

Effect of Neutral Grounding Methods on the Earth Fault Characteristics

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Abstract— Medium voltage (MV) distribution systems use different methods for grounding the neutral point. Influences of these grounding methods on the single line to ground (SLG) fault characteristics are discussed in this paper. Jordanian MV network is used as a case study. The network has both underground cables and overhead lines. Simulation models are implemented in both MATLAB/SIMULINK, and DigSilent/Power Factor software. The models allow detailed investigation of the different fault factors and grounding methods. Results are obtained to evaluate the impact of each grounding method on the SLG fault features. Isolated neutral, solid grounding, resistance grounding and Petersen coil (Arc suppression coil) grounding are compared for different fault locations, fault incidence angles, and fault resistances. Current and voltage waveforms, as well as symmetrical components are used to describe the fault case.

1. INTRODUCTION

The method of grounding has a small influence during normal operation of the system, but becomes important and effective when an earth fault occurs to an overhead line (OHL) or an underground cable (UGC). The selection of system grounding method requires deep analysis. The correct grounding solution may be obtained through a great amount of calculations and simulations of the network during fault. The different grounding methods, in common use are:

- a) Solidly or direct grounding (effective grounding).
- b) Unearthed or Isolated neutral (floating neutral point).
- c) High impedance (resistance) grounding.
- d) Low impedance (resistance) grounding.
- e) Resonant or Petersen Coil grounding (compensated grounding).

A fault on a power system is an abnormal condition that involves failure risks of power system equipment. Generally, two types of failures can occur. The first is an insulation failure that results in a short circuit fault. The second is a failure that results in an interruption of current flow. Short circuit faults can occur between phases, or between phases and earth, or both. When the system is grounded by a low resistance or directly (solidly) grounded, the fault current will be very large. The characteristics of earth-fault current depend on the method of neutral point grounding as shown in this paper.

Many researchers in the past few years discussed the correlation between different types of neutral grounding and earth-fault, including fault localization and detection in MV networks. Jordanian utility in general uses direct or through resistance grounding without considering the nature of the MV feeders and their different configurations.

In [1–4], the authors compared between different types of neutral grounding. The authors in [5–8] studied the system currents and voltages behavior during fault, for the different system parameters. Isolated neutral systems have small fault current levels. These currents depend generally on the capacitances between the phases and the ground. Many researchers developed protection algorithms for compensated networks with high shunt capacitive connections [9–13]. Voltages and currents have non-sinusoidal evolution during the fault occurrence and clearance periods because of a component called dead-beat or free component as discussed in [11]. Analysis of overvoltages generated by SLG faults in Petersen coil grounded MV networks is presented in [14]. The authors in [15] studied the impact of some neutral grounding methods on the fault characteristics in Al Ain distribution company in UAE. Some experimental fault cases were tested under different conditions on a distribution company in Czech republic with Petersen coil grounding. The findings are reported in [16]. Ref. [17] presents an analysis and comparison of earth fault characteristics in the medium voltage distribution networks (20 kV) with high impedance grounding. The results are based on

the evaluation of 476 real case data recordings, obtained from substations of distribution networks, during the observation period of 3 years. The study dealt with the clearing of earth faults, arcing fault characteristics, appearance of transients and magnitudes of fault resistances.

The paper presents fault simulation models implemented in MATLAB/SIMULINK, and DigSilent/Power Factory. The created models allow for detailed investigation of different factors including the method of grounding the neutral point. Grounding transformers, MV distribution lines, and their accurate parameters are included. In the studied Jordanian electrical power system, the neutral grounding is by resistance for both OHL's feeders and UGC's feeders irrespective of their lengths. The single line to ground (SLG) fault currents and voltages are compared for different fault locations, fault resistances, and grounding methods. This can help to select the most proper grounding system for a specific network.

2. SINGLE PHASE TO GROUND FAULT ANALYSIS

The following simplifications are normally made:

- All currents are considered to be zero before the occurrence of the fault.
- Shunt elements in the transformer model are neglected.
- Shunt capacitances of transmission lines in most cases are neglected, but it is considered in case of UGC's.

