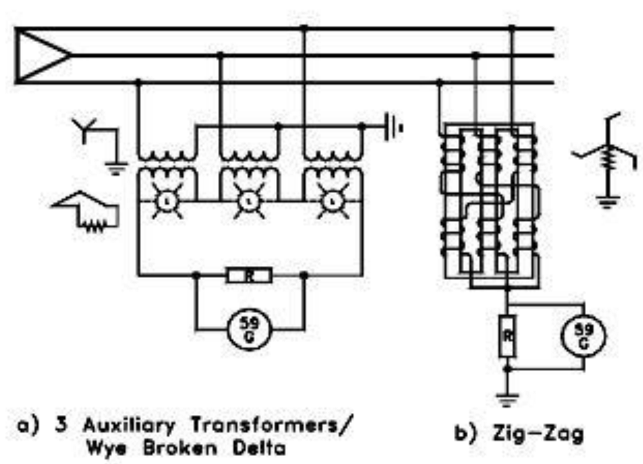


Figure 4.1: High impedance grounding with 3 distribution transformers and a zig-zag transformer

The best way to ground an ungrounded delta system (existing or new) is to derive a neutral point through grounding transformers. This may be accomplished in one of two ways as shown in Fig 4.1. In Fig. 4.1 section a), high resistance grounding is accomplished through three auxiliary transformers connected wye-broken delta [11]. Also, sensing the voltage drop across the resistor can be used to signal an alarm advising that a ground fault has occurred. The three lights across each individual transformer will constitute a version of the normal ground detection scheme currently employed on ungrounded systems.

Grounding Transformers High resistance grounding can also be achieved alternately by a zig-zag grounding transformer as shown in Fig. 4.1 section b). The scheme in Fig. 9a uses the flux in the transformer's iron core to produce secondary voltages with their respective phase relationships [11]. With the zig-zag transformer, the windings are connected in a zig-zag fashion such that the flux in the iron is vectorially summed opposed to vectorially summing the secondary voltages. Consequently it behaves on the system just as the three auxiliary transformers do. The resistor makes it resistance grounded. In both of these cases, either approach accomplishes the same end. Selection should be based on space, weight, size and/or economics as applicable to the system [11]. High resistance grounding offers the best compromise of service continuity of ungrounded circuits and the safety of solidly grounded circuits. A complete high resistance grounding system with ground fault detection and alarming also provides the user with voltage and current information not typically available from ungrounded circuits [11].

4.1: Design of the high-resistance grounding with distribution transformers:

Consider an industrial distribution system with a local generator and a source as shown in Fig 4.2, with grounding applied through 3 distribution transformers. The area of ground protection is the generator to the low-voltage winding transformer and to the high-voltage winding of the unit auxiliary transformer [3].

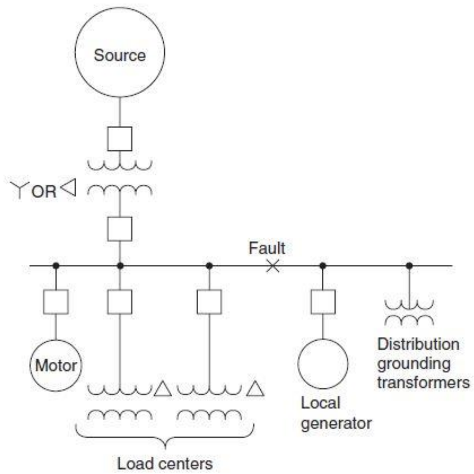


Figure 4.2: Industrial system showing high-resistance grounding with three distribution transformers

The following capacitances to the ground must be considered to calculate the required grounding resistance: Capacitance of the source transformer (C_{st}), capacitance of the local generator (C_{lg}), capacitance of the motor (C_m), capacitance of the power center transformers (C_{pt}), capacitance of the total connecting cables (C_{tc}) and capacitance of the surge capacitor (C_{sc}).

The total capacitance (C) to ground is obtained by the sum of all the above capacitances.

$$C = C_{st} + C_{lg} + C_m + C_{pt} + C_{tc} + C_{sc}$$

The capacitive reactance X_c is found using

$$X_C = \frac{-j*10^6}{2\pi f C}$$

The pu value of the capacitive reactance is:

$$X_{C(pu)} = \frac{S_{Base} X_C}{V_{Base}^2}$$

Thus the charging current for the system is,

$$I_C = \frac{V_B * 10^3}{\sqrt{3} X_C}$$

Design method considers the approach when the grounding resistor is equal in the magnitude to the capacitive reactance. We assume the base value to some convenient number in this study, will take the base as 100 MVA. Since the total system capacitance reactance X_c is in parallel to the resistor in grounding path, the total impedance of this parallel combination is,

$$Z_0 = \frac{R\angle 0° * X_C\angle -90°}{R\angle 0° + X_C\angle -90°}$$

The positive and negative sequence reactance Z_1 and Z_2 which are derived from the circuit as such that X_1 and X_2 are negligible. The currents calculated based on based on short circuit analysis with symmetrical components are with regard to equivalent circuit for this type of short circuit.

$$I_{1pu} = I_{2pu} = I_{0pu} = \frac{Vs}{Zo}$$, where usually V_s is 1 pu

The actual fault currents are calculated as $I_1 = I_2 = I_0 = (I_{1pu})*I_B$, where I_B is the base current

Since the so considered distribution transformer is three phase balanced, for each phase one zero current is drawn. So the zero sequence current from the neutral to the ground is equal to $3I_0$ or $I_a = 3I_0$.

$$I_{OR} = I_0 \cos 45°$$

Distribution transformer is receiving the current on its primary windings. Turn ratio of the transformer is V_{prim}/V_{sec}, On the secondary side of distribution transformer, we have the current

$$I_{OR(sec)} = I_{OR} * \frac{V_{Sec}}{V_{Prim}} \text{ A}$$

The resistor was sized to the X_c value, hence when its reflected to the secondary, the resistor value is,

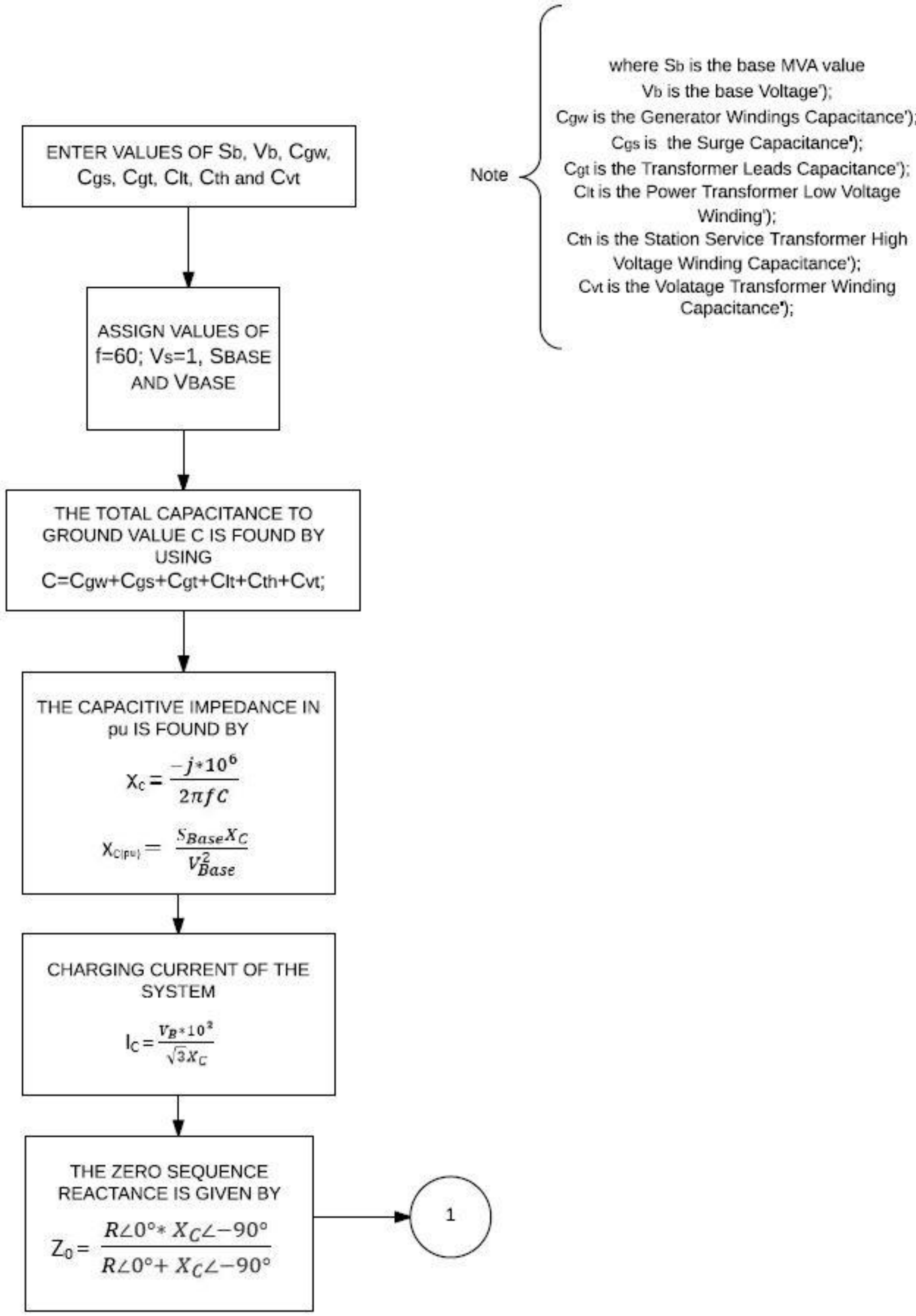
$$3R = 3 * \frac{X_C}{(\frac{V_{Sec}}{V_{Prim}})^2}$$

With the above values, we determine the continuous resistor and transformer ratings:

Resistor: I^2 (3R) kW & Transformer: VI kVA

The line-to-line voltage was used during a fault; this fault appears essentially across the primary winding. If relays are used to trip, short time ratings may be used for the resistor and transformers [3].

The below flowchart considers the high resistance grounding through 3 distribution transformers of an industrial distribution system.


