Grounding the Neutral of Electrical Systems Through Low-Resistance Grounding Resistors: An Application Case

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Abstract—**It seems common knowledge that three-phase short-circuit currents are the worst possible scenario for electrical systems. In reality, single-phase ground-fault currents may be significantly more intense than three-phase fault currents. With the occurrence of high single-phase fault currents, severe damage could be caused to the iron cores of electric machines included in the zero-sequence fault loop. The method of neutral low-resistance grounding will be discussed by applying a step-by-step calculation procedure to an actual case, in order to properly size the grounding resistor, thereby limiting the fault current.**

Index Terms—**Complex numbers, ground-fault current, low-resistance neutral grounding resistor (LRG), positive-, negative-, and zero-sequence impedance, short-circuit current, Thevenin equivalent impedance.**

CONVENTIONS

1) Underlined capital letters designate complex numbers (e.g., $\underline{Z}$).
2) Absolute sign symbol (e.g., $|\underline{Z}|$) designates magnitude of complex numbers.
3) Indexes 0, 1, 2 applied to a complex number (e.g., $\underline{Z1}$) designate, respectively, zero-, positive-, and negative-sequence impedance.
4) Superscript and subscript can be applied to a complex number (e.g., $\underline{Z1}_{XF1}^{7500\ MVA}$) to indicate the reference base (i.e., 7500 MVA) and the component name (i.e., XF1).

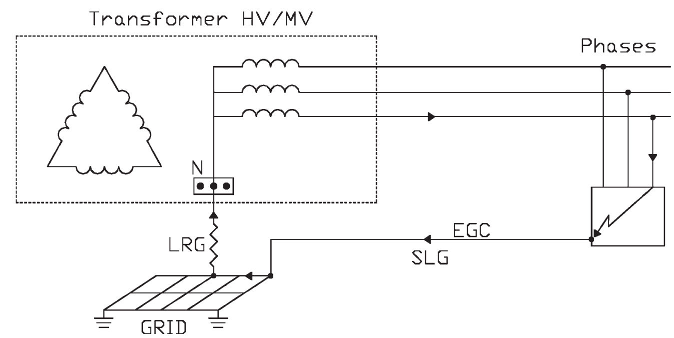

Fig. 1. General fault loop including LRG.

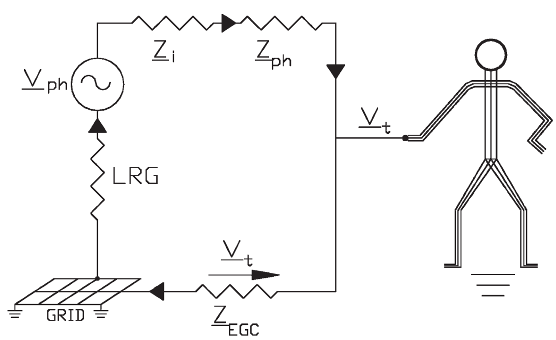

Fig. 2. Touch voltage is proportional to $\underline{Z}_{EGC}$ and not to LRG.

I. INTRODUCTION

LOW-RESISTANCE grounding resistors (LRGs) appear to be a preferred choice for power distribution systems where no neutral-connected load are fed through a delta–wye transformer, particularly when motors are directly supplied at transformer bus. Low-resistance grounding is suitable when continued operation of processes is not critical in the event of a fault.

The state of the neutral of the system is of the essence in determining the magnitude of single-phase ground-fault (SLG) currents. This type of fault occurs most frequently, and three-phase faults are usually an evolution of SLGs. The main purpose of grounding with LRG is to limit the maximum fault current to a predetermined value which will not damage any equipment in the power system yet allowing sufficient circulation of fault current to effectively operate protective relays to clear the fault.

The minimum ground-fault current must be large enough to activate the ground-fault protection device and relay "off" the faulted portion of the system. In other words, current intensity must not be of the same magnitude as the "normal" unbalanced capacitive charging currents, coming from healthy phases, during the regular functioning of the plant. This is necessary in order to avoid nuisance trips of the protection devices.

LRGs are installed as shown in Fig. 1. SLG goes back to the source through the equipment grounding conductors, part of the grounding grid, and the neutral resistance.