2.1. Resistance Earthed Networks

Figure 1 shows modeling of earth fault in a network with resistance earthed neutral for a fault at the end of the cable feeder.

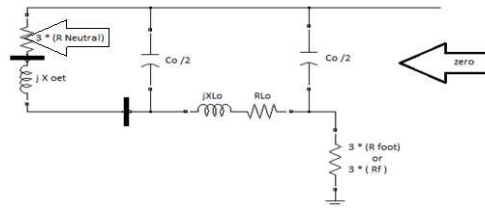


Figure 1: Zero sequence network of resistance earthed system.

The earth fault current in resistance earthed system is [2, 3]:

$$I_f = \frac{3E}{Z_1 + Z_2 + Z_0 + 3R_f} \quad (1)$$

where, E is the phase voltage, Z_1 is the positive sequence impedance, Z_2 is the negative sequence impedance, Z_0 is the zero sequence impedance. R_f is fault resistance and R_{foot} is footing resistance of the faulted tower.

Taking into account the capacitance of the specific faulted feeder only, I_f consists of resistive and reactive components as ($R_f = 0$):

$$I_f = I_R + jI_C = \frac{E}{R_n} + j3\omega C_0 E \quad (2)$$

where, R_n is the neutral grounding resistance.

The magnitude of the neutral displacement voltage will be:

$$V_{0n} = \frac{I_f}{\sqrt{\left(\frac{1}{R_n}\right)^2 + (3\omega C_0)^2}} \quad (3)$$

2.2. Compensated Earthed Networks

Figure 2 shows the modeling of earth fault in a network with resonant earthed neutral for a fault at the end of the cable feeder.

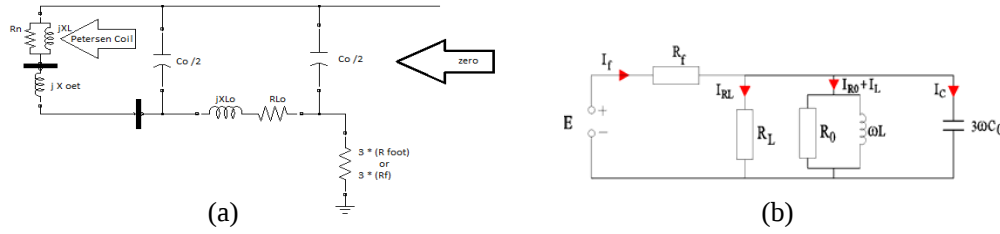


Figure 2: Model of a resonant-earthed neutral system, (a) zero sequence network, (b) Thevenin's equivalent circuit of the zero sequence network.

The solid earth fault current is determined by [2, 3]:

$$I_f = \left[\frac{R_L + R_0}{R_L R_0} \right] E + j \left[3\omega C_0 - \frac{1}{\omega L} \right] E \quad (4)$$

Coil tuning condition is achieved when:

$$3\omega C_0 - \frac{1}{\omega L} = 0 \quad (5)$$

In case of complete compensation, $3LC\omega^2 = 1$, the solid earth fault current will be:

$$I_f = \frac{R_L R_0}{R_L + R_0} E \quad (6)$$

The displacement of neutral point voltage will be:

$$V_{0n} = E \frac{Z_0}{Z_{0f}} \quad (7)$$

where,

$$R_e = \frac{R_L R_0}{R_L + R_0}, \text{ and } Z_{0f} = \frac{(R_e \cdot jX_0) + R_f(R_e + jX_0)}{R_e + jX_0}.$$

X_0 : Equivalent reactance of zero sequence network.

Z_0 : Equivalent impedance without fault resistance.

Z_{0f} : Equivalent impedance in the presence of fault resistance.

