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Identification of Ground–fault Current in Various Transformer Connection and Generator Grounding using Symmetrical Components Method

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Abstract. Single line to ground-fault (SLG) fault is the record frequent fault probable to occur in an electric power system. The effect of ground-fault is determined by using grounding method and transformer connections. In this study, the simulation showed the performance of a simple power system within the SLG fault in the system at various transformer connection and generator grounding method. New approach the application of ground fault current calculation using symmetrical components method on unit generator transformers. A symmetrical components method applied with simulation was conducted in Matlab software. The results were then analyzed, presenting a comparison with the fault impact at various transformer connection and generator grounding method. The models of transformer connection for each side (primary and secondary) used were wye (Y), wye-grounded (Yn) and delta (Δ). It was clearly shown that the ground-fault currents at the generator bus had significantly an effect on the type of the transformer connections used during the ground-fault at the secondary side of the transformer.
Keywords; symmetrical components method, ground-fault, transformer connection

1. Intoduction

In general, a step up transformer at electric power station can be categorized as either unit generator-transformer configuration, unit generator-transformer configuration with generator breaker, cross-compound generator and generator involving a unit transformer [1, 2]. Ground-fault on the transmission line or busbar can affect the system configuration of the generator.   Knowledge on ground-fault at transformer winding connection is essential in selecting the most suitable transformer for service requirement.

Several papers have deliberated the impact of variation transformer connections within a power system but no one has discussed, in particular, about the effect of ground fault current. The transformer configurations with the propagation of voltage sags [3] can influence the performance of voltage sags inside the industry facility, depending on the function of transformer connection used in the service transformer. It is known that the *Yn-Yn* transformer connected across the generator and the *Δ-Yn* transformer connected across the load will reduce the unbalance voltage[4]. Reference [5] describes the effect of the voltage transformers on the operating conditions of a ground-fault protection system for unit-connected generators. The different transformer connections was highly dependent on the unbalance voltage in the power system [6,7]. The influences of transformer connection on operation are discussed [8] focus on operation involved insulation stresses, autotransformer under various condition operations but not included for grounding.

There are many factors that can affect the level of ground-fault currents in unit generator transformer. The ground-fault current magnitude, particularly in the generator and transformers, are determined by

analyzing the generator and transformer winding impedance [1, 9, 10]. This paper presents the effect of generator grounding method and three-phase transformer connections. The generator grounding method included solid grounding, resistance grounding and reactance grounding. Transformer connections were denoted as wye (*Y*), wye-grounded (*Yn*) and delta (*Δ*) in each primary and secondary side for a simple power system in unit generator-transformer configuration.
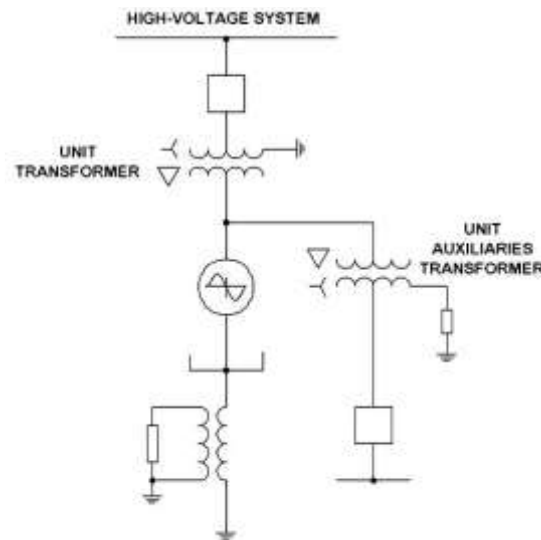
Figure 1. Unit generator-transformer configuration [1]

2. Principle

2.1 Transformer Connections
The primary and secondary winding of the transformer can be connected either in combinations of *Y, Yn* or *Δ* connections, which can result in nine possible connection combinations [9, 11] *Y-Y, Y-Yn, Y-Δ, Yn-Yn, Yn-Y, Yn-Δ, Δ-Y, Δ-Yn* and *Δ-Δ*.