It is clear how the actual earth is not included in the fault loop. The presence of the LRG does not pose any particular safety issues. The touch voltage $\underline{V}_t$ for a fault on equipment on the secondary side of the substation (e.g., medium-voltage

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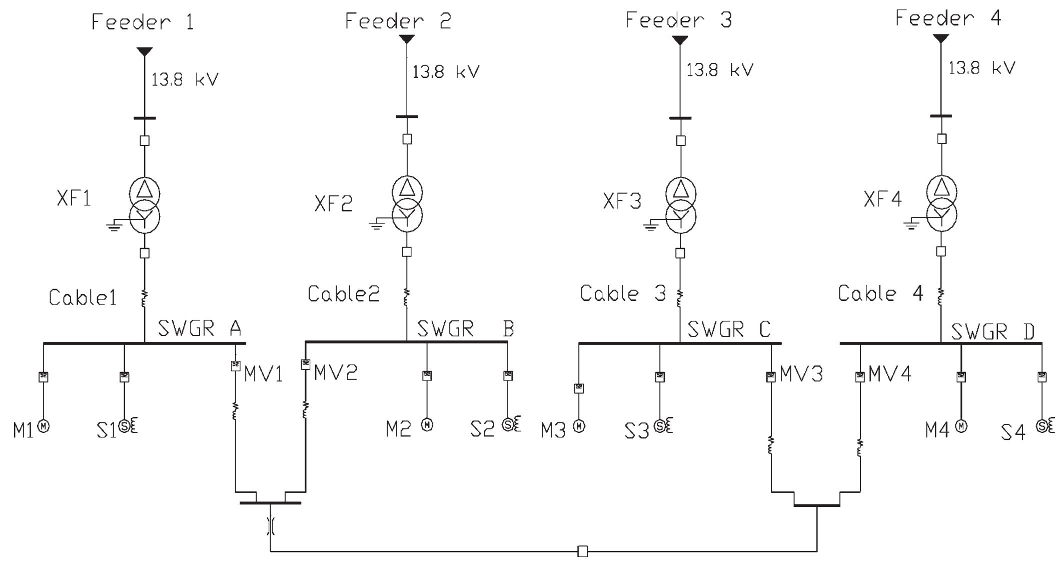


Fig. 3. Oversimplified electrical distribution one-line diagram.

motors), in fact, is proportional to the equipment-grounding-conductor impedance $\underline{Z}_{\mathrm{EGC}}$ and not to LRG, as shown in Fig. 2.

In general, $\underline{Z}_{\mathrm{EGC}}$ is very small if compared to the neutral grounding resistor (e.g., fraction of ohms) and, thus, so is the touch voltage.

In addition, the medium-voltage loads are, generally, protected by zero-sequence impedance relays, which instantaneously trip, limiting the exposure time to the fault potential.

Reference [2] calls for neutral grounding resistors' size of at least 100 A but considers more usual a range from 200 to 1000 A. In some unusual circumstances, the resistors may even allow a fault current as high as 1200 A. This range of currents safeguards the electric machines' ferromagnetic cores included in the zero-sequence fault loop, by containing both the thermal stress and the ground-resistor copper loss. The rule of thumb proposed by Beeman [3] is to limit the level of ground-fault currents to values from 5% to 20% of the three-phase short-circuit current at the same point of fault.

The ratings of current transformers and type of relays must be chosen accordingly once the SLG's minimum value has been determined.

Neutral grounding resistors are rated in line-to-neutral volts (the line-to-neutral rating of the system), initial current in amperes, maximum temperature rise, and allowable "on" time in seconds. They must be capable of carrying rated current for the allowable "on" time, without exceeding the permissible temperature rise established in [1]. The most common "on" time is 10 s, but also 60 s can be specified.

Grounding resistors, suitable for outdoor service, are customized by manufacturer, according to the electrical designer's specifications.

II. Method of Symmetrical Components

Method of symmetrical components, as described in [4] by its inventor, allows an effective evaluation of the ground-fault currents, once the Thevenin equivalent impedance at the fault point has been calculated. By Thevenin impedance, we mean the impedance as seen at any couple of points of the distribution system once their circuital connection has been opened and the system has been "passivated," i.e., all the voltage generators have been short circuited and all the current generators have been opened. This method utilizes positive-, negative-, and zero-sequence impedances of all the components involved in the fault.