3. THE SYSTEM UNDER STUDY

A real system in Jordan (Tareq S/S) is used as a case study. The network is depicted in Figure 3 and consists of:

- A three 80 MVA three phase transformers 132/33 kV with YNd1 connection.
- 200 KVA three phase transformers 33/0.4 kV with ZNyn11 connection. This creates an artificial neutral point for grounding. The zero sequence impedance of this transformer is 38.8 Ω/phase (given by the manufacturer).
- Feeders, connected to the MV busbar, and made up of 7 UGCs, and 3 OHLs. The OHL is made up of ACSR (Aluminum Conductor Steel Reinforced) conductors with 150 mm² cross section area, while the UGC is made up of aluminum conductors with XLPE (Cross Linked Polyethylene) insulation, with 300 mm² cross section area.
- The existing grounding method is by a resistance of 19.05 ohm. This resistance is connected to a collecting point for the three neutral points of the zigzag transformers.

Simulation models of the system are constructed in both MATLAB/SIMULINK and DIGSILE-NT environments. Simulation results are presented and compared to the analytically calculated ones.

4. SIMULATION RESULTS

Investigation of SLG faults on “Safe way A” feeder (single circuit UGC feeder) for all different cases of neutral point grounding is presented. Digsilent program results are displayed by figures that show:

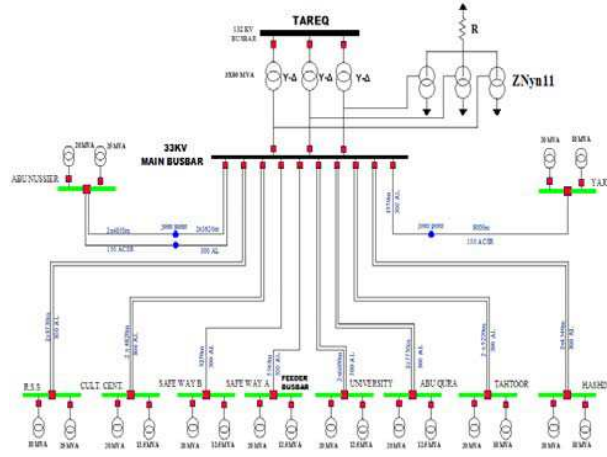
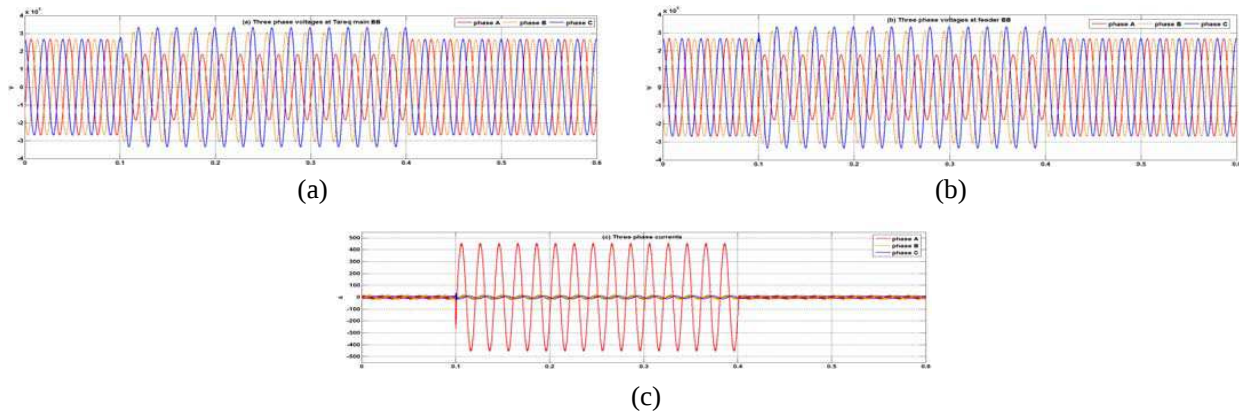


Figure 3: Single line diagram of case study system.

Figure 4: Fault at the end of the line (Safe way A), for low resistance grounded system, $R_f = 40 \Omega$, (a) three phase voltages at Tareq main BB, (b) three phase voltages at feeder BB, and (c) three phase currents.