The zero-phase sequence (ZPS) impedance of a transformer depends on the configuration of the winding. The ZPS impedance of a *Δ* winding is infinite, whereas the ZPS impedance of a Y-connected winding is a composite series with the ZPS impedance of a transformer and an impedance of any neutral grounding devices that might be present. Thus, an ungrounded Y-winding would present infinite zero-sequence impedance because of the absence of a neutral grounding connection that would appears as an open circuit in series with the ZPS impedance of the transformer winding itself [12, 13].

The sequence equivalent circuits of three-phase transformer depend on the connections of the primary and secondary winding. The different combinations of Y and Δ windings determine the configurations of the ZPS circuits. Figure 2 presents some of the connection diagram of a transformer connection and their ZPS equivalent network [9, 12]

2.2 Generator Grounding Method
Grounding systems can be categorized into four general groups : ungrounded, effectively grounded, low impedance, and high-impedance grounded. Ungrounded systems have no physical connection between the generator neutral and ground. Effectively grounded systems have a direct connection from the generator neutral to system ground. The phase-to-ground fault current on an effectively grounded system is very high; in many cases higher than that of a three-phase fault. A low-impedance grounded system has minimal impedance connected between the generator neutral and ground. This impedance limits the ground fault current to a value typically between 100 A and the magnitude of a three-phase fault. In a high-impedance grounded system, the ground-to-neutral impedance is large enough to limit the ground

fault current to a value between 2 and 15 A [10]. For generator grounding, the grounding methods dominants are resistance grounding (39.4%), followed by solidly grounding (25.7%) then neutral reactor grounded (17.3 %) [13].

2.3 Symmetrical Components Method

Fortescue proposed the theory of symmetrical components in a famous paper in 1918. It was used to analyze the unbalanced short-circuit and open-circuit fault in practical power systems. This theory applies to a system of N unbalanced phasors, including the case of three unbalanced phasors representing a three-phase power system. The theory enables the transformation of three unbalanced phasors into a three set of balanced phasor, called the positive phase sequence (PPS), negative phase sequence (NPS), and zero-phase sequence (ZPS) [13].

The magnitude of a ground-fault current, especially at the generator and transformer are determined by generator and transformer winding impedance [1, 9, 10]. The ground-fault current magnitude is calculated by using the following equation [13, 14]:

$$I_{SLG} = \frac{3.V_f}{Z_0 + Z_1 + Z_2 + 3.Z_f} \qquad \dots (1)$$

Where V_f is the pre-fault voltage source. Z_1, Z_2, and Z_0 are the PPS, NPS, and ZPS impedances for network of different sequence respectively. Z_f represents the impedance of the ground return path including the fault arc, the grounding network, and the intended neutral impedance, when present. Generally, two settings of pre-fault voltages are assumed for fault currents calculation. Firstly, all the pre-fault voltages are assumed equal to 1 pu, i.e., the loads are neglected [9]. Secondly, the values of the pre-fault voltages are determined using load flow algorithms [14, 15]. The use of 1 pu makes the fault calculation simpler [16].

If one assumes Z_f=0 and Z_1=Z_2= Z_0, the magnitude of a ground-fault current will be :

$$I_{SLG} = \frac{V_f}{Z_1} \qquad \dots (2)$$

In resistance grounded systems (all reactance's set to zero), the ground resistor restricts the ground-fault current to a particular value regardless of the fault type or fault location. The ground-fault protective sensitivity can be relatively independent of continuous load current values and, therefore, can have a lower pick up setting than phase protective devices. The ground-fault currents are not transferred through system power transformers that are connected in Δ-Y or Δ-Δ, as the ground-fault. The Protection for each system voltage stage is independent of the protection at other voltage stages.

3. Research Method

This section presents the performance of various transformer connections and generator grounding method at the generator bus during SLG fault at each bus in the form of the single line diagram for analysis, as illustrated in Figure 2. Assume that the generators are operating at no-load and at their rated voltage at the occurrence of fault.