ENTER VALUES OF Sb, Vb, Cgw, Cgs, Cgt, Clt, Cth and Cvt
ASSIGN VALUES OF f=60; Vs=1, SBASE AND VBASE
THE TOTAL CAPACITANCE TO GROUND VALUE C IS FOUND BY USING
C=Cgw+Cgs+Cgt+Clt+Cth+Cvt;
THE CAPACITIVE IMPEDANCE IN pu IS FOUND BY
$X_c = \frac{-j*10^6}{2\pi f C}$
$X_{C(pu)} = \frac{S_{Base} X_C}{V_{Base}^2}$
CHARGING CURRENT OF THE SYSTEM
$I_C = \frac{V_B*10^3}{\sqrt{3} X_C}$
THE ZERO SEQUENCE REACTANCE IS GIVEN BY
$Z_0 = \frac{R\angle 0° * X_C \angle -90°}{R\angle 0° + X_C \angle -90°}$
1
Note
where Sb is the base MVA value
Vb is the base Voltage');
Cgw is the Generator Windings Capacitance');
Cgs is the Surge Capacitance');
Cgt is the Transformer Leads Capacitance');
Clt is the Power Transformer Low Voltage Winding');
Cth is the Station Service Transformer High Voltage Winding Capacitance');
Cvt is the Volatage Transformer Winding Capacitance');

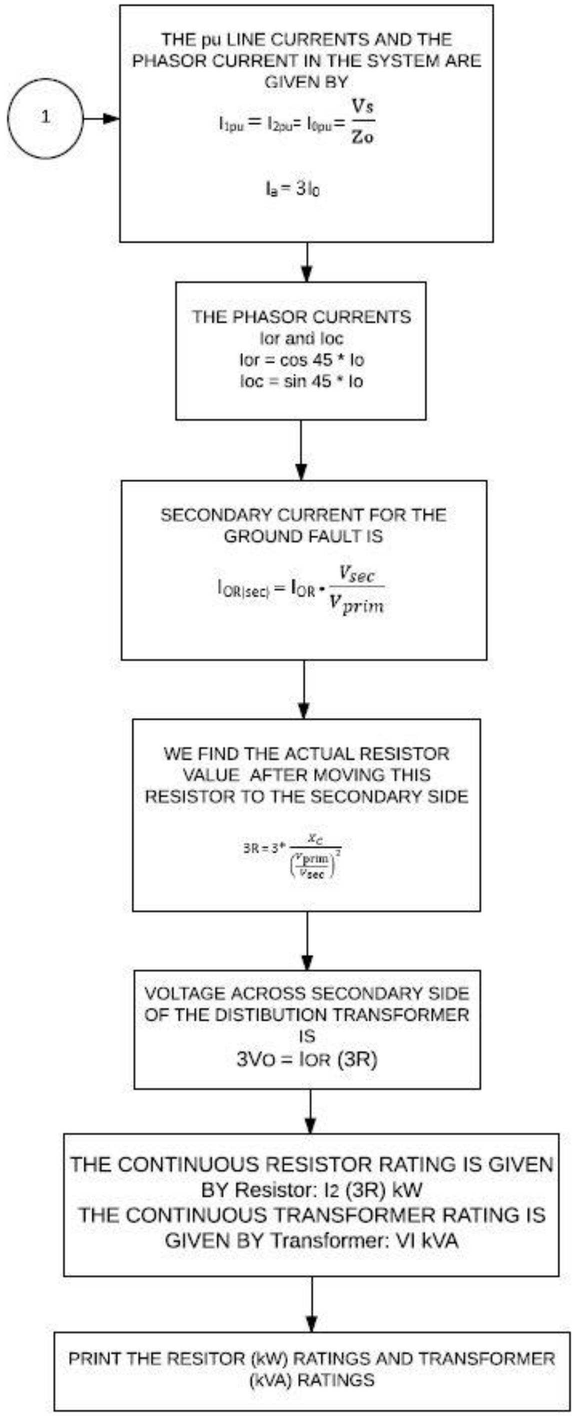


Figure 4.3: Flowchart for high-resistance grounding three distribution transformers

Based on the flowchart program is developed and is given in the appendix.

4.2: Example of a typical high-resistance grounding with three distribution transformers:

Consider an industrial plant 13.8kV system as illustrated in the Figure 4.4. The main source is the utility, but the plane has a small local generator. Either the supply transformer or the generator could be grounded with a resistor in the neutral (if the supply transformer is wye secondary), but it is possible that either the local generator or the utility supply may be out of service [3]. Thus, this system is to be grounded using a high-resistance grounding with three distribution transformers as shown in the Figure 4.4.

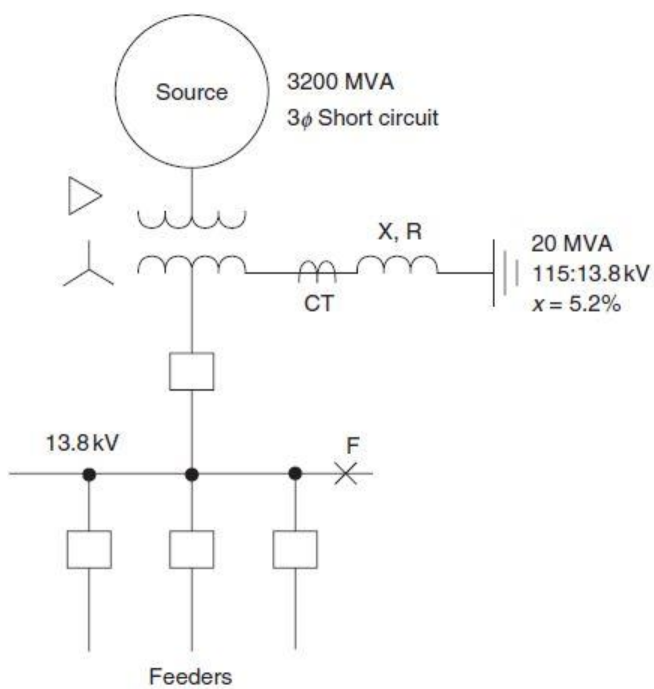


Figure 4.4: Example of high-resistance grounding with three distribution transformers

From estimating data and specific tests, we have the following capacitances to ground (microfarads per phase):

Source transformer (C_{st}) 0.004

Local generator (C_{lg})	0.11
Motor (C_m)	0.06
Power center transformers (C_{pt})	0.008
Total connecting cables (C_{tc})	0.13
Surge capacitor (C_{sc})	0.25
Total capacitance to ground (C)	0.0562

The capacitive reactance X_c is found using

$$X_C = \frac{-j*10^6}{2\pi f C} = \frac{-j*10^6}{2(3.14)(60)(0.0562)} = 4719.9\ \Omega/\text{phase}$$

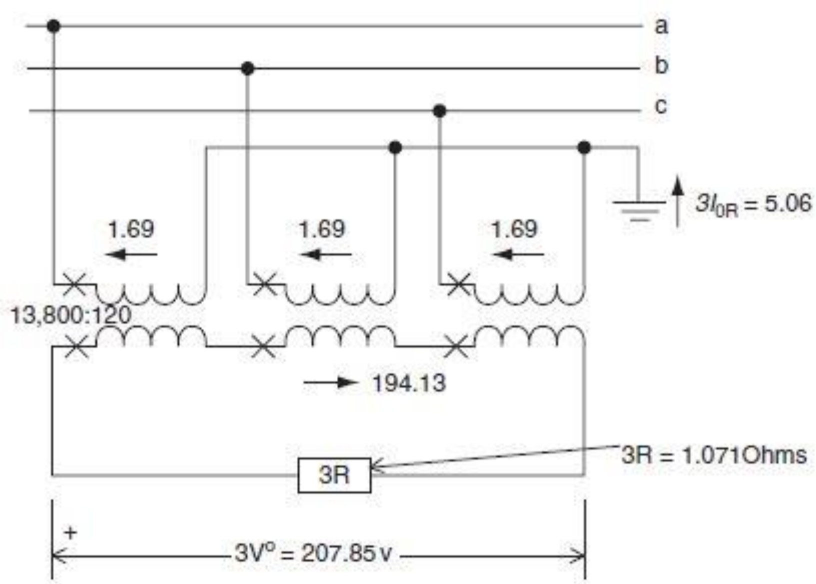


Figure 4.5: Currents flowing for the ground faults

The pu value of the capacitive reactance on a 20 MVA 13.8 kV base is:

$$X_{C(pu)} = \frac{S_{Base} X_C}{V_{Base}^2} = \frac{100 \quad *4719.9}{13.8^2} = 495.68 \text{ pu}$$

Thus the charging current for the system is,

$$I_C = \frac{V_B * 10^3}{\sqrt{3} X_C} = \frac{13{,}800}{\sqrt{3} * 4719.9} = 1.69 \text{ A / phase at 13.8 kV}$$

For high-resistance grounding, R = $X_{oc,}$ so R in the zero-sequence network is 495.68 pu. For the system

$$Z_0 = \frac{495.7\angle 0° * 495.7 \quad \angle -90°}{495.7\angle 0° + 495.7 \quad \angle -90°} = 350.5\angle -45° \text{ pu}$$

For a line to ground fault the positive and negative sequence values of the system are very small and can be ignored. Thus, for a line-to-ground fault on this 13.8 kV system, the pu values of the fault currents are given by

$$I_{1pu} = I_{2pu} = I_{0pu} = \frac{1}{350.5\angle -45°} = 0.00285\angle 45° \text{ pu}$$

$$I_B = \frac{20{,}000}{\sqrt{3} * 13.8} = 836.74 \text{ A at 13.8 kV}$$

The actual fault currents are found by

$$I_1 = I_2 = I_0 = (I_{1pu}) * I_B, \text{ where } I_B \text{ is the base current}$$

$$I_1 = I_2 = I_0 = 0.00285(836.74) = 2.39 \text{ A at 13.8 kV}$$

The phasor current is $I_a = 3I_0$ = 0.00856 pu = 7.16 A at 13.8 kV

$$I_{OR} = I_0 \cos 45° = 2.39 \cos 45° = 1.69 \text{ A at 13.8 kV}$$

Thus moving I_{OR} to the secondary side of the transformer for the ground fault is,

$$I_{OR(sec)} = I_{OR} * \frac{V_{Sec}}{V_{Prim}} = 1.69 * \frac{13,800}{120} = 1.69\ (115) = 194.13\ A$$

The resistor was sized to the X_c value, hence when its reflected to the secondary, the resistor value becomes

$$3R = 3 * \frac{X_C}{(\frac{V_{Sec}}{V_{Prim}})^2} = 3 * \frac{4719.9}{115^2} = 1.071\ \Omega$$

With the above values, we determine the continuous resistor and transformer ratings:

$$\text{Resistor: } I^2\ (3R) = \frac{194.13^2\ (1.071)}{1000} = 40.36\ kW$$

$$\text{Transformer: } VI = \frac{1.69\ (13,800)}{1000} = 23.3\ Kva$$

The line-to-line voltage was used during a fault; this fault appears essentially across the primary winding. If relays are used to trip, short time ratings may be used for the resistor and transformers.

Based on the program developed for high resistance grounding for 3 distribution transformers the same grounding method was analyzed using the program developed. The results of the program match with the calculations in the above example.

CHAPTER 5: LOW IMPEDANCE GROUNDING

The low-impedance-grounding limits line-to-ground fault currents to approximately 50 to 600 A primary. It is used to limit the fault current, yet permit selective protective relaying by magnitude differences in fault current by the power system impedances [3]. There are also cost advantages because line-to neutral equipment insulation can be used, for the unfaulted phase voltages are not increased significantly by the ground faults.

Most typically, this type of grounding is accomplished by a reactor or resistor in the system neutral. In a distribution station it would be in the neutral of the delta–wye supply transformer. Several generator units that are connected to a common bus may be grounded in this manner. Neutral Grounding Resistors (NGR's) limit the fault current when one phase of the system shorts or arcs to ground [8]. In the event that a ground fault condition exists, the NGR typically limits the current to 200-400A, though most resistor manufacturers label any resistor that limits the current to 25A or greater as low resistance. A particular resistor may be specified as 2400V L-N, 400A, 10 seconds, meaning that the impedance of the resistor is such that 2400V applied across it will result in 400A of current through it, and that the unit can only carry this current for 10 seconds before overheating [8]. As a rule of thumb, NGR's are designed with a continuous current rating equal to approximately 10% of its rated current. A unit that is rated 400A for 10 seconds may carry

40A (10% of 400A) continuously. to prevent the NGR from overheating, overcurrent protective devices must be designed to trip before the resistor's damage curve is breached [8] [11].

The advantages of low resistance grounding [8] [11]:

1. Limits phase-to-ground currents to 200-400A.
2. Reduces arcing current and, to some extent, limits arc-flash hazards associated with phase-to-ground arcing current conditions only.
3. May limit the mechanical damage and thermal damage to shorted transformer and rotating machinery windings.
4. Does not require a ground fault detection system.
5. May be utilized on medium or high voltage systems. GE offers low resistance grounding systems up to 72kV line-to-line.
6. Conductor insulation and surge arrestors must be rated based on the line-to-line voltage. Phase-to-neutral loads must be served through an isolation transformer.