- i Fault impedance in ohm (resistance R_f and reactance X_f).
- ii Feeder under consideration (i.e., the label of faulted feeder) for example, "Safe way A" feeder.
- iii Sequence voltages (labeled as 0-1-2 sequence voltages, U_0 , U_1 , and U_2) in kV with phase angles in degrees.
- iv Short circuit level in MVA (labeled as "Sk").
- v Short circuit current (labeled as I_{kss}) in kA with phase angle in degrees.
- vi Sequence currents (labeled as 0-1-2 sequence currents, I_0 , I_1 , and I_2) in kA with phase angles in degrees.
- vii Example feeder line to ground voltages (labeled as A, B, C values at observation location) in kV with phase angle in degrees. It shows the statement "SHC on line: Safe way A" which means short circuit on the example feeder "Safe way A".

4.1. Low Resistance Grounding

Assume an A-G fault at the end of the line (Safe way A) with $R_f = 40 \Omega$. The presence of R_f , in addition to the grounding resistance, causes an appreciable reduction in distortion of voltages and currents waveforms. The fault current and the phase voltages obtained by the two softwares are shown in Figures 4–6. The neutral displacement voltage is less than 6 kV as determined by both softwares.

4.2. High Resistance Grounding

For A-G fault at the end of the line (Safe way A) with $R_f = 40 \Omega$, simulation results are shown in Figures 7–9. The current flow in the neutral is limited, while the current at fault location is higher because of the contribution of capacitive currents. Neutral displacement voltage and neutral current curves at clearance time do not converge to zero value instantaneously because of the nine

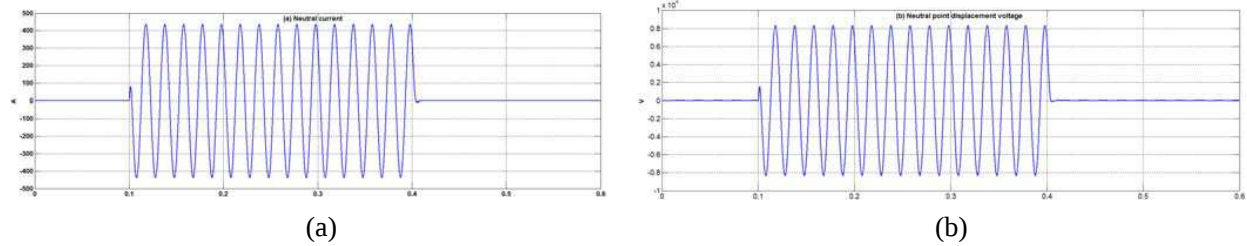


Figure 5: Fault at the end of the line (Safe way A), for low resistance grounded system, $R_f = 40 \Omega$, (a) neutral current and (b) neutral point displacement voltage.

verification:																			
Short-circuit calculation complete					single phase to ground /														
Short-circuit duration		Break Time		Fault Impedance															
		0.10 s		Resistance, Rf		40.00 Ohm													
				Reactance, Xf		0.00 Ohm													
Short circuit location					0-1-2 Sequence voltages [kV] [deg]		Ik1		Ikss		0-1-2 Sequence currents [kA] [deg]								
safeway A					U1 19.41 -42.94 A		6.613		0.347		145.08 11 0.116 145.08								
					U2 0.15 -147.90 B		0.000		0.000		0.116 145.08								
					U0 5.99 116.79 C		0.000		0.000		0.00 3*120 0.347 145.08								
Grid: Tareq Feeders					System Stage: Tareq Feeders					Annex: / 2									
rtd.v. Line to Ground Voltages					0-1-2 Sequence Voltages					Ik1 Currents 0-1-2 Sequence Currents									
values at Observation Location					[kV] [deg]					[kV] [deg]									
SMC on line: safeway A																			
A 13.88 -34.08					U1 19.41 -42.94														
B 21.13 -178.88					U2 0.15 -147.90														
C 24.48 86.16					U0 5.99 116.79														

Figure 6: Digsilent outputs for low resistance grounded system, Fault is at the end of the line (Safe way A), $R_f = 40 \Omega$.