There are many factors affecting the level of ground-fault currents in unit generator transformer. Here, the influence of transformer configuration and generator grounding method are studied. Extensive simulation (a symmetrical components method) tests were carried out using Matlab Software. The adjusted parameters were as follows:

- The kind of generator grounding method was a change. The kinds of grounding method were solidly (0 ohm), reactance (all resistances set to zero) and resistance (all reactances set to zero) grounding.
- The type of two-winding transformer connection was changed. The types of transformer connection were *Y, Yn* and *Δ* as primary and secondary transformer connections with initial connection as *Yn-Yn* for transformer-1 (T_1) and *Yn-Yn* for T_2.
- Both the type of transformer connections and generator grounding method were changed.
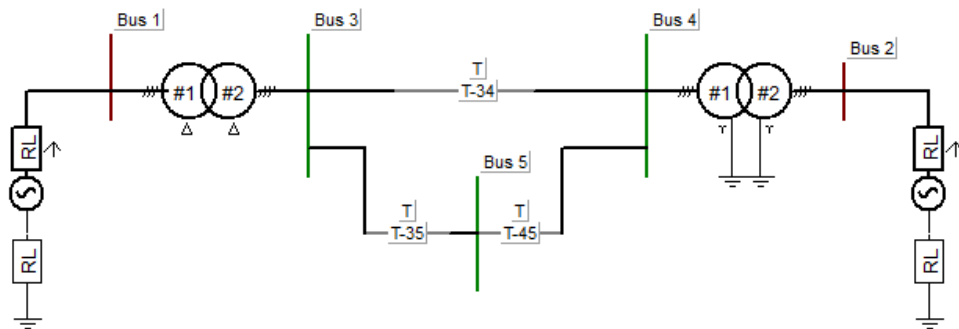
Figure 2. Single-line diagram for analysis

4. Analysis of simulation result

There are many factors that can affect the ground-fault current. Here, the effect of a transformer connection and generator grounding method are discussed. Simulations had been carried out using a symmetrical component method to study the effect of a generator grounding method and transformer connections onto the unit generator transformer. Simulation was conducted under three conditions: firstly was under the impact of a generator grounding method on ground-fault currents; secondly was under the effects of a transformer configuration distinct on ground-fault currents, and lastly was under the condition of combined effects of a generator grounding method and transformer configuration variations.

4.1 Effect of generator grounding method on ground-fault currents

Simulations were performed for solidly, resistance and reactance grounding method for *Yn-Yn* transformer connections using bolted fault impedance. This was done at two locations, namely SLG fault location nearby, and also far from the generating station.

4.1.1 Ground-faults closer to the generating station. For this condition, SLG fault was at Bus-1. The effect of grounding the generator through a solidly grounding, reactance and resistance grounding can be seen in Figure 3. This figure shows that, in solidly generator grounding (0 ohm), the fault current supplied to Bus-1 by Generator-1 was 5.0 per unit. In general, a large increase in the value of a resistance and reactance grounding would cause a decrease of the current. For the same impedance value, the value of a ground-fault current in resistance grounding was smaller than the reactance grounding. In contrast, the figure shows that the value under 26 ohms of the resistance grounding, asset value of ground-fault current was greater than the value of reactance grounding.
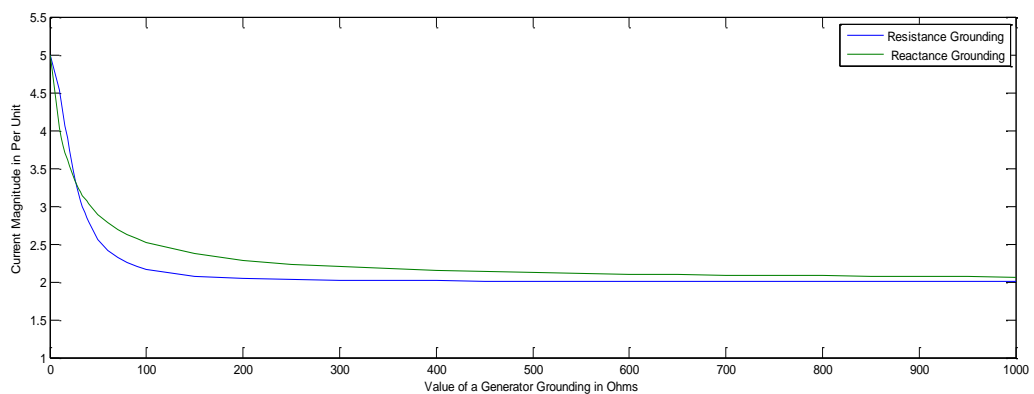
Figure 3. Magnitude of a generator current for SLG fault at Bus-1 for reactance and resistance grounding of the generator