It can be proved that the general expression (1) yields the aforementioned SLG current, involving any of the phases, in amperes

$$\underline{I_{\mathrm{SLG}}} = \underline{3I_0} = \frac{3\underline{E}}{\underline{Z1} + \underline{Z2} + \underline{Z0} + 3\underline{Z_{\mathrm{G}}}} \tag{1}$$

where $\underline{\mathrm{E}}$ represents the line-to-neutral voltage phasor in volts; $\underline{\mathrm{Z1}}$, $\underline{\mathrm{Z2}}$, and $\underline{\mathrm{Z0}}$ are, respectively, positive-, negative-, and zero-sequence impedances in ohms per phase; $\underline{\mathrm{Z}}_{\mathrm{G}}$ is the limiting impedance of the neutral grounding equipment, if present; and $\underline{\mathrm{I}}_0$ is the zero-sequence current.

III. Application Case

Make reference to the oversimplified one-line diagram shown in Fig. 3.

The 4.16-kV system (Fig. 1), constituted by a permanent parallel-of-four solidly grounded main substations, directly supplies four induction motors (M_1, M_2, M_3, and M_4, 2500 hp each) and four synchronous motors (S_1, S_2, S_3, and S_4, 800 hp each). Let us calculate the fault current at Switchgear A, assuming to isolate the Switchgear A from the rest of the distribution system, by opening the breaker MV1.

The electrical utility, upon request of the designer, communicated the following values as positive-, negative-, and zero-sequence impedances at the 13.8-kV property-line supply box

$$\underline{Z1}_{\mathrm{Utility}} = \underline{Z2}_{\mathrm{Utility}} = 0.89 + j1.26 \text{ p.u.} \tag{2}$$

$$\underline{Z0}_{\mathrm{Utility}} = 2.16 + j3.89 \text{ p.u.} \tag{3}$$

Calculation *Base Values* used for the earlier quantities were also communicated by the utility to be $V_{\mathrm{B}} = 13.8$ kV e,

$S_{\mathrm{B}} = 100$ MVA. We will use the same base values for our calculations.

The *Base Impedance* is

$$Z_{\mathrm{B}} = \frac{V_{\mathrm{B}}^2}{S_{\mathrm{B}}} = \frac{13\,800^2}{100 \cdot 10^6} = 1.904\ \Omega \text{ at } 13.8\text{ kV} \tag{4}$$

which yields the following absolute ohmic values of the sequence impedances:

$$\underline{Z1}_{\mathrm{Utility}} = \underline{Z2}_{\mathrm{Utility}} = \underline{Z1}_{\mathrm{Utility}} \cdot Z_{\mathrm{B}} = 1.6987 + j2.3976\ \Omega \tag{5}$$

$$\underline{Z0}_{\mathrm{Utility}} = \underline{Z0}_{\mathrm{Utility}} \cdot Z_{\mathrm{B}} = 4.1135 + j7.4176\ \Omega. \tag{6}$$

These values allow the calculation of the three- and single-phase short-circuit fault currents as follows:

$$|\underline{I}_{sc3}| = \left|\frac{\underline{V}_\Phi}{\underline{Z1}_{\mathrm{Utility}}}\right| = \frac{13\,800}{\sqrt{3} \cdot 2.9384} = 2711.5\text{ A} \tag{7}$$

$$|\underline{I}_{\mathrm{SLG}}| = \left|\frac{3\underline{V}_\Phi}{2\underline{Z1}_{\mathrm{Utility}} + \underline{Z0}_{\mathrm{Utility}}}\right| = \frac{3 \cdot 13\,800}{\sqrt{3} \cdot 14.338} = 1667\text{ A}. \tag{8}$$

The short-circuit apparent powers associated to the currents given by (7) and (8) are, respectively, as follows:

$$S_{\mathrm{SC3}} = 1.732 \cdot V_{\mathrm{LL}} \cdot I_{\mathrm{sc3}} = 1.732 \cdot 13\,800 \cdot 2711.5 = 64.8\text{ MVA} \tag{9}$$

$$S_{\mathrm{SLG}} = I_{\mathrm{SLG}} \cdot V_\Phi = 1667 \cdot 7967.7 = 13.3\text{ MVA}. \tag{10}$$