Low resistance grounding has been selected for large electrical systems where there is a high investment in capital equipment or prolonged loss of service of equipment has a significant economic impact. A resistor is connected from the system neutral point to ground and generally sized to permit only 200 A to 1200 A of ground fault current to flow [8].

5.1: Design of Low Impedance Grounding:

Consider a typical system with a source generator as shown in Fig 5.1, to which a grounding reactor has to be applied to limit the maximum line-to-ground fault.

At the source, the impedances are given by

$$X_1 = X_2 = \frac{S_{Base}}{S_{SC}}$$

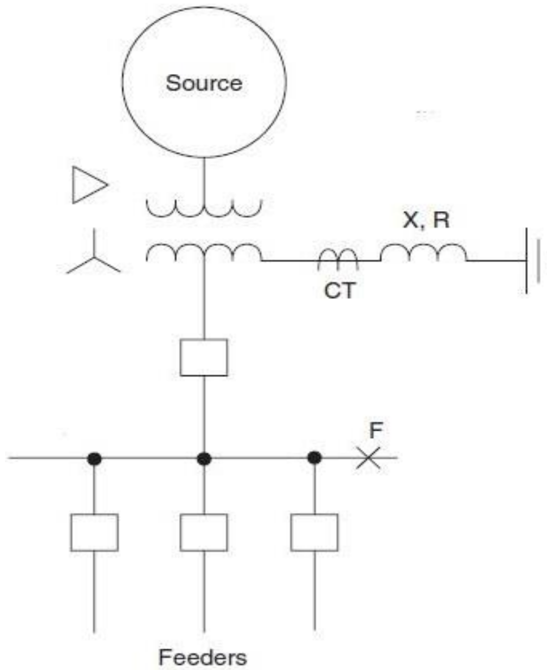


Figure 5.1: Typical example of low-impedance grounding

Selecting the grounding resistor to be equal to the capacitive reactance and using convenient 100 MVA base, 3R in the zero-sequence network would be the same as $X_{C(pu)}$. For a solid fault in this area,

$$Z_0 = \frac{R\angle 0° * X_C\angle -90°}{R\angle 0° + X_C\angle -90°}$$

The positive and negative sequence reactance Z_1 and Z_2 which are derived from the circuit as such that X_1 and X_2 are negligible. The pu values of the fault currents are given by

$$I_{1pu} = I_{2pu} = I_{0pu} = \frac{Vs}{Zo}$$, where usually V_s is 1 pu

The actual fault currents are found by

$I_1 = I_2 = I_0 = (I_{1pu})*I_B$, where I_B is the base current

The low impedance value X is found by $Xpu = \frac{1}{3}(\frac{V_S}{I_{1pu}} - (X_1 + X_2 + X_T))$. The actual value of X is the low impedance grounding reactance used for the given system. When this grounding is used for generator units, tripping the units is recommended, so that these rating could be short time ratings rather than continuous ratings.

The below flowchart considers the low resistance neutral reactor grounding of an industrial distribution system:

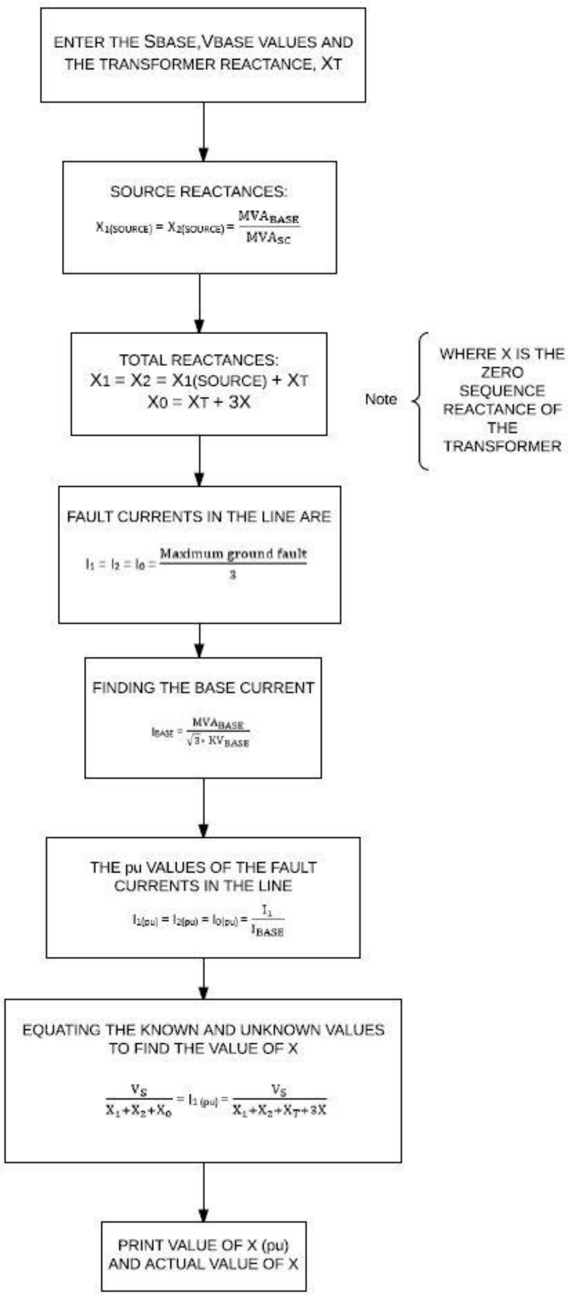


Figure 5.2: Flowchart for low resistance neutral reactor grounding

5.2: Example of Low Impedance Grounding:

Consider a typical system with a source generator as shown in Fig 5.3, to which a grounding reactor has to be applied to limit the maximum line-to-ground fault.

At the source, the impedances are given by

$$X_1 = X_2 = \frac{S_{Base}}{S_{SC}} = 20/3200 = j0.00625 \text{ pu}$$

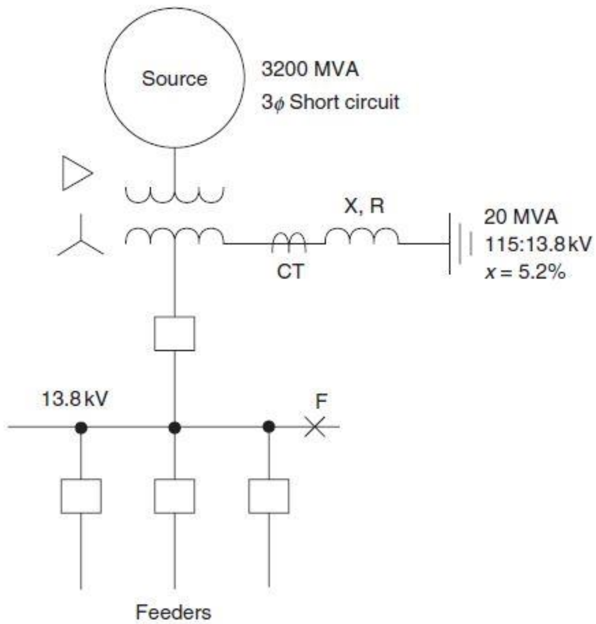


Figure 5.3: Typical example of low-impedance grounding

Selecting the grounding resistor to be equal to the capacitive reactance and using convenient 100 MVA base, 3R in the zero-sequence network would be the same as $X_{C(pu)}$. For a solid fault in this area,

$$Z_0 = \frac{R\angle 0° * X_C\angle -90°}{R\angle 0° + X_C\angle -90°} = j(0.052+3X) \text{ pu, where X is the impedance of the}$$

resistor

The positive and negative sequence reactance Z_1 and Z_2 which are derived from the circuit asuch that X_1 and X_2 are negligible. The pu values of the fault currents are given by

$$I_{1pu} = I_{2pu} = I_{0pu} = \frac{Vs}{Zo} = j1.0/(j0.1685 + 3X)$$

From the above, we can find X value by 0.159 = j1.0/(j0.1685 + 3X)

$$X = 2.036 \text{ pu}$$

The actual fault currents are found by

$$I_1 = I_2 = I_0 = (I_{1pu})*I_B \text{ , where } I_B \text{ is the base current}$$

The low impedance value X is found by $X_{pu} = \frac{1}{3}(\frac{V_S}{I_{1pu}} - (X_1 + X_2 + X_T))$

$$X_{pu} = 2.036\text{pu} = (13.8^2\,(2.036))/20 = 19.38\ \Omega \text{ at } 13.8\text{kV}$$

The actual value of X is the low impedance grounding reactance used for the given system. When this grounding is used for generator units, tripping the units is recommended, so that these rating could be short time ratings rather than continuous ratings [3].

CHAPTER 6: SOLID GROUNDING

Multiple motor failures in numerous industrial plants were seen and were due to severe overvoltages caused by arcing or resonant ground faults on the ungrounded systems. To prevent these overvoltages, many power system neutrals were grounded, usually solidly. There were many factors that contributed to the change to solidly grounded systems and these factors are still important today [12].

First, solid grounding very effectively limits the maximum phase-to-ground voltage. Second, it allows phase-to-neutral loads to be served without encountering dangerous neutral-to-ground voltages underground fault conditions. Third, simple and effective ground relaying systems can be used to isolate the defective portion of the system under ground-fault conditions [12].

6.1: Design of Solid Grounding:

Consider the system in the figure 6.1 assuming that the system is solidly grounded, which means X,R is equal to zero. For the given fault reactances and with the given base values, the total reactance is calculated as

$$X_T = X_1 + X_2 + X_0$$

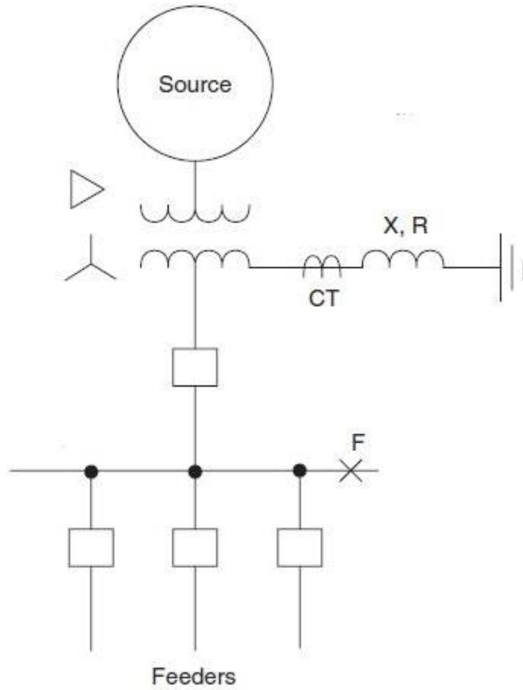


Figure 6.1 Example of Solid Grounding

The line currents are calculated as

$$I_{1pu} = I_{2pu} = I_{0pu} = \frac{Vs}{Zo}, \text{ where usually } V_s \text{ is 1 pu}$$

The actual fault currents are found by

$$I_1 = I_2 = I_0 = (I_{1pu})*I_B, \text{ where } I_B \text{ is the base current}$$

While this was calculated with actual values, the fault current was found to be almost 37 times larger than the low-impedance grounded system. So we calculate the solid impedance value for a three-phase fault at the fault location.

$$I_{1pu} = \frac{Vs}{X_1}$$

In the Figure 6.1, a typical distribution transformer is connected to a very large power system source. Thus, relatively the source impedance is very low compared to the distribution transformer.

For a three phase fault on the bus,

$$I_{3Ø} = \frac{1}{X_1} \text{ pu}$$

$$I_{gØ} = \frac{1}{2X_1+X_0} \text{, where } X_1 = X_2$$

If the source impedance is included, then X_1 and X_2 are greater than X_0 and $I_{Gø}$ is greater than $I_{3Ø}$.