4.1.2 Ground-faults away from the generating stations. In this condition, the SLG fault simulation was done at Bus-3 and Bus-5 as shown in Figure 4. The same conditions for SLG faults were closer to the generator. Using the identical value of the resistance / reactance, the resistance grounding had a lower magnitude of fault current. From Figure 4, it is apparent that the further the location of interference from Generator-1, the smaller current measure would be supplied by Generator-1 than when SLG fault occurred at Bus-3. This condition was influenced by reactance of the transmission line. The effects of disturbance would be smaller if the distance between generating station and fault location was further.
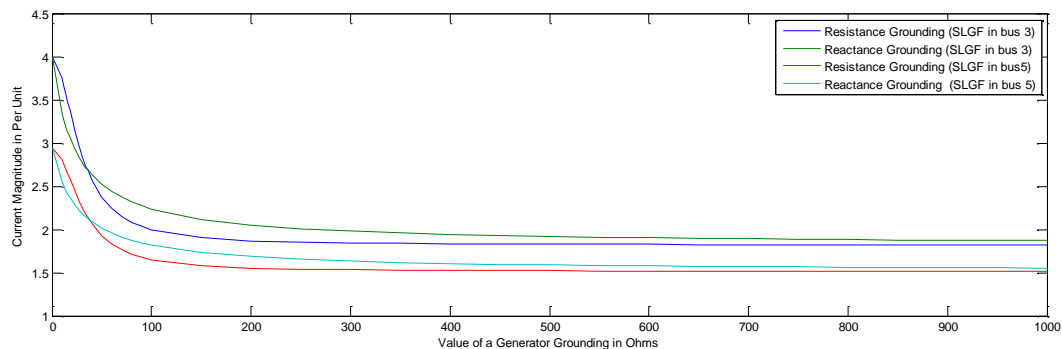
Figure 4. Magnitude of a generator current for SLG fault at Bus-3 and Bus-5 for reactance and resistance grounding of the generator

4.2 Effect of transformer connections on ground-fault current

Types of transformer connection used for this simulation were only *Yn, Y* and *Δ* at both primary and secondary of the transformer. According to the type of a ZPS transformer diagram, a ZPS circuit is similar for *Yn-Y* and *Y-Δ; Y-Yn* and *Δ*-Y, therefore, the transformer connection simulation was only performed on *Yn-Yn, Yn-Y, Y-Yn, Yn-Δ, Δ-Yn, Y-Y* and *Δ-Δ* transformer connections. Simulations were performed for solid generator grounding with bolted fault impedance. This was done at two locations, namely SLG fault location nearby, and far from the generating station.
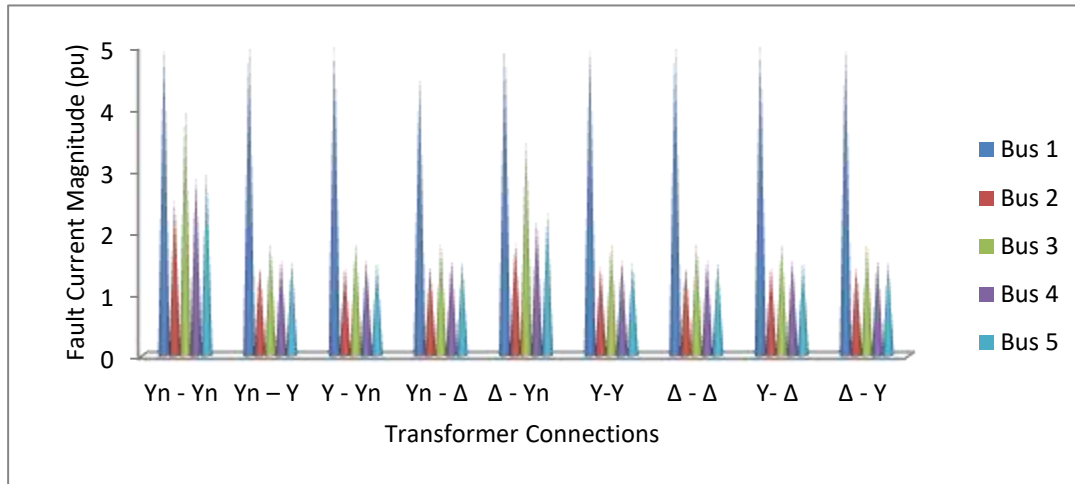
4.2.1 Ground-faults closer to the generating station. For this condition, SLG fault at Bus-1. Figure 5 shows the comparison the effect of transformer connections on ground-fault current supplied by Generator-1 during SLG fault at various buses. Therefore, fault occurring at Bus-1, where the current supplied from the generator to the fault location at Bus-1 was equal to 5.0 per unit for all transformer connections, except for the *Yn-Δ* Connection transformer, in which the fault current supplied by the generator-1 was smaller with 4.5157 per unit. This was due to the ZPS reactance to Bus-1, where the value would become larger with the additional reactance of a transformer-1 at 0.05 per unit.