Both loads and revolving loads have sequence-impedance values, provided by the manufacturer, in per unit on the base of their nameplate rating of power and voltage. Therefore, these data have to be converted to the new common base. Let us recall the basic formulas necessary for this conversion

$$Z_{\mathrm{pu}} = \frac{Z_{\mathrm{actual}}}{Z_{\mathrm{base}}} \tag{11}$$

$$Z_{\mathrm{base}} = \frac{V_{\mathrm{base}}^2}{S_{\mathrm{base}}} \tag{12}$$

$$\begin{aligned} Z_{\mathrm{pu_{new}}} &= \frac{1}{Z_{\mathrm{base_{new}}}} \cdot \frac{Z_{\mathrm{pu_{old}}} \cdot V_{\mathrm{base_{old}}}^2}{S_{\mathrm{base_{old}}}} \\ &= Z_{\mathrm{pu_{old}}} \cdot \left(\frac{V_{\mathrm{base_{old}}}}{V_{\mathrm{base_{new}}}}\right)^2 \cdot \left(\frac{S_{\mathrm{base_{new}}}}{S_{\mathrm{base_{old}}}}\right). \end{aligned} \tag{13}$$

In our model (Fig. 1), we have transformers which "separate" two levels of voltages (13.8 and 4.16 kV). The chosen calculation voltage base ($V_{\mathrm{B}} = 13.8$ kV) must also comply with the following equation for each of the two voltage levels:

$$a_{12} = \frac{V_{\text{Base at level1}}}{V_{\text{Base at level2}}} \tag{14}$$

where a_{12} is the transformers' nameplate voltage ratio.

For the transformer XF1, we will have

$$\begin{aligned} \underline{Z1}_{\mathrm{XF1}}^{7500\text{ MVA}} &= \underline{Z2}_{\mathrm{XF1}}^{7500\text{ MVA}} \\ &= \underline{Z0}_{\mathrm{XF1}}^{7500\text{ MVA}} \\ &= 0.0043 + j0.0648\text{ p.u.} \end{aligned} \tag{15}$$

The value is provided by the manufacturer in per unit on the base of nameplate rating of power and voltage of equipment ($S_{\mathrm{n}} = 7500$ kVA, $V_{\mathrm{LL}} = 13.8$ kV).

Applying (13), we will have

$$\begin{aligned} \underline{Z1}_{\mathrm{XF1}}^{100\text{ MVA}} &= \underline{Z2}_{\mathrm{XF1}}^{100\text{ MVA}} \\ &= \underline{Z0}_{\mathrm{XF1}}^{100\text{ MVA}} \\ &= 0.058 + j0.864\text{ p.u.} \end{aligned} \tag{16}$$

The value is expressed on the new calculation base $S_{\mathrm{B}} = 100$ MVA, $V_{\mathrm{B}} = 13.8$ kV.

Motor 1 ($S_{\mathrm{n}} = 2403$ kVA) is modeled through its subtransient impedance

$$\underline{Z1}_{\mathrm{Motor1}}^{2403\text{ kVA}} = \underline{Z2}_{\mathrm{Motor1}}^{2403\text{ kVA}} = 0.005 + j0.167\text{ p.u.} \tag{17}$$

The value is provided by the manufacturer in per unit on the base of nameplate rating of power and voltage of equipment ($S_{\mathrm{n}} = 2403$ kVA, $V_{\mathrm{LL}} = 4.16$ kV).

Applying (13), we will have

$$\underline{Z1}_{\mathrm{Motor1}}^{100\text{ MVA}} = \underline{Z2}_{\mathrm{Motor1}}^{100\text{ MVA}} = 0.21 + j6.94\text{ p.u.} \tag{18}$$

The value is expressed on the new calculation base $S_{\mathrm{B}} = 100$ MVA, $V_{\mathrm{B}} = 13.8$ kV.

The zero-sequence impedance of rotating machines greatly depends upon the nature of stator connection with respect to ground. The earlier induction-motor stator is wound as an isolated wye; therefore, the zero-sequence impedance is very high, virtually infinite. Thus, we do not have any contribution to the Thevenin equivalent zero-sequence impedance at the point of fault.

The zero-sequence impedance of the synchronous machines, whose stator is, on the contrary, a solidly grounded wye, is very low and equal to

$$\begin{aligned} \underline{Z1}_{\mathrm{Synch1}}^{780.1\text{ kVA}} &= \underline{Z2}_{\mathrm{Synch1}}^{780.1\text{ kVA}} = \underline{Z0}_{\mathrm{Synch1}}^{780.1\text{ kVA}} \\ &= 0.006 + j0.15\text{ p.u.} \end{aligned} \tag{19}$$

The value is provided by the manufacturer in per unit on the base of nameplate rating of power and voltage of equipment ($S_{\mathrm{n}} = 780.1$ kVA, $V_{\mathrm{LL}} = 4.16$ kV).