With the possibility of very low ground fault currents out on long rural or urban feeders that are difficult or impossible to isolate, solid grounding of the distribution transformers is recommended to provide as much ground fault current as possible for detection by the relays [3].

The below flowchart considers the solid resistance grounding of an industrial distribution system and based on the flowchart program is developed and is given in the appendix.

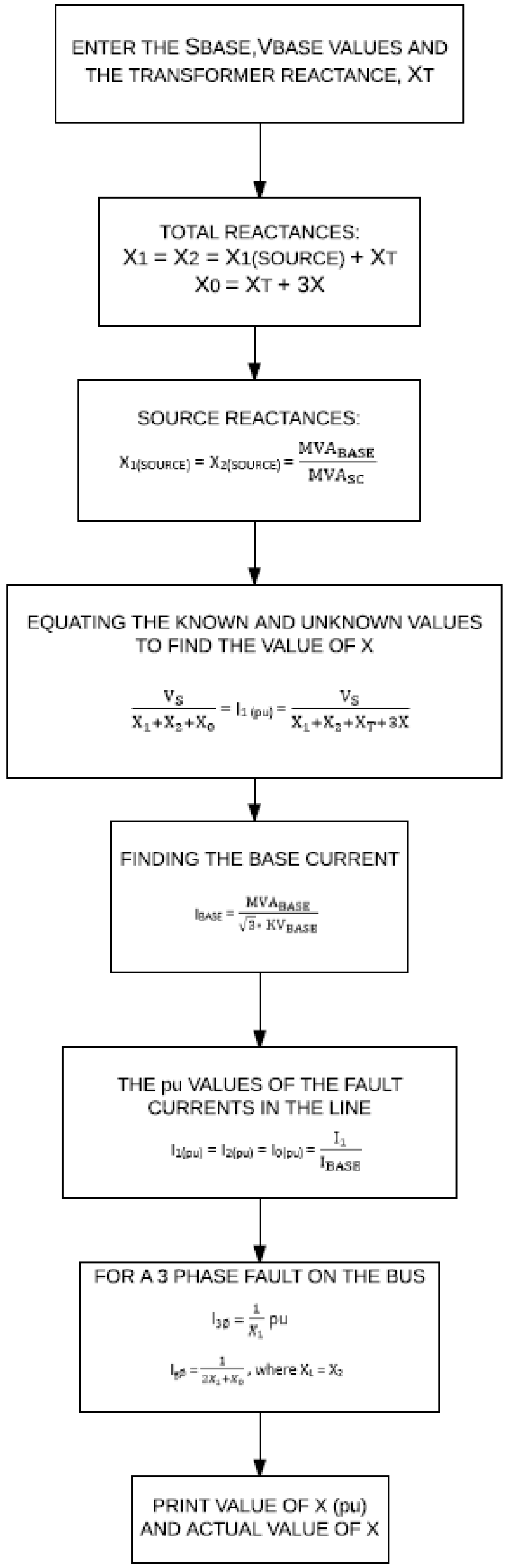


Figure 6.2: Flowchart for Solid grounding

CHAPTER 7: LARGE SCALE POWER SYSTEM WITH THE SUBSYSTEM FOR GROUNDING CONSIDERATION

We are analyzing in this chapter, the grounding of the subsystem which is a part of a large scale system. To perform this, we need large scale analysis i.e. short circuit analysis as final needed results for the subsystem grounding. In this chapter we will provide the analysis of the large scale system, for which we analyze the Z-bus and short circuit.

If one, or two, or all three phases break or if insulators break due to fatigue or inclement weather, this fault is called a permanent fault. Approximately 75% of all faults in power systems are transient in nature. Knowing the magnitude of the fault current is important when selecting protection equipment (type, size, etc..) [2] and that is one of the reasons for fault current calculations in this chapter. To determine the fault current in a large power system we have to create a Thevenin's equivalent circuit of the power system using either sub-transient reactances in case we are analyzing the subtransient currents or transient reactances in case we are analyzing the transient currents. Finding the Thevenin equivalent circuit looking from the fault point, then divide the Thevenin voltage by the Thevenin impedance is the next step determine the fault. Thevenin's equivalent circuit for either one or for both transient and subtransient analysis from fault currents is calculated. The voltage at the bus before the fault is Thevenin's equivalent voltage. Based on these two, we calculate the transient current.

7.1: Z-bus and short circuit currents:

Z-bus is bus impedance matrix which is used in fault analysis. This matrix helps in finding the values of fault current. The elements of matrix are the impedances of transmission line connected between two buses. Z-bus is the inverse of bus admittance matrix [14]. Z-bus relates the nodal current injections to the nodal voltages. While developing fault analysis methods, we will choose to work with Z-bus. The main reason for choosing to work with Z-bus in fault analysis is that, as we will see, Z-bus quantities characterize conditions when all current injections are zero except one, corresponding to the faulted bus [14].

Significance of Short Circuit Currents:

Short circuits may occur in power systems due to system over voltages caused by lightning or switching surges or due to equipment insulation failure or even due to insulator contamination. Sometimes even mechanical causes may create short circuits [15]. Other well-known reasons include line-to-line, line-to-ground, or line-to-line faults on overhead lines. The resultant short circuit has to be interrupted within few cycles by the circuit breaker [15]. In the following section, we discuss the calculation of fault currents with the z-bus calculations. This fault current is required for the grounding of the subsystem which the user requires.

7.2: Short Circuit current calculation using Z-bus for a given system:

Starting from the relation $V = Z_{bus} I$, where the node or bus voltages V_i, $i = 1, \ldots, n$ are the open circuit voltages. Let us assume that the currents injected in buses $1, \ldots, k - 1$ and $k + 1, \ldots, n$ are zero when a short circuit occurs at bus k . Then Thevenin impedance at bus k is

$$Z_{th,k} = \frac{V_k}{I_k} = Z_{kk} \tag{1}$$

Let us now find the Thevenin impedance between two buses *j* and *k* of a power system. Let the open circuit voltages be defined by the voltage vector $V°$ and corresponding currents be defined by $I°$ such that

$$V° = Z_{bus} I° \tag{2}$$

Now suppose the currents are changed by ΔI such that the voltages are changed by ΔV. Then

$$V = V° + \Delta V = Z_{bus}\left(I° + \Delta I\right) \tag{3}$$

Comparing (2) and (3) we can write

$$\Delta V = Z_{bus} \Delta I \tag{4}$$

Let us now assume that additional currents ΔI_k and ΔI_k are injected at the buses *k* and *j* respectively while the currents injected at the other buses remain the same. Then from (4) we can write

$$\Delta V = Z_{bus} \begin{bmatrix} 0 \\ \vdots \\ \Delta I_j \\ \Delta I_k \\ \vdots \\ 0 \end{bmatrix} = \begin{bmatrix} Z_{1j}\Delta I_j + Z_{1k}\Delta I_k \\ \vdots \\ Z_{jj}\Delta I_j + Z_{jk}\Delta I_k \\ Z_{kj}\Delta I_j + Z_{kk}\Delta I_k \\ \vdots \\ Z_{nj}\Delta I_j + Z_{nk}\Delta I_k \end{bmatrix} \tag{5}$$

We can therefore write the following two equations form (5)

$$V_j = V_j^o + \Delta V_j = V_j^o + Z_{jj}\Delta I_j + Z_{jk}\Delta I_k$$

$$V_k = V_k^o + \Delta V_k = V_k^o + Z_{kj}\Delta I_j + Z_{kk}\Delta I_k$$

The above two equations can be rewritten as

$$V_j = V_j^o + (Z_{jj} - Z_{jk})\Delta I_j + Z_{jk}(\Delta I_j + \Delta I_k) \tag{6}$$

$$V_k = V_k^o + Z_{kj}(\Delta I_j + \Delta I_k) + (Z_{kk} - Z_{kj})\Delta I_k \tag{7}$$

Since $Z_{jk} = Z_{kj}$ the network can be drawn as shown in Fig. 6.1. By inspection we can see that the open circuit voltage between the buses *k* and *j* is

$$V_{oc,kj} = V_k^o - V_j^0 \tag{8}$$

and the short circuit current through these two buses is

$$I_{sc,kj} = \Delta I_j = -\Delta I_k \tag{9}$$

Also during the short circuit V_k- V_j = 0. Therefore combining (6) and (7) we get

$$V_k - V_j = (V_k^o - V_j^o) + (2Z_{kj} - Z_{jj} - Z_{kk})I_{sc,kj} = 0 \tag{10}$$

Combining (8) to (10) we find the Thevenin impedance between the buses *k* and *j* as

$$Z_{th,kj} = \frac{V_{oc,kj}}{I_{sc,kj}} = Z_{jj} + Z_{kk} - 2Z_{kj} \tag{11}$$

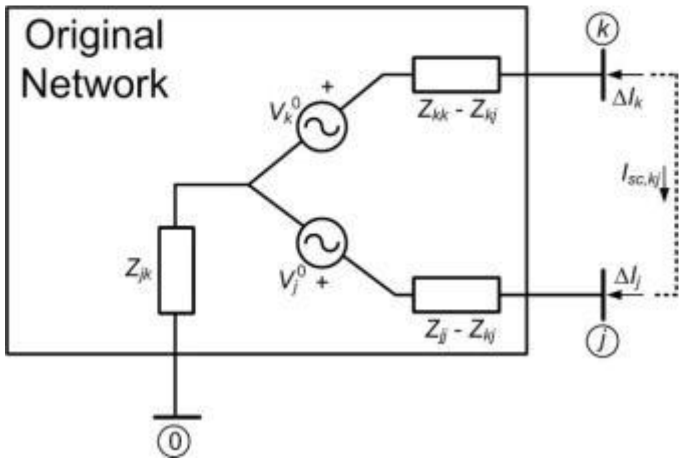


Figure 7.1: Thevenin equivalent between buses k and j

We know that, V=ZI (12)

Since (2) represents a set of linear equations, superposition holds, and we may write:

$$\Delta V = Z\ \Delta I \tag{13}$$

This says that the change in voltage at all buses $\Delta \underline{V}$ may be computed if the change in injections at all buses $\Delta \underline{I}$ are known. We can write eq. (13) in expanded form as:

$$\begin{bmatrix} \Delta V_1 \\ \vdots \\ \Delta V_k \\ \vdots \\ \Delta V_N \end{bmatrix} = \begin{bmatrix} Z_{11} & \cdots & Z_{1k} & \cdots & Z_{1N} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ Z_{k1} & \cdots & Z_{kk} & \cdots & Z_{kN} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ Z_{N1} & \cdots & Z_{Nk} & \cdots & Z_{NN} \end{bmatrix} \begin{bmatrix} \Delta I_1 \\ \vdots \\ \Delta I_k \\ \vdots \\ \Delta I_N \end{bmatrix} \tag{14}$$

Now consider a fault at bus k, where the pre-fault voltage at bus k is V_f. Let the fault current be I''_f, and assume that the fault impedance $Z_f=0$ (this is typically worst-case scenario).

Since a fault is a short circuit, then $\Delta V_k=-V_f$.