4.2.2 Ground-faults away from the generating stations. In this condition, the SLG fault simulation was done at Bus-2, Bus-3, Bus-4 and Bus-5. In the event of SLG fault at Bus-2, the magnitude of fault current supplied from the generator to the fault location for *Yn-Yn* and *Yn - Δ* transformer connections were 4.0 per unit and 3.4776 per unit respectively. Meanwhile, the magnitude of fault current for connection of other transformers was 1.8212 *pu*. Similarly, for disturbance at Bus-3, Bus-4 and Bus-5, transformer connections of *Yn-Yn* and *Δ-Yn* had the fault current greater than the other models of transformer connections. This was due to the ZPS diagrams for the transformer connections *Yn-Yn* and *Δ-Yn* which had the relationship between the primary and the secondary side of the transformer, as well as the additional reactance to ground at the bus of *Δ-Yn* transformer.

## 4.3 Combined effect of generator grounding method and transformer connections

For this simulation, the models being used for generator grounding were solidly grounding, resistance grounding and reactance grounding. Magnitude of reactance and resistance impedance for grounding

was varied between 0 to 1000 ohms. Simulations were done for the transformer connection on *Yn-Yn, Yn-Y, Y-Yn, Yn-Δ, Δ-Yn, Y-Y* and *Δ-Δ* transformer connections. Simulations were also performed for generator grounding with solidly bolted fault impedance. This was done at two locations, namely SLG fault location nearby, and far from the generating station.


Figure 5. Comparison of fault current magnitude from Generator-1
for various locations of SLG fault