Applying (13), we will have

$$\underline{Z1}_{\mathrm{Synch1}}^{100\text{ MVA}} = \underline{Z2}_{\mathrm{Synch1}}^{100\text{ MVA}} = \underline{Z0}_{\mathrm{Synch1}}^{100\text{ MVA}} = 0.83 + j19.22\text{ p.u.} \tag{20}$$

The values are expressed on the new calculation base $S_{\mathrm{B}} = 100$ MVA, $V_{\mathrm{B}} = 13.8$ kV.

The 500-kcmil EPR cables at 4.16 kV, 181 ft long each, have sequence impedances, provided by the manufacturer, in physical absolute values as follows:

$$\underline{Z1} = \underline{Z2} = 0.0051 + j0.0076\ \Omega \tag{21}$$

$$\underline{Z0} = 0.0081 + j0.0204\ \Omega. \tag{22}$$

Let us convert (21) and (22) using (11) and (12) to our common base

$$Z_{\mathrm{B}} = \frac{V_{\mathrm{B}}^2}{S_{\mathrm{B}}} = \frac{4160^2}{100 \cdot 10^6} = 0.17\ \Omega \text{ at } 4.16\text{ kV} \tag{23}$$

$$\underline{Z1}_{\mathrm{Cable}}^{100\ \mathrm{MVA}} = \underline{Z2}_{\mathrm{Cable}}^{100\ \mathrm{MVA}} = 0.03 + j0.04 \text{ p.u.} \tag{24}$$

$$\underline{Z0}_{\mathrm{Cable}}^{100\ \mathrm{MVA}} = 0.05 + j0.12 \text{ p.u.} \tag{25}$$

The positive (and negative) Thevenin equivalent impedance at Switchgear A is given by the series of utility, transformer XF1, and Cable1 contributions, which is in parallel with both the induction *motor1* and synchronous *synch1* positive (and negative)-sequence impedance. The results are as follows:

$$\begin{aligned}\underline{Z1}_{\mathrm{Parallel-M1S1}} &= \underline{Z2}_{\mathrm{Parallel-M1S1}} \\ &= \frac{\underline{Z1}_{\mathrm{Motor1}} \cdot \underline{Z1}_{\mathrm{Synch1}}}{\underline{Z1}_{\mathrm{Motor1}} + \underline{Z1}_{\mathrm{Synch1}}} \\ &= 0.17 + j5.1 \text{ p.u.} = 5.1\ \mathrm{e}^{\mathrm{j}88^\circ} \text{ p.u.}\end{aligned} \tag{26}$$

$$\begin{aligned}\underline{Z1}_{\mathrm{SwgrA}} &= \underline{Z2}_{\mathrm{SwgrA}} \\ &= \frac{\left(\underline{Z1}_{\mathrm{Utility}} + \underline{Z1}_{\mathrm{XF1}} + \underline{Z1}_{\mathrm{cable1}}\right) \cdot \underline{Z1}_{\mathrm{Parallel-M1S1}}^{\mathrm{Th}}}{\underline{Z1}_{\mathrm{Utility}} + \underline{Z1}_{\mathrm{XF1}} + \underline{Z1}_{\mathrm{cable1}} + \underline{Z1}_{\mathrm{Parallel-M1S1}}^{\mathrm{Th}}} \\ &= 0.49 + j1.57 \text{ p.u.} = 1.64\ \mathrm{e}^{\mathrm{j}72.6^\circ} \text{ p.u.}\end{aligned} \tag{27}$$

The equivalent Thevenin zero-sequence impedance is given by the summation of transformer XF1 and Cable1 contributions in parallel with the zero-sequence impedance of the synchronous machine. The result is as follows:

$$\begin{aligned}\underline{Z0}_{\mathrm{SwgrA}} &= \frac{\left(\underline{Z0}_{\mathrm{XF1}} + \underline{Z0}_{\mathrm{cable}}\right) \cdot \underline{Z0}_{\mathrm{Synch1}}}{\underline{Z0}_{\mathrm{XF1}} + \underline{Z0}_{\mathrm{cable}} + \underline{Z0}_{\mathrm{Synch1}}} \\ &= 0.09 + j0.93 \text{ p.u.} = 0.94\ \mathrm{e}^{\mathrm{j}84^\circ} \text{ p.u.}\end{aligned} \tag{28}$$