Also, since the fault current is out of bus k, then $\Delta I_k = - I''_f$. Substituting these into eq. (14) results in

$$\xrightarrow[row\,k]{} \begin{bmatrix} \Delta V_1 \\ \vdots \\ -V_f \\ \vdots \\ \Delta V_N \end{bmatrix} = \begin{bmatrix} Z_{11} & \cdots & Z_{1k} & \cdots & Z_{1N} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ Z_{k1} & \cdots & Z_{kk} & \cdots & Z_{kN} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ Z_{N1} & \cdots & Z_{Nk} & \cdots & Z_{NN} \end{bmatrix} \begin{bmatrix} 0 \\ \vdots \\ -I''_f \\ \vdots \\ 0 \end{bmatrix} \quad (15)$$

Note that the right-hand-side results in, for each row j, only the Z_{jk} being multiplied by a non-zero current.

$$\xrightarrow[row\,k]{} \begin{bmatrix} \Delta V_1 \\ \vdots \\ -V_f \\ \vdots \\ \Delta V_N \end{bmatrix} = \begin{bmatrix} -Z_{1k} I''_f \\ \vdots \\ -Z_{kk} I''_f \\ \vdots \\ -Z_{Nk} I''_f \end{bmatrix} \quad (16)$$

We observe from row k that:

$$-V_f = -Z_{kk} I_f'' \quad (17)$$

Solving (17) for I_f'' results in

$$I''_f = \frac{V_f}{Z_{kk}} \quad (18)$$

Now substitute eq. (18) into eq. (16) to get:

$$\xrightarrow[\text{row}\,k]{} \begin{bmatrix} \Delta V_1 \\ \vdots \\ -V_f \\ \vdots \\ \Delta V_N \end{bmatrix} = \begin{bmatrix} \left(-Z_{1k}/Z_{kk}\right)V_f \\ \vdots \\ -V_f \\ \vdots \\ \left(-Z_{Nk}/Z_{kk}\right)V_f \end{bmatrix} \qquad (19)$$

Now eq. (19) provides the change in the bus voltages due to the fault. It is the change from the voltage without the fault, i.e., it is the pre-fault voltage.

Consider any bus, let's say bus j, with a pre-fault voltage of V_j. Then we can compute the bus j voltage under the faulted condition as

$$V_{jf} = V_j + \Delta V_j \qquad (20)$$

From eq. (19), we know that

$$\Delta V_j = -\frac{Z_{jk}}{Z_{kk}} V_f \qquad (21)$$

Substitution of (21) into (20) results in

$$V_{jf} = V_j - \frac{Z_{jk}}{Z_{kk}} V_f \qquad (22)$$

Now eq. (22) is useful for computing fault currents in the circuits. Consider Fig 7.2.

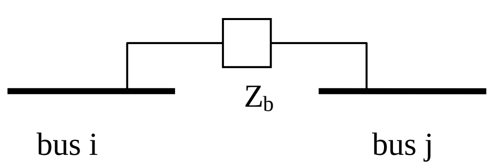


Figure 7.2 Example to calculate Z bus value

We can use eq. (22) to write down the voltages under the faulted condition for buses i and j, as

$$V_{if} = V_i - \frac{Z_{ik}}{Z_{kk}} V_f \tag{23}$$

$$V_{jf} = V_j - \frac{Z_{jk}}{Z_{kk}} V_f \tag{24}$$

Now we can compute the subtransient current flowing from bus i to bus j under the fault condition as

$$I''_{ij} = \frac{V_{if} - V_{jf}}{Z_b} \tag{25}$$

Substituting eqs. (23) and (24) into (25) results in

$$\begin{aligned} I''_{ij} &= \frac{V_i - \frac{Z_{ik}}{Z_{kk}} V_f - V_j - \frac{Z_{jk}}{Z_{kk}} V_f}{Z_b} \\ &= \frac{V_i - V_j}{Z_b} - V_f \frac{Z_{ik} - Z_{jk}}{Z_b Z_{kk}} \end{aligned} \tag{26}$$

We can use eq. (26) to get the fault current in the circuits. These values provide us with the appropriate information for selecting the circuit breakers in the lines.

Zbus should be developed using subtransient reactances in generator/motor models. Because fault currents are typically much larger than load currents, it may be assumed that there are no loads.

- All pre-faults currents are 0.

- All buses have voltage (pre-fault) equal to V_f.

- Equation (26) becomes:

$$I''_{ij} = -V_f \frac{Z_{ik} - Z_{jk}}{Z_b Z_{kk}} \tag{27}$$

From (26) and (27), we see that only the kth column of the Z-bus is required to analyze a fault at bus k.

The last observation can be utilized in an effective fashion when performing fault analysis. Let's assume that we want to compute the short circuit currents for a fault at only one bus k. So we just want to get the kth column of Z-bus, but we do not need the entire Z-bus.

The flowchart below shows the Z-bus calculation in an undefined system and the derivation of the fault currents. The above flowchart is divided into sections to explain the algorithm with which the flowchart is built upon. The sections (a), (b) and (c) focus on obtaining the data from the user and the sections (d), (e) are for the calculation of z-bus and section (f) is the fault calculation.

Section (a): Since the system is of the choice of the user, we need to obtain every detail from the user. First we need to the number of buses in the system and then we check for generators in each bus. If a generator is present at a particular bus then we also get the generator impedance from the user, which is represented as Z_G(i) in the flowchart, where I is the bus at which the generator is present. This is repeated for every bus till we check with all possible buses for generators. If the generator is not available for an end bus, we get the impedance between the bus and the ground, which is represented as Z_1(i) in the flowchart.

Section (b): Now that we have checked for the availability of generators, we also check for the presence of transformers at each bus. Since the transformer is usually placed between any two buses, we check for transformers for every possible combination of buses. If the transformer is available between any two buses, we ask for the user to enter the impedance of the transformer which is represented by $Z_T(i,j)$, where i and j are the buses between which the transformer is available. If the transformer is not available then we get the line impedance between the buses i and j which is represented as $Z_L(i,j)$.

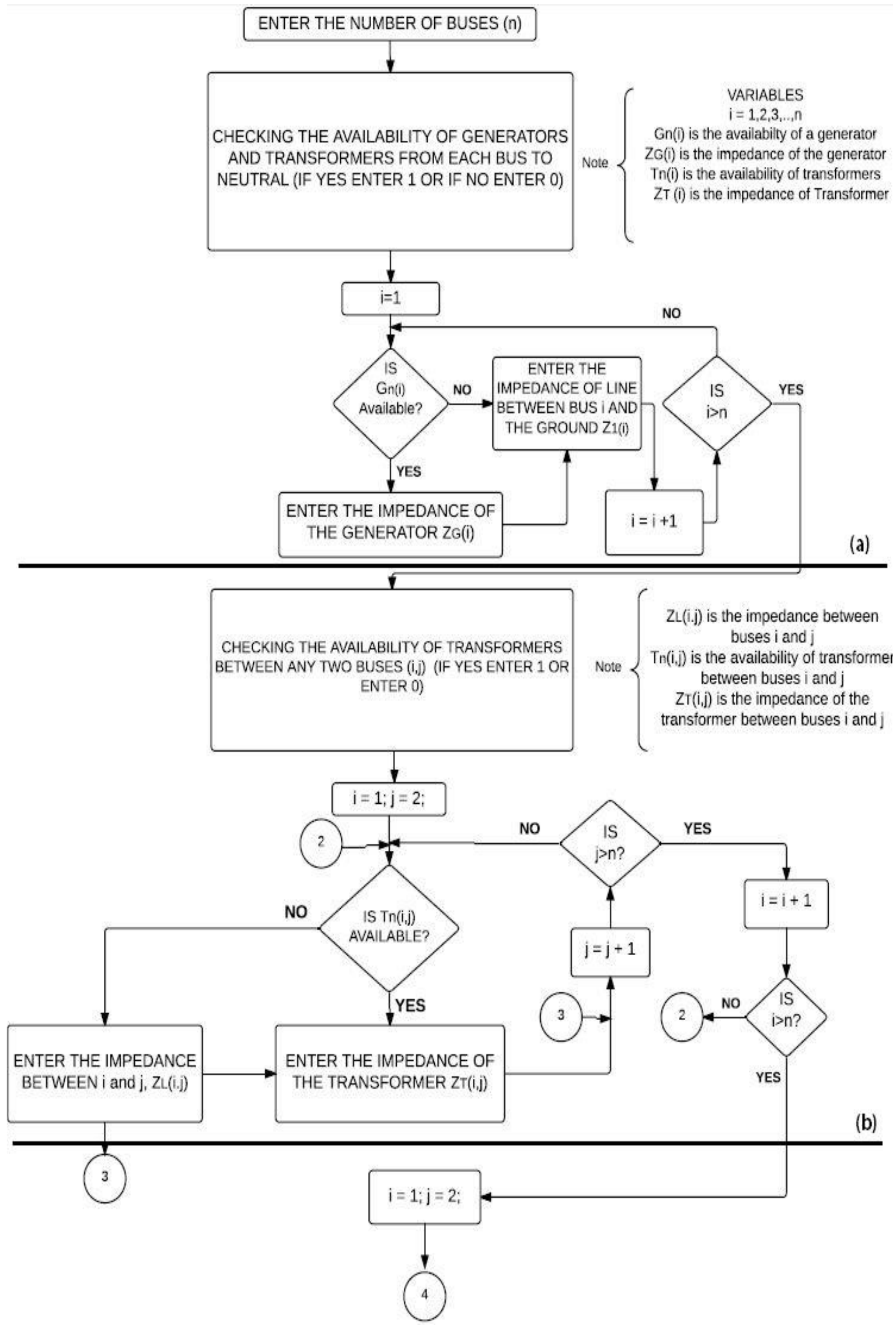
Section (c): Since we have obtained all of the required impedances in the user's system, we now calculate the total line impedances required to formulate the Z-bus. If the generators or transformers are available at a bus, then we calculate the total line impedance by adding the generator impedance $Z_G(i)$ and the line impedance $Z_1(i)$ or by adding the transformer impedance $Z_T(i,j)$ and the line impedance $Z_L(i,j)$. Otherwise, the total line impedance is the same as the $Z_L(i,j)$ entered earlier. The total line impedance is represented as $Z_1(i)$ or $Z_2(i,j)$, where i and j are the buses of the system.