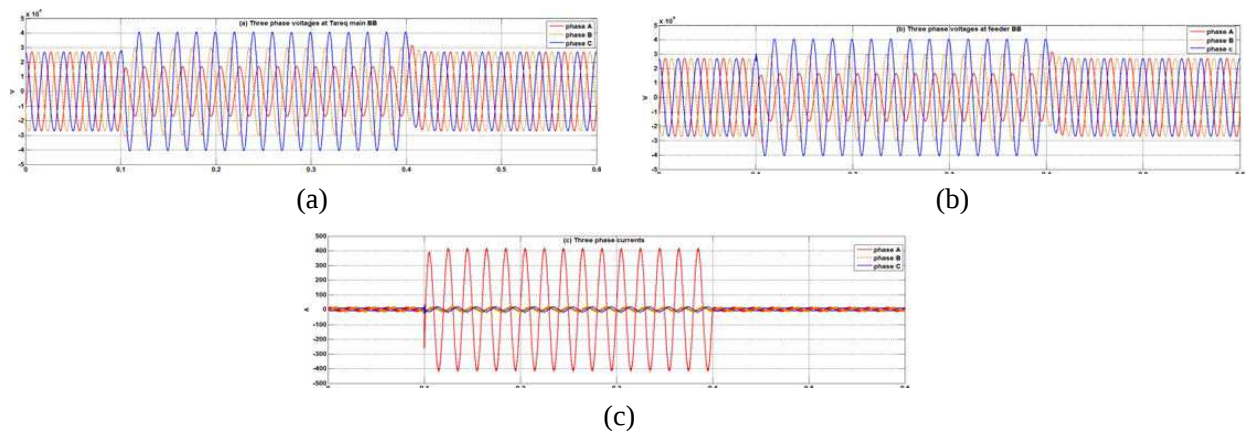


Figure 7: Fault at the end of the line (Safe way A), for high resistance grounded system, $R_f = 40 \Omega$, (a) three phase voltages at Tareq main BB, (b) three phase voltages at feeder BB, and (c) three phase currents.

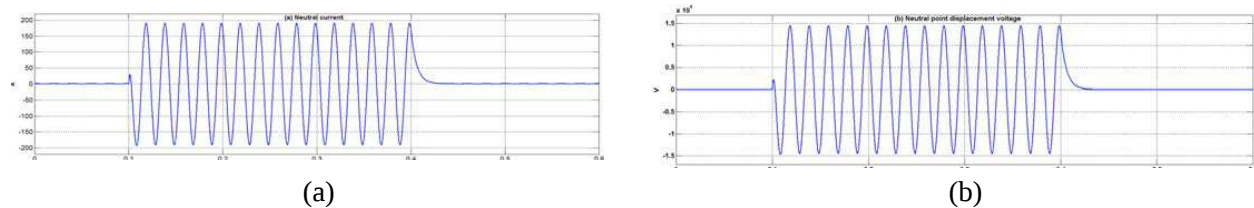


Figure 8: Fault at the end of the line (Safe way A), for high resistance grounded system, $R_f = 40 \Omega$, (a) neutral current and (b) neutral point displacement voltage.

healthy feeders affecting the response of currents and voltages. In case the healthy feeders are disconnected the neutral current converge to zero instantaneously. The location of the fault and the presence of R_f in addition to HRG explains why small fault current exists. The disturbances and distortion disappears because of R_f existence and the fault location is far away from the supply point. The figures show similar results for the two softwares.

verification											
Short-circuit calculation complete											
Single Phase to Ground /											
Short-circuit duration		0.10 s		Fault impedance		40.00 Ohm					
Break Time				Resistance, Rf		0.00 Ohm					
Short circuit Location		0-1-2 sequence voltages [deg]		[sk°]		[skss]		0-1-2 sequence currents [deg]			
Safety A		U1 19.45 -42.97 A 5.950 0.312 162.02 11 0.104 162.02		U2 0.15 -130.76 B 0.000 0.000 0.00 22 0.104 162.02		U0 8.96 92.32 C 0.000 0.000 0.00 1*10 0.312 162.02					
grid: Tareq feeders System Stage: Tareq feeders Annex: / 2											
r.d.v. Line to ground voltages [kV]		0-1-2 sequence voltages [kV]		[deg]		[MVA]		[sk°] currents [kA]		0-1-2 sequence currents [kA]	
[deg]		[deg]		[deg]		[deg]		[deg]		[deg]	
values at observation Location											
SNC on time: Safety A											
A		14.46 -17.05 U1 19.45 -42.97		U2 0.15 -130.76		U0 8.96 92.32					
B		19.09 170.26		U2 0.15 -130.76		U0 8.96 92.32					
C		19.33 61.98		U0 8.96 92.32							

Figure 9: Digsilent outputs for high resistance grounded system, Fault at the end of the line (Safe way A), $R_f = 40 \Omega$.