Thus, the fault currents, three-phase and phase-to-ground, expressed in per unit, at Switchgear A are

$$|\underline{I}_{sc3}|_{\mathrm{SwgrA}} = \frac{1 \text{ p.u.}}{\left|\underline{Z1}_{\mathrm{SwgrA}}^{\mathrm{Th}}\right|} = 0.6 \text{ p.u.} \tag{29}$$

$$|\underline{I}_{\mathrm{SLG}}|_{\mathrm{SwgrA}} = \frac{3 \cdot 1 \text{ p.u.}}{\left|2 \cdot \underline{Z1}_{\mathrm{SwgrA}}^{\mathrm{Th}} + \underline{Z0}_{\mathrm{SwgrA}}^{\mathrm{Th}}\right|} = 0.71 \text{ p.u.} \tag{30}$$

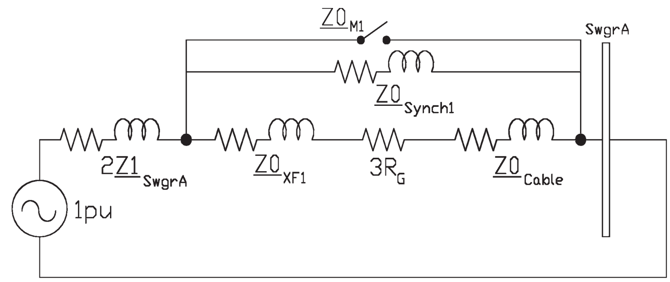


Fig. 4. Thevenin equivalent ground fault loop with grounding resistor R_{G} for calculating the zero-sequence current.

In "physical" values, the earlier quantities at Switchgear A become (32) and (33)

$$I_{\mathrm{B}} = \frac{S_{\mathrm{B}}}{\sqrt{3} \cdot V_{\mathrm{B}}} = 13\,879 \text{ A at } 4.16\text{ kV} \tag{31}$$

$$|\underline{I}_{sc3}|_{\mathrm{SwgrA}} = |\underline{I}_{sc3}| \cdot I_{\mathrm{B}} = 8327 \text{ A} \tag{32}$$

$$|\underline{I}_{\mathrm{SLG}}|_{\mathrm{SwgrA}} = |\underline{I}_{\mathrm{SLG}}| \cdot I_{\mathrm{B}} = 9867 \text{ A.} \tag{33}$$

We note that the single-phase fault current is larger than the three-phase one.

Restoring the parallel with the other three substations, a similar calculation procedure, here omitted for brevity, yields the following results at the same location:

$$|\underline{I}_{sc3}|_{\mathrm{SwgrA}} = 32.81 \text{ kA} \tag{34}$$

$$|\underline{I}_{\mathrm{SLG}}|_{\mathrm{SwgrA}} = 38.59 \text{ kA.} \tag{35}$$

The SLG current (35) at Switchgear A is even greater than the short-circuit three-phase current and could seriously damage any equipment through which it had to circulate. Consequently, steps to minimize this risk must necessarily be taken.

IV. Minimization of the Ground-Fault Current at the Single Transformer

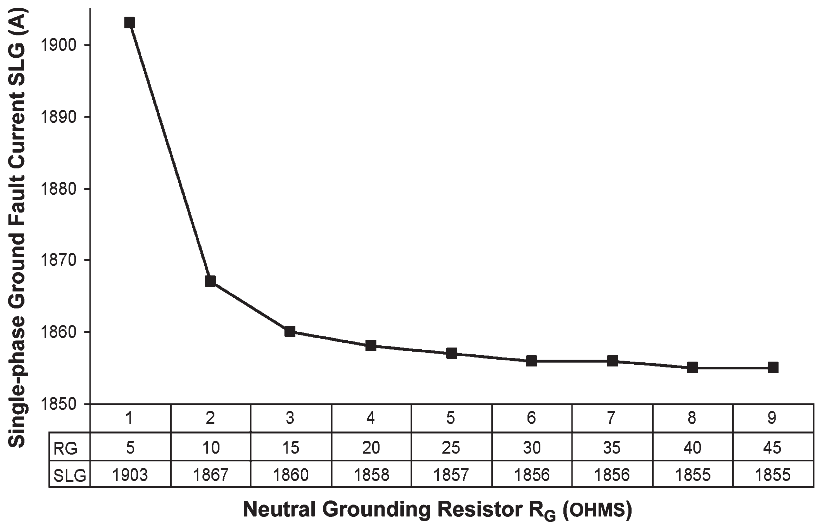
In order to minimize the risk of burning and melting of equipment, a neutral grounding resistor R_{G} is introduced into the neutral of each transformer. Adding such a resistor, while it does not modify the positive- and negative-sequence impedances, changes the Thevenin equivalent zero-sequence impedance at Switchgear A (Fig. 4). To be conservative in the calculation, we neglect the reactive component of the grounding resistor, even if tripled in the zero-sequence loop, because actual grounding resistors, usually, have high power factor (e.g., 98%).