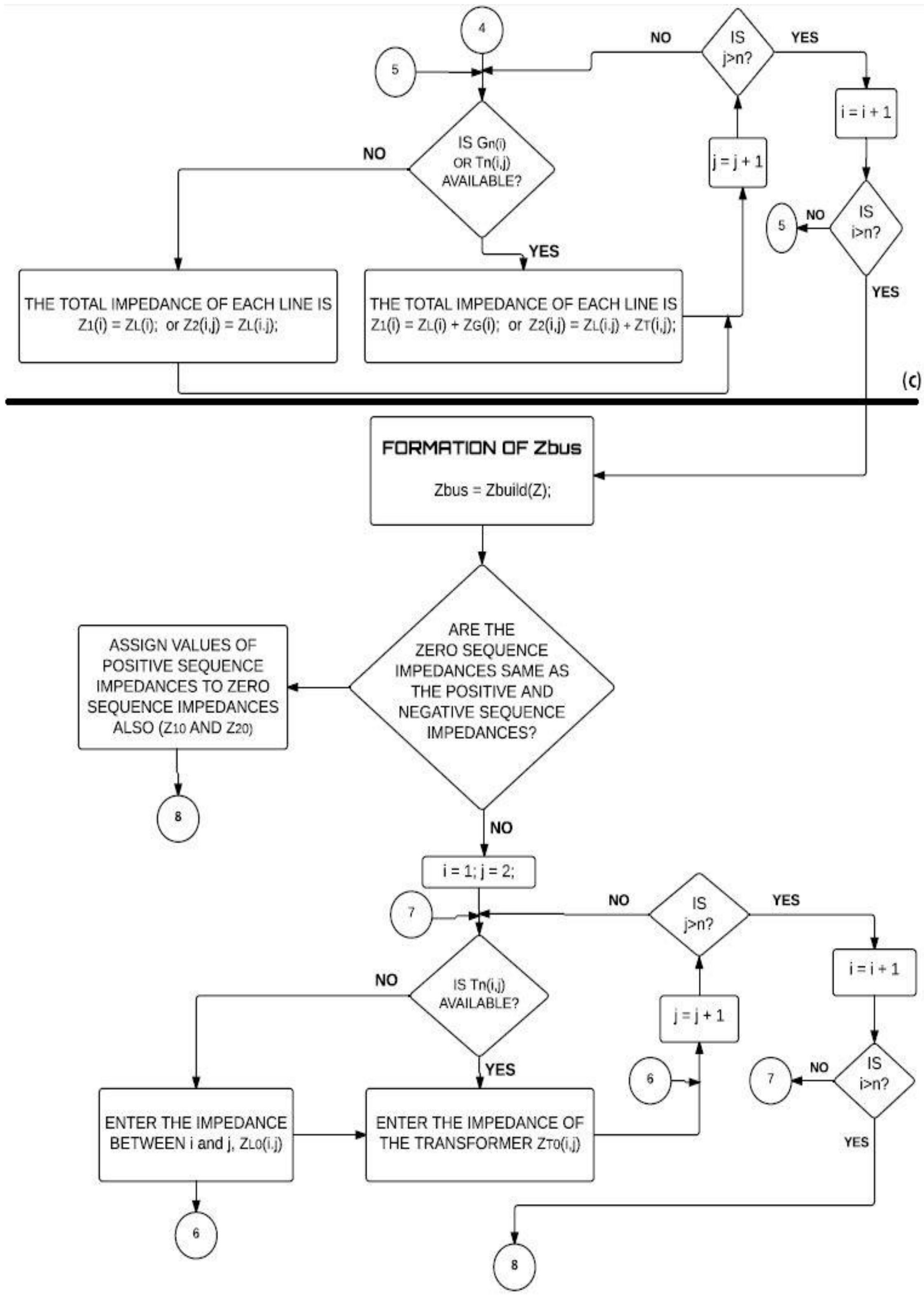
Section (d): This section of the flowchart involves the formation of the required Z-bus. With the above impedance matrices, we develop an initial zero sequence matrix from the data obtained. We call that the $Z_{data\_zerSeq}(i,j)$ and this is before we check to see if the Zero sequence is the same as the positive and negative sequence matrices.

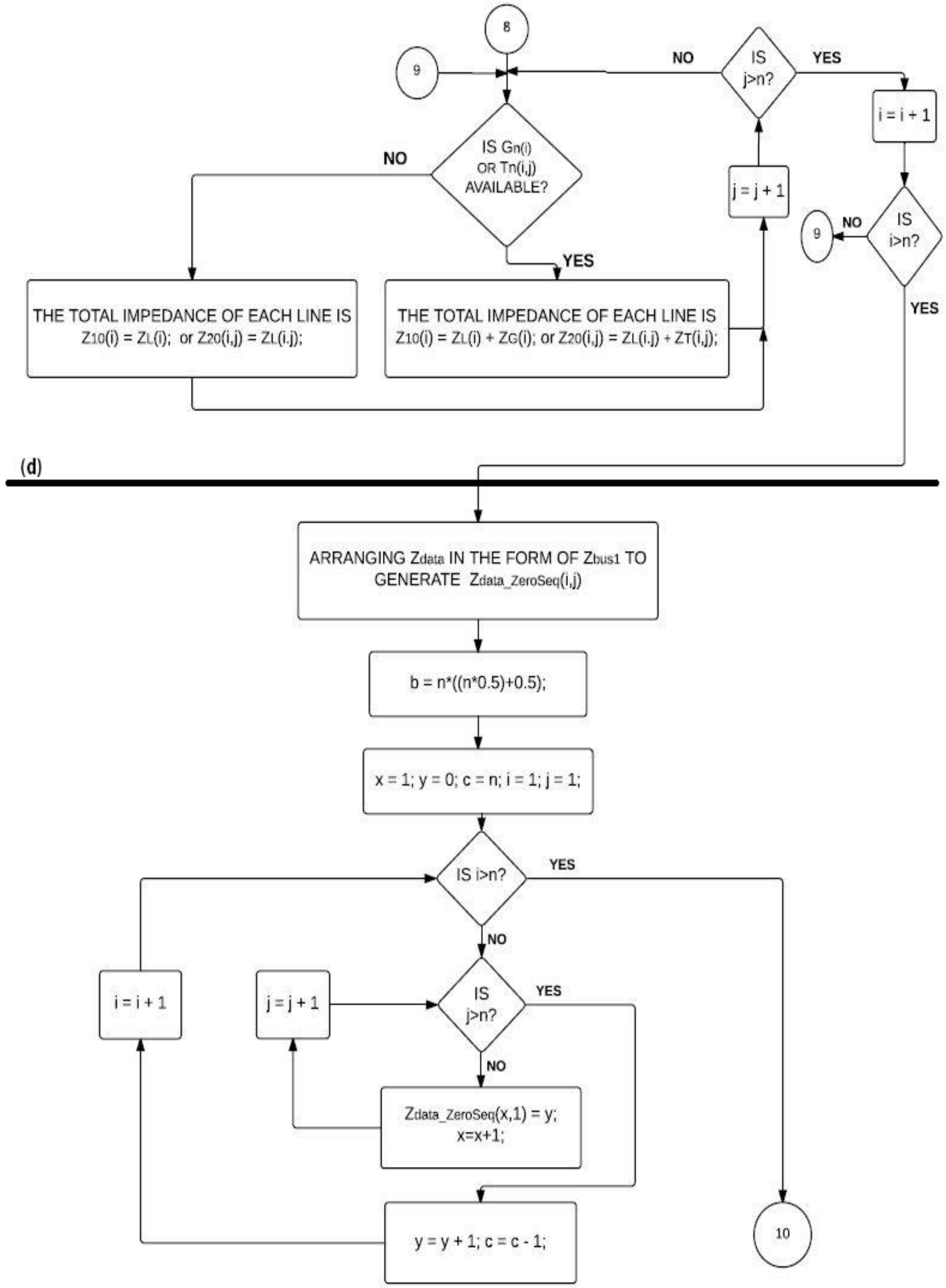
Section (e): If the positive and negative sequences are the same as zero sequence matrix, then we assign the same value for positive and negative sequence matrices. If it is not the same, then we repeat the entire process again to obtain new values for positive and negative sequence matrices.

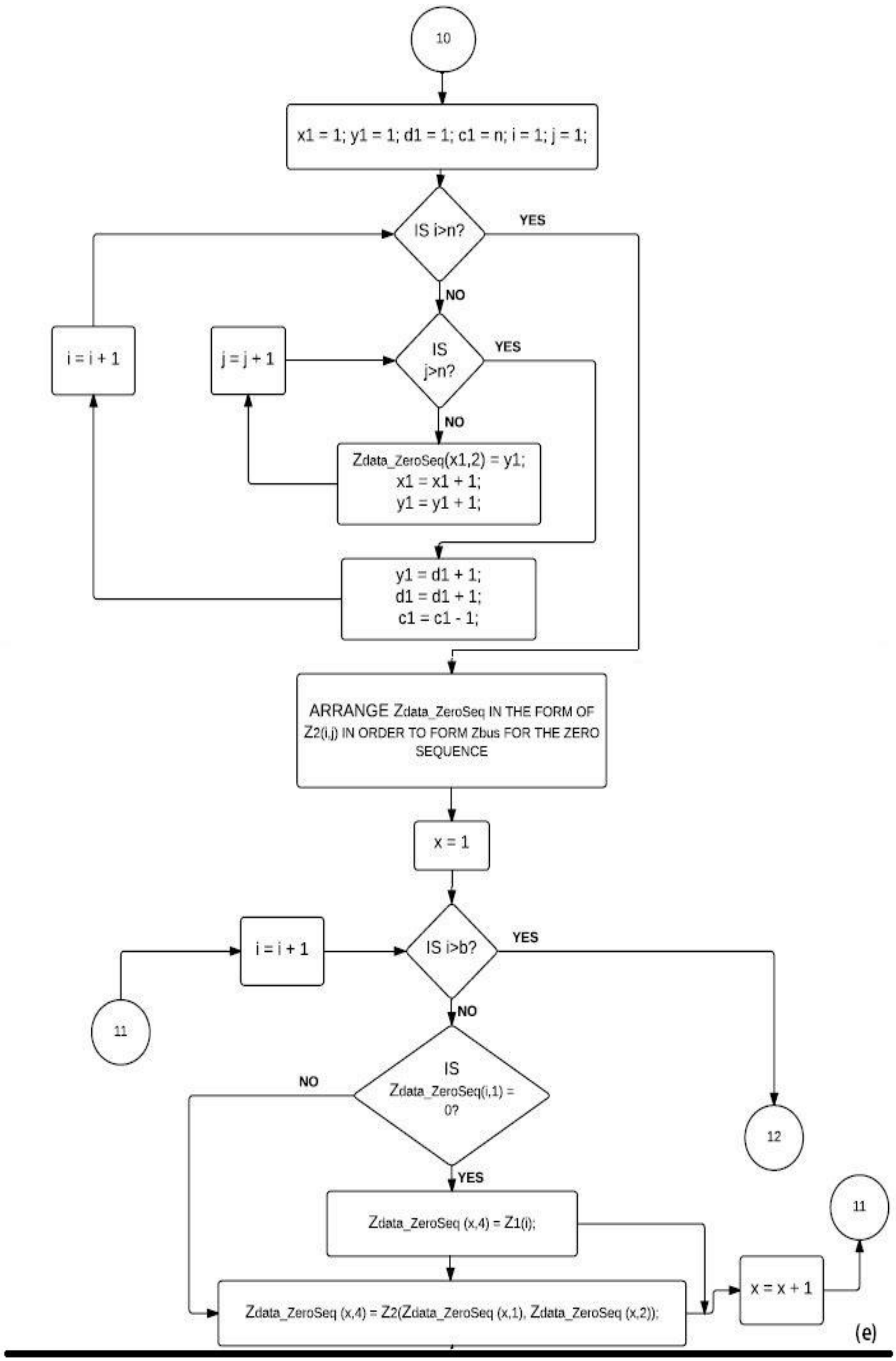
Section (f): This section involves calculation of fault currents required for the grounding methods. The user selects the type of fault in the system and when the program runs for the particular fault, the user selects the location of the fault. The output of this section of flowchart is the fault currents and the phase currents at the location of the fault.