4.3. Petersen Coil (Resonant) Grounding

For A-G fault at the end of the line (Safe way A) with $R_f = 0 \Omega$, simulation results are shown in Figures 10 to 12. As can be seen, the current resulting from the fault is small with resonant grounding due to the compensating effect of the Petersen coil. The system discharging and charging in SLG fault depends on the capacitances of the feeders with ground, and on the location of the fault. For resonant grounding (compensated) networks this process is changed, the current through Petersen coil compensates and reduces the capacitive current through the fault location. When a SLG fault occurs the faulty phase starts discharging to the ground through the fault. Healthy feeders, plus the other two healthy phases starts charging to the ground. These charging currents can be determined as zero sequence currents.

Table 1 gives the results in case of Petersen coil neutral grounding method with solid earth fault. The total capacitive current in the system is about 0.5 kA. Fault current has a small value because of high percentage of compensation (actual Petersen coil has a controller with tap changing or plunger to control tuning of the system from zero to near 100% of compensation). This small value of fault current enables the system to continue in feeding the consumers under fault for a long time. To compensate for the capacitive earth fault current of the feeder “Safe way A” (with 5.44 km

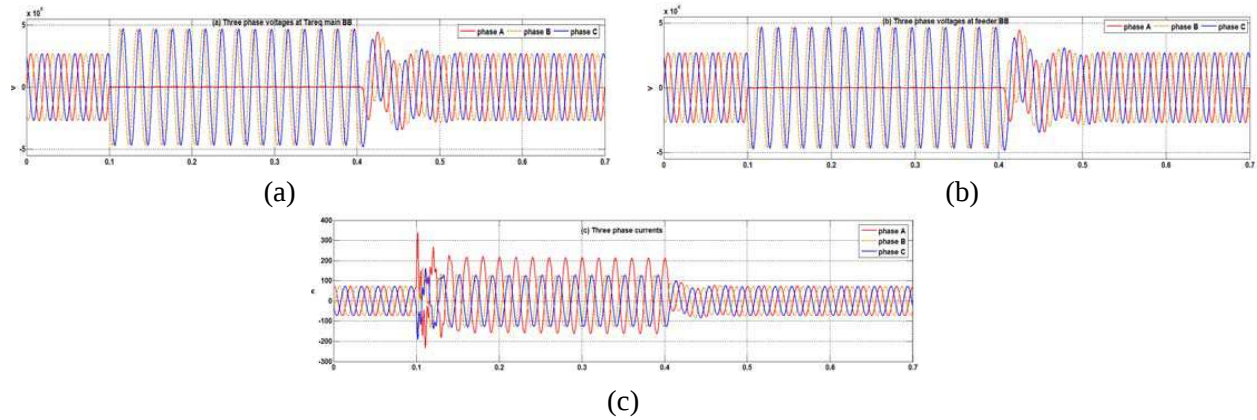


Figure 10: Fault at the end of the line (Safe way A), for Petersen coil grounding system, $R_f = 0 \Omega$, (a) three phase voltages at Tareq main BB, (b) three phase voltages at feeder BB, and (c) three phase currents.