Let us study the single transformer supposing Switchgear A isolated from the parallel (MV1 open).

Thevenin equivalent zero-sequence impedance at Switchgear A is expressed by (36) as complex function of the real variable R_{G}

$$\underline{Z0}_{\mathrm{SwgrA}} = \frac{\left(\underline{Z0}_{\mathrm{XF1}} + 3R_{\mathrm{G}} + \underline{Z0}_{\mathrm{cable}}\right) \cdot \underline{Z0}_{\mathrm{Synch1}}}{\underline{Z0}_{\mathrm{XF1}} + 3R_{\mathrm{G}} + \underline{Z0}_{\mathrm{cable}} + \underline{Z0}_{\mathrm{Synch1}}} \tag{36}$$

where R_{G} is the unknown zero-sequence value of the neutral grounding resistor at the transformer XF1. The magnitude of



	1	2	3	4	5	6	7	8	9
RG	5	10	15	20	25	30	35	40	45
SLG	1903	1867	1860	1858	1857	1856	1856	1855	1855

Fig. 5. Graph of $|\underline{I}_{\mathrm{SLG}}|$ as a function of R_{G}.

the resulting SLG current in per unit as a function of R_{G} is

$$|\underline{I}_{\mathrm{SLG}}| = \frac{3 \cdot 1 \text{ p.u.}}{|2 \cdot \underline{Z1}_{\mathrm{SwgrA}} + \underline{Z0}_{\mathrm{SwgrA}}|}. \tag{37}$$

This author studied this expression as a function of R_{G}, and the result is shown in Fig. 5 in physical amperes.

I observed how the fault current "saturates," unfortunately at a high value, when the ohmic value of the neutral grounding resistor reaches 15 Ω. The electrical system, i.e., results to be "insensitive" to the variation in size of the neutral resistor.

This makes problematic the limitation of the ground-fault current by using the LRG at the transformer neutral. For instance, when LRG equals 15 Ω, the obtained SLG current at Switchgear A is still 1860 A, and upon restoring the parallel with the other substations, all equipped with LRGs, is as high as 5834 A. The neutral grounding resistors, although installed at each substation, fail to limit the ground-fault current to value not exceeding 1000 A.

V. Possible Solutions

The reason for the failure of the current limitation from the LRGs lies in the parallel branch in the circuit shown in Fig. 2. If the synchronous machine's zero-sequence impedance were an open circuit (i.e., very high), the machine would still contribute to the ground fault at Switchgear A but only by means of its positive and negative impedances. The zero-sequence impedance would no longer be a parallel branch in the equivalent circuit (Fig. 6), as the center-star of the synchronous machine's stator would be "isolated" from ground.

According to manufacturer general standards, these are the possible options for the synchronous machine.

1) Stator neutral not accessible, closed inside the stator.
2) Stator neutral accessible in the conduit box (three cables for phase leads and one neutral closing connection bar).
3) Six cables accessible in the conduit box (three cable sets for phase leads and three cable sets for neutral leads).

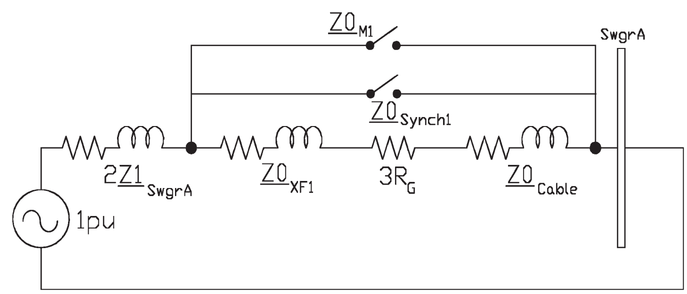


Fig. 6. Zero-sequence Thevenin equivalent ground fault loop with grounding resistor R_{G} and synchronous motor's stator isolated from ground.

The manufacturer, generally, does not connect the neutral lead to a grounding terminal, as this choice is up to the customer.