Below is the flowchart showing the calculation of Z-bus and determination of the short circuit currents with respect to the occurred fault:


ENTER THE NUMBER OF BUSES (n)
CHECKING THE AVAILABILITY OF GENERATORS AND TRANSFORMERS FROM EACH BUS TO NEUTRAL (IF YES ENTER 1 OR IF NO ENTER 0)
Note
VARIABLES
i = 1,2,3,..,n
Gn(i) is the availabilty of a generator
ZG(i) is the impedance of the generator
Tn(i) is the availability of transformers
ZT (i) is the impedance of Transformer
i=1
IS Gn(i) Available?
NO
YES
ENTER THE IMPEDANCE OF LINE BETWEEN BUS i AND THE GROUND Z1(i)
IS i>n
NO
YES
ENTER THE IMPEDANCE OF THE GENERATOR ZG(i)
i = i +1
(a)
CHECKING THE AVAILABILITY OF TRANSFORMERS BETWEEN ANY TWO BUSES (i,j) (IF YES ENTER 1 OR ENTER 0)
Note
ZL(i,j) is the impedance between buses i and j
Tn(i,j) is the availability of transformer between buses i and j
ZT(i,j) is the impedance of the transformer between buses i and j
i = 1; j = 2;
2
NO
IS j>n?
YES
IS Tn(i,j) AVAILABLE?
NO
YES
i = i + 1
j = j + 1
3
2
NO
IS i>n?
YES
ENTER THE IMPEDANCE BETWEEN i and j, ZL(i,j)
ENTER THE IMPEDANCE OF THE TRANSFORMER ZT(i,j)
(b)
3
i = 1; j = 2;
4


4
5
NO
IS j>n?
YES
i = i + 1
IS Gn(i) OR Tn(i,j) AVAILABLE?
NO
YES
j = j + 1
5
NO
IS i>n?
YES
THE TOTAL IMPEDANCE OF EACH LINE IS
Z1(i) = ZL(i); or Z2(i,j) = ZL(i,j);
THE TOTAL IMPEDANCE OF EACH LINE IS
Z1(i) = ZL(i) + ZG(i); or Z2(i,j) = ZL(i,j) + ZT(i,j);
(c)
FORMATION OF Zbus
Zbus = Zbuild(Z);
ARE THE ZERO SEQUENCE IMPEDANCES SAME AS THE POSITIVE AND NEGATIVE SEQUENCE IMPEDANCES?
ASSIGN VALUES OF POSITIVE SEQUENCE IMPEDANCES TO ZERO SEQUENCE IMPEDANCES ALSO (Z10 AND Z20)
8
NO
i = 1; j = 2;
7
NO
IS j>n?
YES
i = i + 1
IS Tn(i,j) AVAILABLE?
NO
YES
j = j + 1
6
7
NO
IS i>n?
YES
ENTER THE IMPEDANCE BETWEEN i and j, ZL0(i,j)
ENTER THE IMPEDANCE OF THE TRANSFORMER ZT0(i,j)
6
8


8
9
NO
IS
j>n?
YES
i = i + 1
IS Gn(i)
OR Tn(i,j)
AVAILABLE?
NO
j = j + 1
NO
9
IS
i>n?
YES
YES
THE TOTAL IMPEDANCE OF EACH LINE IS
Z10(i) = ZL(i); or Z20(i,j) = ZL(i.j);
THE TOTAL IMPEDANCE OF EACH LINE IS
Z10(i) = ZL(i) + ZG(i); or Z20(i,j) = ZL(i.j) + ZT(i,j);
(d)
ARRANGING Zdata IN THE FORM OF Zbus1 TO GENERATE Zdata_ZeroSeq(i,j)
b = n*((n*0.5)+0.5);
x = 1; y = 0; c = n; i = 1; j = 1;
IS i>n?
YES
NO
i = i + 1
j = j + 1
IS
j>n?
YES
NO
Zdata_ZeroSeq(x,1) = y;
x=x+1;
y = y + 1; c = c - 1;
10


10
x1 = 1; y1 = 1; d1 = 1; c1 = n; i = 1; j = 1;
IS i>n?
YES
NO
i = i + 1
j = j + 1
IS j>n?
YES
NO
Zdata_ZeroSeq(x1,2) = y1;
x1 = x1 + 1;
y1 = y1 + 1;
y1 = d1 + 1;
d1 = d1 + 1;
c1 = c1 - 1;
ARRANGE Zdata_ZeroSeq IN THE FORM OF Z2(i,j) IN ORDER TO FORM Zbus FOR THE ZERO SEQUENCE
x = 1
i = i + 1
IS i>b?
YES
NO
11
IS Zdata_ZeroSeq(i,1) = 0?
NO
YES
12
Zdata_ZeroSeq (x,4) = Z1(i);
11
Zdata_ZeroSeq (x,4) = Z2(Zdata_ZeroSeq (x,1), Zdata_ZeroSeq (x,2));
x = x + 1

(e)

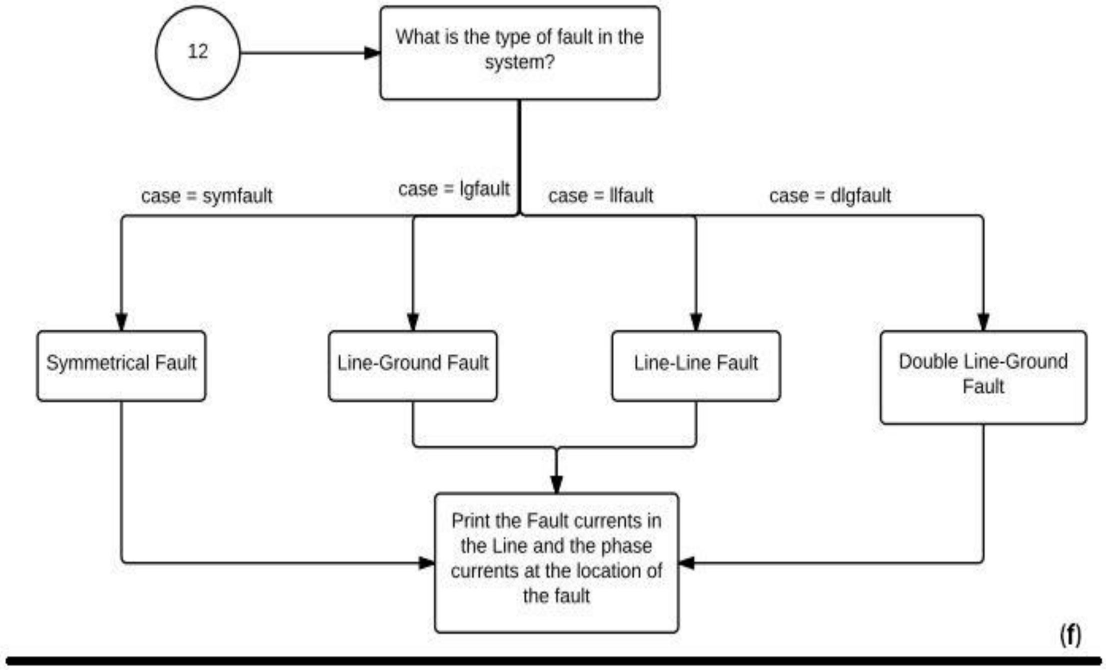


Figure 7.3: Flowchart showing the Z-bus calculation and derivation of the fault currents

CHAPTER 8: CONCLUSION

With the number of short circuits occurring in power systems due to system over voltages, grounding system policies are necessary in a subsystems in order to protect the large scale system. The aim of the thesis was to create a procedure to attach different grounding system policies to a system with a short circuit fault. Beginning with the automation of Z-bus calculation and short circuit current calculation, we continue to developing programs for every grounding system method. Large scale system at the point of short circuit is connected to our system and is analyzed from the grounding point of view. We use the large scale system to get the Thevenin's equivalent and we replace large scale system with Thevenin's equivalent for our system under consideration. For every grounding method (i.e.), High-resistance neutral grounding, High-resistance grounding with three distribution transformers, Low-impedance grounding, and Solid grounding, we start with explanation of the procedure then we continue to propose a flowchart for the so explained procedure in order to develop the program for the methods. The program so developed for each of the grounding methods is cross verified with the manually calculated example. All of the 4 grounding systems are integrated in one program. It gives the user an option to analyze every single method or any number of methods or all of the methods. The program allows the user to go back and review his/her options. The user can add another grounding method again, and can continue till they use all of the grounding methods. Once the user has used all of the methods, he has arrived at the maximum possible options to be selected and the program ends.

The work presented in this thesis can serve as a platform to dive into advanced topics and methods to be utilized in system grounding. The thesis allows the future methods developed to be attached to the algorithm in addition to the 4 current methods. For instance, if a new grounding system method is to be attached to the current thesis, it is just attached at the end of the algorithm right after Solid grounding. The advantage of this model is that we can attach types of groundings to different subsystems in the same large scale power system. That means the large scale system can have more than one short circuit occurring and grounding methods can be attached to every single subsystem at the location of faults.

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APPENDIX A: PROGRAMS FOR ALL THE GROUNDING METHODS

A1.Program for the selection of grounding methods:

```
fprintf('\n Enter the type of fault occured at the main system which is if LL fault enter 1, LG fault enter 2, DLG fault enter 3 and in case of symmetrical fault enter 4');
x=input('');
Isc = getVariable(1,'If');
for n =1:4
   fprintf('Enter the type of grouding you would like to pick for your subsystem: /n High Resistanc Neutral Grounding = Case 1 /n High Resistance Grounding with three distribution transformers = Case 2  /n Low Impedance Grounding = Case 3 /n Solid Grounding = Case 4');
   i=input('');
   switch i
      case 1
         High_Impedance_Grounding(If);
      case 2
         High_Imp_3_Dist(If);
      case 3
         Low_Impedance_Grounding(If);
      case 4
         Solid_Grounding(If);
```

```
    end
    n=n+1;
    fprintf('Would you like to add another grounding method to your system?');
    j=input('\n If yes type 1 and if no type 2 = ');
    if(j==2)
        n=4;
    end
end
```

A2.High Impedance Grounding with Neutral Resistor:

```
Sb=input('Enter the base MVA value');
Vb=input('Enter the base Voltage');
Cgw=input('Enter the Generator Windings Capacitance');
Cgs=input('Enter the Surge Capacitance');
Cgt=input('Enter the Transformer Leads Capacitance');
Clt=input('Enter the Power Transformer Low Voltage Winding');
Cth=input('Enter the Station Service Transformer High Voltage Winding Capacitance');
Cvt=input('Enter the Voltage Transformer Winding Capacitance');
f=60; Vs=1;
C=Cgw+Cgs+Cgt+Clt+Cth+Cvt;
Xc=-1i*(10^6)/(2*pi*f*C);
Xcpu=(Sb(Xc))/(Vb*Vb);
```

```
Zo=(Xcpu*(-i*Xc))/(Xcpu+(-i*Xc));

I1pu=Vs/Zo;

I2pu=I1pu; I0pu=I1pu;

Ib=Sb/(sqrt(3)*Vb);

I1=I1pu*Ib

I2=I1; I0=I1;

Ia=3*I0;

R=Xc/3;

Rs=R/((Vprim/Vsec)^2);

Ior=cos(45)*I0; Ioc=sin(45)*I0;

Is=(3*I0)/((Vsec/Vprim)^2);

Vs=Is*Rs;

Rloss=(Rs*Is*Is)/1000;

S=(Vb*(3*Ior))/(sqrt(3));

Ic=Vb/(sqrt(3)*Xc);

DFp= 0.51 ; DFn= 0.49;

Ia1= iIc+0.51*I0(0.707+(1i*0.707));

Ib1= Ic(0.866-1i*0.5)+0.51*I0(0.26+(1i*0.966));

Ic1=-jIc+0.51*I0(-0.97+(1i*0.26));

fprintf('The three phase sequence current distribution is: Ia1=%d \t Ib1=%d \t

Ic1=%d',Ia1,Ib1,Ic1);
```

A3.High impedance grounding with 3 distribution transformer:

```
Sb=input('Enter the base MVA value');

Vb=input('Enter the base Voltage');

Cst=input('Enter the Source Transformer Capacitance');

Clg=input('Enter the Local Generator Capacitance');

Cm=input('Enter the Motor Capacitance');

Cpt=input('Enter the Power Center Transformer Capacitance');

Ctc=input('Enter the Total Connecting Cables Capacitance');

Csc=input('Enter the Surge Capacitance');

f=60; Vs=1;

C=Cst+Clg+Clg+Cm+Cpt+Ctc+Csc;

Xc=-1i*(10^6)/(2*pi*f*C);

Xcpu=(Sb(Xc))/(Vb*Vb);

Ic=(Vb*(10^3))/(sqrt(3)*Xc);

Zo=(Xcpu*(-i*Xc))/(Xcpu+(-i*Xc));

I1pu=Vs/Zo;

I2pu=I1pu; I0pu=I1pu;

Ib=Sb/(sqrt(3)*Vb);

I1=I1pu*Ib;

I2=I1; I0=I1;

Ia=3*I0;

Ior=cos(45)*I0; Ioc=sin(45)*I0;
```

```
Ior(sec)=Ior*(Vsec/Vprim);
3R=(3*Xc)/((Vsec/Vprim)^2);
3V0=Ior*3*R;
Rrating=(Ior^2)*3*R;
Trating=Vs*Ior;
fprintf('The resistor and transformer ratings are: Resistor rating=%d kW \t Transformer
rating=%d kVA \t',Rrating,Trating);
```