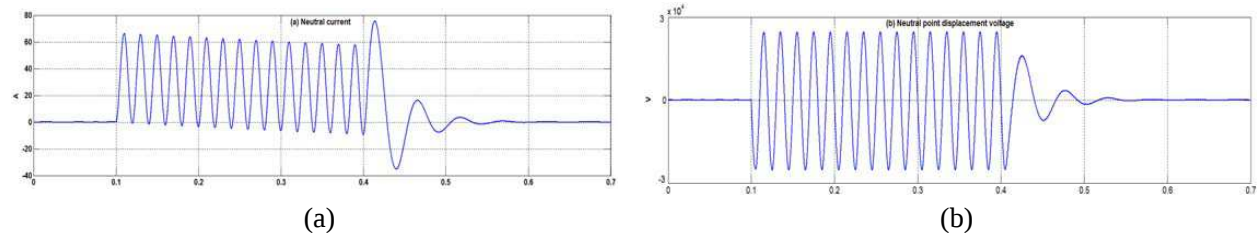


Figure 11: Fault at the end of the line (Safe way A), for Petersen coil grounding system, $R_f = 0 \Omega$, (a) neutral current and (b) neutral point displacement voltage.

Verification Short-circuit calculation complete										Single phase to ground /																													
Short-circuit duration Break time					0.10 s		Fault impedance Resistance, Rf Reactance, Xf					0.00 ohm 0.00 ohm																											
Short circuit location										0-1-2 sequence voltages [kV] [deg]					0-1-2 sequence currents [A] [deg]																								
Safeway A										U1 19.43 -89.85 A					U2 0.00 -114.43 B																								
										U0 19.46 110.12 C					I1 0.008 178.67																								
															I2 0.000 0.00																								
															I0 0.000 0.00																								
															3*I0 0.025 178.67																								
Grid: Tareq feeders										Byzone Stage: Tareq feeders																													
r.d.v.										Line to Ground Voltages [kV]										0-1-2 Sequence Voltages [kV]					S _{sc} [MVA]					Currents [kA]					0-1-2 Sequence Currents [kA]				
Values at Observation Location																																							
SMC on line: Safeway A										A 0.00 -86.30 U1 19.45 -89.85										B 31.89 140.12 U2 0.01 -114.43										C 33.71 80.16 U0 19.46 110.12									

Figure 12: Digsilent outputs for Petersen coil grounding system, Fault at the end of the line (Safe way A), $R_f = 0 \Omega$.

Table 1: MATLAB results for petersen coil grounding, fault at the end of the line (Safe way A), $R_F = 0 \Omega$.

Neutral Voltage	19432.20 Vrms -179.74°
Neutral Current	24.74 Arms 90.33°
Compensated Fault Current	472.73 Arms 89.41°

cable length), the zero sequence capacitance is approximately $0.28 \mu\text{F}/\text{km}$, the total capacitive impedance of 5.44 km cable X_{C0} is 2089.744Ω . The inductance of local compensation grounding coil is 2.2173 H, the resistive losses is about 2.4% with local coil resistance of 17.4146Ω . Neutral point displacement voltage reaches near phase to ground voltage, the results from Matlab program is 19.43 kV and 19.46 kV from Digsilent.

5. CONCLUSIONS

Fault calculation models are implemented in both MATLAB/SIMULINK, and DigSilent for a MV network in Jordan. The models enable the detailed investigation of the earth fault under different fault factors and methods of grounding the neutral point. For Low resistance neutral grounding systems, SLG fault current can be controlled by adjusting the value of the earthing resistance. The charging currents of line to ground capacitors (especially UGC) contribute to the fault current. Voltages at healthy phases are slightly higher than 80% of the line to line voltages and higher than voltage levels of solidly grounded networks. For high resistance neutral grounding systems, SLG fault current can be reduced to near load currents. Voltages of healthy phases may equal the line to line voltage, during fault. Protection schemes may malfunction. For isolated neutral systems, fault current is low and is determined mainly by charging capacitors in case of mostly UGC feeders. Voltages to ground at healthy phases reach and may exceed line to line voltages. For compensated neutral grounding (Petersen coil), charging capacitive current of healthy phases that flow through the neutral wire are greatly damped. Petersen coil can be adjusted to match MV network changes. The resistive part of Petersen coil determines the amount of the fault current through neutral. Maximum voltage of healthy phases can reach line to line voltage level. Traditional relaying schemes can not be effective in this case. Enhanced earth-fault relay designs are required if Petersen coil grounding is applied.

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