According to the aforementioned standards, "isolation" from ground can be achieved through the following solutions:

1) grounding of the neutral lead through the resistor (or reactor);
2) ungrounding the machine neutral, if neutral is accessible (simply changing the stator connection from grounded wye to ungrounded delta would not work without also changing the line voltage; in fact, the synchronous-stator magnetic field would also change, and the motor would not function).

For both solutions, the clearance of the relay engineer is indispensable, as the protection of the machine is dependent on the state of its neutral.

In our application, let us suppose that the transformer is solidly grounded and that the synchronous motor is isolated from ground; the resulting module of the SLG current at Switchgear A, in per unit and physical amperes, will, respectively, be

$$|\underline{I}_{\mathrm{SLG}}|_{\mathrm{SwgrA}} = \frac{3 \cdot 1 \text{ p.u.}}{|2 \cdot \underline{Z1}_{\mathrm{SwgrA}} + \underline{Z0}_{\mathrm{XF1}} + \underline{Z0}_{\mathrm{Cable}}|} = 0.70 \text{ p.u.} \tag{38}$$

$$|\underline{I}_{\mathrm{SLG}}|_{\mathrm{SwgrA}} = |\underline{I}_{\mathrm{SLG}} \cdot I_{\mathrm{B}}| = 9715 \text{ A}. \tag{39}$$

Inserting the neutral grounding resistor R_{G} (Fig. 4), the magnitude of the same SLG current will have the following expression in per unit:

$$|\underline{I}_{\mathrm{SLG}}|_{\mathrm{SwgrA}} = \frac{3 \cdot 1\ \mathrm{p.u.}}{|2 \cdot \underline{Z1}_{\mathrm{SwgrA}} + \underline{Z0}_{\mathrm{XF1}} + 3R_{\mathrm{G}} + \underline{Z0}_{\mathrm{Cable}}|}. \tag{40}$$

From the earlier expression, it is possible to solve for R_{G} in order to limit the fault current to 0.014 p.u. or 200 A

$$R_{\mathrm{G-p.u.}} = \left| \frac{1\ \mathrm{p.u.}}{0.014} - \left(\frac{2 \cdot \underline{Z1}_{\mathrm{SwgrA}} + \underline{Z0}_{\mathrm{XF1}} + \underline{Z0}_{\mathrm{Cable}}}{3} \right) \right| = 71\ \mathrm{p.u.} \tag{41}$$

In ohmic value, we will have

$$R_{\mathrm{G}} = R_{\mathrm{G-p.u.}} \cdot Z_{\mathrm{Base}} = 71 \cdot 0.17 = 12\ \Omega. \tag{42}$$

Such LRG, installed at each transformer, upon restoring of the parallel among the substations, will limit the circulation of fault current to no more than 800 A, as expected.

VI. Conclusion

The core of the problem lies in that ground-fault currents must be determined, accounting for all the contributions at the fault point, before the resistor can be selected and specified.

LRGs with the same rating can allow a different amount of current to flow to ground as a function of the rotating loads connected at the bus whose SLG current is being limited. In our example, the presence of the 800-hp synchronous motor at Switchgear A, supposed X_{F1} solidly grounded, increases the ground-fault current by 8%. In particular, the motor loads with solidly grounded stators (i.e., very low zero-sequence impedance) are the major contributors to the SLG.

It is important to understand that electrical systems might not respond to the increase in the LRG's value, with a proportional decrease of the SLG, because of a "saturation" relationship between the two quantities, as seen previously.

To address the problem of limiting the SLG, the designer may want to specify motors with stator isolated from ground or resistor/reactor grounded, providing the machine is protected accordingly. This solution is acceptable, and practiced, as the machine's regular operation is not affected by the nature of stator connection with respect to ground.

In specifying LRG, the mechanical requirements of the neutral resistors are usually emphasized, as they might work in classified areas, and its rating is indicated in amperes. In detailed specifications for LRG, which contractors will bid on, the engineer may want to be more specific and provide the actual calculated ohmic value of the neutral grounding resistor. As seen, this value depends on the entire distribution system and not on single transformers. It is the contractor's responsibility/right to be aware/told the aforementioned ohmic value in order to finalize his offer for an effective means of grounding.

Last but not least, the LRG's ohmic value must always allow sufficient current to effectively actuate the relay protection, which means that both ratings of current transformers and type of relays must be accordingly chosen.

Acknowledgment

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References

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