A4.Low Impedance Grounding:

```
Sb=input('Enter the base MVA value');
Vsc=input('Enter the MAVsc Voltage');
Xt=input('Enter the Transformer Reactance');
Vs=input('Enter the source Voltage');
Vb=13.8;
X1s=Sb/Vsc;
X2s=X1s;
X1=X1s+Xt;
X2=X1;
Ib=Sb/(sqrt(3)*Vb);
I1=I1pu*Ib
I2=I1; I0=I1;
```

```
Xpu=((Vs/I1)-(X1+X2+Xt))/3;

X=Xpu*((Vb*Vb)/Sb);

fprintf('The pu value of low impedance grounding reactance used is: Xpu=%d pu',Xpu);

fprintf('The actual value of low impedance grounding reactance used is: X=%d ohms',X);
```

A5.Data File:

```
Sb=input('Enter the base MVA value');

Sb = 160

Vb=input('Enter the base Voltage');

Vb = 18

Cgw=input('Enter the Generator Windings Capacitance');

Cgw = 0.24

Cgs=input('Enter the Surge Capacitance');

Cgs = 0.25

Cgt=input('Enter the Transformer Leads Capacitance');

Cgt = 0.004

Clt=input('Enter the Power Transformer Low Voltage Winding');

Clt = 0.03

Cth=input('Enter the Station Service Transformer High Voltage Winding Capacitance');

Cth = 0.004

Cvt=input('Enter the Voltage Transformer Winding Capacitance');
```

```
Cvt = 0.0005

Cst=input('Enter the Source Transformer Capacitance');

Cst = 0.24

Clg=input('Enter the Local Generator Capacitance');

Clg = 0.25

Cm=input('Enter the Motor Capacitance');

Cm = 0.004

Cpt=input('Enter the Power Center Transformer Capacitance');

Cpt = 0.03

Ctc=input('Enter the Total Connecting Cables Capacitance');

Ctc = 0.004

Csc=input('Enter the Surge Capacitance');

Csc = 0.0005

Vsc=input('Enter the MAVsc Voltage');

Vsc = 3200

Xt=input('Enter the Transformer Reactance');

Xt = i0.052

Vs=input('Enter the source Voltage');

Vs = 1
```

APPENDIX B: PROGRAM FOR CALCULATION OF Z-BUS AND SHORT CIRCUIT VALUES

In this appendix is given a program for calculation of Z-bus for a given system and also the calculation of fault currents in the line and at the phases, according to the faults occurring based on the user as shown in flowchart Fig 7.3 and in the Chapter 6: Short circuit current and Z-bus calculation:

```
n = input('Enter the number of buses = ');
i=1; j=0;

for i=1:n
    fprintf('Input the number of generators at bus %d = ',i);
    b(i)=input('');
    fprintf('Input the number of transformers between buses %d and ground = ',i);
    a1(i)=input('');
end
   for i=1:n
      for j=1:n
         if(i~=j)
    fprintf('Input the number of transformers between buses %d and %d = ',i,j);
    a(i,j)=input('');
         end
```

```
      end
  end


for i=1:n
  fprintf('Input the line impedance between buses %d and ground = ',i);
  z1(i)=input('');
end
for i=1:n
      for j=1:n
          if(i~=j)
  fprintf('Input the line impedance between buses %d and %d = ',i,j);
  z(i,j)=input('');
          end
      end
end


for i=1:n
    if(b(i)~=0)
        fprintf('Input the impedance of generator at bus %d = ',i);
        b1(i)=input('');
    end
end
```

```
for i=1:n
    if(a1(i)~=0)
       fprintf('Input the impedance of transformer between bus %d and ground = ',i);
       a3(i)=input('');
    end
end

for i=1:n
      for j=1:n
          if(i~=j)
              if(a(i,j)~=0)
   fprintf('Input the impedance of transformer between buses %d and %d = ',i,j);
   a2(i,j)=input('');
              end
          end
      end
end

for i=1:n
  %calculating line impedances from each bus to ground
   if(b(i)==1)
       z3(i) = z1(i)+b1(i)+a3(i);
   else
```

```
        z3(i) = z1(i);
    end
    disp(z3(i));
        for j=2:n
            if(a(i,j)==1)
                z2(i,j) = z(i,j)+a2(i,j);
            else
                z2(i,j) = z(i,j);
            end
        end
        disp(z2(i,j));
  end
 %building up of Zdata bus
b=n*((n*0.5)+0.5);
Zdata=zeros(b,4);
Zdata
x=1; y=0; c=n;
for i=1:n
    for j=1:c
        Zdata(x,1)=y;
        x=x+1;
    end
    y=y+1; c=c-1;
```

```
end
x1=1; y1=1; d1=1; c1=n;
for i=1:n
   for j=1:c1
      Zdata(x1,2)=y1;
      x1=x1+1;
      y1=y1+1;
   end
   y1=d1+1;
   d1=d1+1;
   c1=c1-1;
end
disp(Zdata);
x=1;
for i=1:b
   if(Zdata(i,1)==0)
      Zdata(x,4)=z3(i);
   else
      Zdata(x,4) = z2(Zdata(x,1),Zdata(x,2));
   end
   x=x+1;
end
Zdata1 = Zdata;
```

```
for i=1:b
   if(Zdata1(i,4)==0)
      Aa(i)=i;
   else
      Aa(i)=0;
   end
end
for i=1:b
   if(Aa(i)~=0)
      Zdata1(i,:)=[];
   end
end
Zdata1
Zbus1 = zbuild(Zdata1);
Zbus1

fprintf('Are the zero sequence impedances different from the positive and negative
sequence impedances?');
Ab = input('\n If yes type 1 and if no type 2 = ');

if (Ab==1)
   fprintf('Please re-enter the values of line impedances of the zero sequence again');
```

```
%Re-calculating the Zbus for the Zero sequence by getting new values
%from the user%

for i=1:n
 fprintf('Input the line impedance between buses %d and ground = ',i);
 z1(i)=input('');
end
for i=1:n
    for j=1:n
        if(i~=j)
 fprintf('Input the line impedance between buses %d and %d = ',i,j);
 z(i,j)=input('');
        end
    end
end

for i=1:n
   if(b(i)~=0)
       fprintf('Input the impedance of generator at bus %d = ',i);
       b1(i)=input('');
   end
end
```

```
for i=1:n
    if(a1(i)~=0)
       fprintf('Input the impedance of transformer between bus %d and ground = ',i);
       a3(i)=input('');
    end
end

for i=1:n
      for j=1:n
          if(i~=j)
              if(a(i,j)~=0)
   fprintf('Input the impedance of transformer between buses %d and %d = ',i,j);
   a2(i,j)=input('');
              end
          end
      end
end

for i=1:n
  %calculating line impedances from each bus to ground
   if(b(i)==1)
       z3(i) = z1(i)+b1(i)+a3(i);
   else
```

```
        z3(i) = z1(i);
      end
      disp(z3(i));
        for j=2:n
          if(a(i,j)==1)
            z2(i,j) = z(i,j)+a2(i,j);
          else
            z2(i,j) = z(i,j);
          end
        end
        disp(z2(i,j));
    end
   %building up of Zdata bus
  b=n*((n*0.5)+0.5);
  Zdata_ZeroSeq=zeros(b,4);
  Zdata_ZeroSeq
  x=1; y=0; c=n;
  for i=1:n
    for j=1:c
      Zdata_ZeroSeq(x,1)=y;
      x=x+1;
    end
    y=y+1; c=c-1;
```

```
end
x1=1; y1=1; d1=1; c1=n;
for i=1:n
   for j=1:c1
      Zdata_ZeroSeq(x1,2)=y1;
      x1=x1+1;
      y1=y1+1;
   end
   y1=d1+1;
   d1=d1+1;
   c1=c1-1;
end
disp(Zdata_ZeroSeq);
x=1;
for i=1:b
   if(Zdata_ZeroSeq(i,1)==0)
      Zdata_ZeroSeq(x,4)=z3(i);
   else
      Zdata_ZeroSeq(x,4) = z2(Zdata_ZeroSeq(x,1),Zdata_ZeroSeq(x,2));
   end
   x=x+1;
end
Zdata1_ZeroSeq = Zdata_ZeroSeq;
```

```
for i=1:b
   if(Zdata1_ZeroSeq(i,4)==0)
      Aa(i)=i;
   else
      Aa(i)=0;
   end
end
for i=1:b
   if(Aa(i)~=0)
      Zdata1_ZeroSeq(i,:)=[];
   end
end
Zdata1_ZeroSeq
Zbus1_ZeroSeq = zbuild(Zdata1_ZeroSeq);
Zbus1_ZeroSeq


end
X1=zeros(n,2);
X2=zeros(n,n,2);
fprintf('\n In case the tranformer connection is either ungrounded Y or Delta connected, 
enter 1 or if the tranformer connection is grounded Y, enter 2');
for i=1:n
   if(a1(i)==1)
```

```
            fprintf('\n Enter the transformer connection at the side attached to bus %d =',i)
            X1(i,1) = input('');
            X1(i,2) = input('\n Enter the transformer connection at the side attached to the
ground = ');
    end
    for j=1:n
        if(a(i,j)==1)
            fprintf('\n Enter the transformer connection at the side attached to bus %d =',i);
            X2(i,j,1) = input('');
            fprintf('\n Enter the transformer connection at the side attached to bus %d =',j);
            X2(i,j,2) = input('');
        end
    end
end
 for i=1:n
    for j=1:n
        if(X1(i,1)==1)
            z3(i)=inf;
        end
        if(X1(i,2)==1)
            z3(i)=inf;
        end
        if(a(i,j)==1)
```

```
        if(X2(i,j,1)==1)
          z2(i,j)=inf;
        end
        if(X2(i,j,2)==1)
          z2(i,j)=inf;
        end
        end
      end
    end
    x=1;
    for i=1:b
      if(Zdata(i,1)==0)
        Zdata(x,4)=z3(i);
      else
        Zdata(x,4) = z2(Zdata(x,1),Zdata(x,2));
      end
      x=x+1;
    end
    Zdata1_ZeroSeq = Zdata;
    for i=1:b
      if(Zdata1_ZeroSeq(i,4)==0)
        Aa(i)=i;
      else
```

```
        Aa(i)=0;
    end
end
for i=1:b
    if(Aa(i)~=0)
        Zdata1_ZeroSeq(i,:)=[];
    end
end
Zdata1_ZeroSeq
Zbus1_ZeroSeq = zbuild(Zdata1_ZeroSeq);
Zbus1_ZeroSeq
fprintf('\n What is the type of fault in the system?');
fault_type = input('');
 switch fault_type
    case 'symfault'
        symfault(Zdata1,Zbus1);
    case 'lgfault'
        lgfault(Zdata1_ZeroSeq,Zbus1_ZeroSeq,Zdata1,Zbus1,Zdata1,Zbus1);
    case 'llfault'
        llfault(Zdata1,Zbus1,Zdata1,Zbus1);
    case 'dlgfault'
        dlgfault(Zdata1_ZeroSeq,Zbus1_ZeroSeq,Zdata1,Zbus1,Zdata1,Zbus1);
end
```