4.3.1 Ground-faults are closer to the generating station. For this condition, the SLG fault was at Bus-1. Figure 6 and Figure 7 present the current magnitude supplied from the generator to fault locations (Bus-1) in various grounding methods and transformer connections, based on the method of symmetrical components and data such as the appendix. It was clear that for solidly grounding, reactance grounding and resistance grounding, the *Yn-Δ* transformer connection produced the smallest ground-fault current compared to the others. The *Yn-Yn* transformer connection produced most of the fault currents. The *Yn-Y, Y-Yn , Δ-Yn, Y-Y* and *Δ-Δ* transformer connection had an identical ZPS circuit to produce the same ground-fault current.It can be seen that the highest ground-fault current for various transformer connection would be produced when the generator used was solid grounding. For the same value of impedance, the fault current of resistance grounding was greater than the reactance grounding.
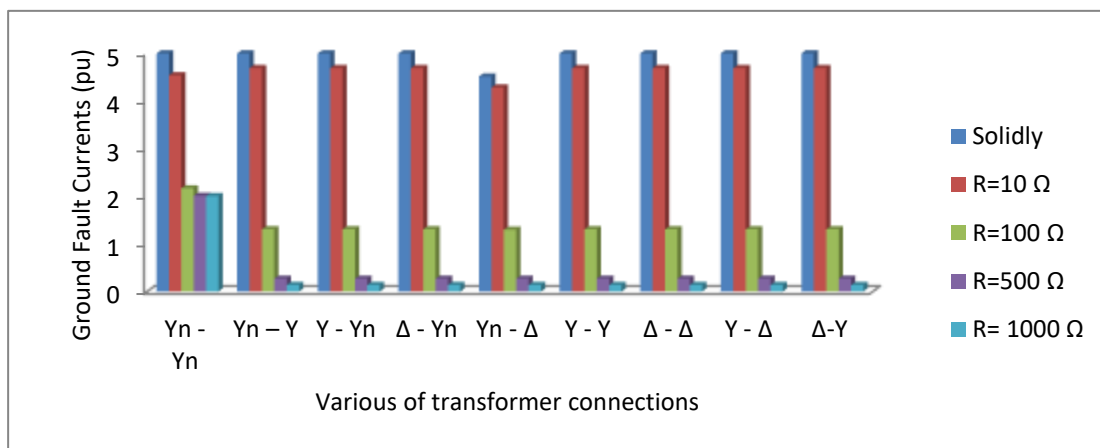
Figure 6. Magnitude of fault current in Generator-1 for distinct value of resistance grounding of a
generator during SLG fault in Bus-1
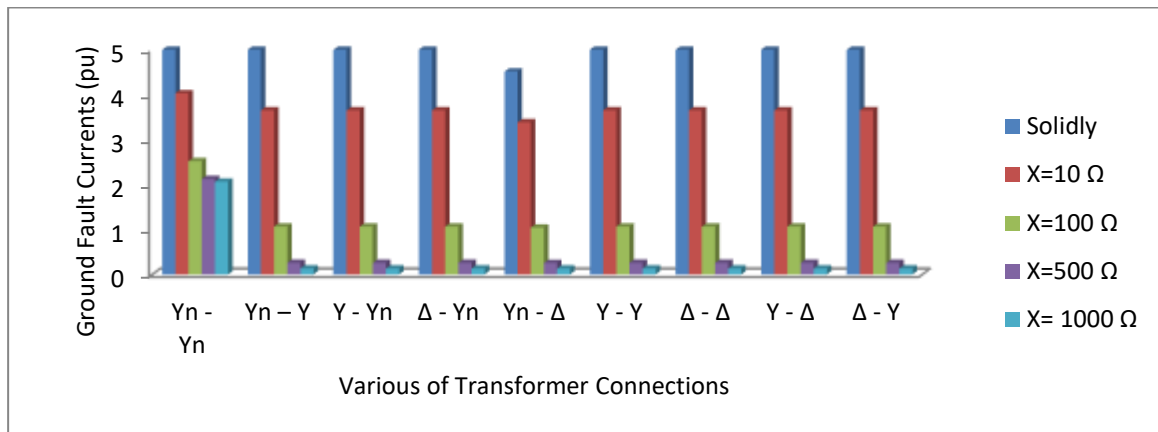
Figure 7. Magnitude of fault current in Generator-1 for distinct value of reactance grounding of a generator during SLG fault in Bus-1

4.3.2 Ground-faults away from the generating stations. In this condition, the SLG fault simulation was done at Bus-3 and Bus-5 separately. Table 1 and Table 2 show the comparison of magnitude of SLG fault current supplied by the generator to the fault location by applying symmetrical components method. From these tables, the *Yn-Y, Y-Yn, Δ-Yn, Y-Y* and *Δ-Δ* transformer connections had similar fault current for both of the faults through the generator grounding. This was because the isolation between Bus-1 and Bus-3 in the ZPS network led to 1.8212 *pu* at SLG fault at Bus-3 and 1.5162 *pu* at SLG fault at Bus-5. This value was not affected by the changes of the type and value of generator grounding. Similarly, for *Yn-Δ* transformer connection, the magnitude of fault current was equal to 3.4776 *pu* at SLG fault at Bus-3 and 2.2995 *pu* at SLG fault at Bus-5. As for the *Yn-Yn* transformer connection, a change of SLG fault current was affected by the value of generator grounding impedance. The higher value of the grounding impedance would produce the smaller of the ground-fault current.

It was also observed that if the fault location was far from the Generator-1, the ground-fault current would be smaller. At fault location of Bus-5, the ground-fault total was the combination of both from Generator-1 and Generator-2. When the source was multiplied, the fault current analysis became more complex.

Table 1 .Fault current of SLG at Bus-3 with various transformer connections and generator grounding

Grounding method	SLG fault current at various transformer connections (per unit)								
	Yn-Yn	*Yn – Y*	*Y - Yn*	*Δ-Yn*	*Yn - Δ*	*Y - Y*	*Δ-Δ*	*Δ-Y*	*Y-Δ*
Solidly	4.000	1.8212	1.8212	1.8212	3.4776	1.8212	1.8212	1.8212	1.8212
R=10 Ω	3.7533	1.8212	1.8212	1.8212	3.4776	1.8212	1.8212	1.8212	1.8212
R=100 Ω	1.9981	1.8212	1.8212	1.8212	3.4776	1.8212	1.8212	1.8212	1.8212
R=500 Ω	1.8290	1.8212	1.8212	1.8212	3.4776	1.8212	1.8212	1.8212	1.8212
R= 1000 Ω	1.8232	1.8212	1.8212	1.8212	3.4776	1.8212	1.8212	1.8212	1.8212
X=10 Ω	3.3540	1.8212	1.8212	1.8212	3.4776	1.8212	1.8212	1.8212	1.8212
X=100 Ω	2.2390	1.8212	1.8212	1.8212	3.4776	1.8212	1.8212	1.8212	1.8212
X=500 Ω	1.9199	1.8212	1.8212	1.8212	3.4776	1.8212	1.8212	1.8212	1.8212
X= 1000 Ω	1.8717	1.8212	1.8212	1.8212	3.4776	1.8212	1.8212	1.8212	1.8212

Table 2. Fault current when SLG at Bus-5 with various transformer connections and generator grounding

Grounding method	SLG fault current at various transformer connections (per unit)								
	Yn-Yn	*Yn – Y*	*Y - Yn*	*Δ-Yn*	*Yn - Δ*	*Y - Y*	*Δ-Δ*	*Δ-Y*	*Y-Δ*

Solidly	2.9412	1.5162	1.5162	1.5162	2.2995	1.5162	1.5162	1.5162	1.5162
R=10 Ω	2.8067	1.5162	1.5162	1.5162	2.2995	1.5162	1.5162	1.5162	1.5162
R=100 Ω	1.6512	1.5162	1.5162	1.5162	2.2995	1.5162	1.5162	1.5162	1.5162
R=500 Ω	1.5222	1.5162	1.5162	1.5162	2.2995	1.5162	1.5162	1.5162	1.5162
R= 1000 Ω	1.5177	1.5162	1.5162	1.5162	2.2995	1.5162	1.5162	1.5162	1.5162
X=10 Ω	2.5546	1.5162	1.5162	1.5162	2.2995	1.5162	1.5162	1.5162	1.5162
X=100 Ω	1.8180	1.5162	1.5162	1.5162	2.2995	1.5162	1.5162	1.5162	1.5162
X=500 Ω	1.5889	1.5162	1.5162	1.5162	2.2995	1.5162	1.5162	1.5162	1.5162
X= 1000 Ω	1.5535	1.5162	1.5162	1.5162	2.2995	1.5162	1.5162	1.5162	1.5162

5. Conclusion

This paper presents simulations using symmetrical components method to investigate the effect of transformer connections and generator grounding method on SLG fault at the generator-transformer unit. In the event of ground-fault at the primary side of a transformer, the transformer connection did not affect the magnitude of the SLG fault current. The ground-fault current was only affected by the generator grounding method. It was obviously shown that the solid grounding method produced the larger current than the other generator grounding methods. In the event of ground-fault at the secondary side of a transformer, it was clearly shown that the SLG fault at secondary side or line transmission depended on the transformer connection and generator grounding method used. All transformer connections, except for *Yn-Yn* with both neutral grounded, were produced in isolation between the primary and secondary in the ZPS circuit.

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