Report submitted to

EMPRIMUS - Critical Infrastructure Protection

Grid Impact of Neutral Blocking for GIC Protection:

Impact of neutral blocking capacitor on effective grounding

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1.0 Introduction

A commonly proposed solution to block the flowing of geomagnetically induced currents (GIC) in power transmission lines during solar storms is to ground the transformer neutrals through capacitors. This report details the impact of neutral blocking capacitors used for GIC blocking on effective grounding of the power system.

According to IEEE C62.92.1-2000 [1], the objectives of system grounding are

a) Voltage ratings and degree of surge-voltage protection available from surge arresters
b) Limitation of transient line-to-ground overvoltages
c) Sensitivity, operating time, and selectivity of the ground-fault relaying
d) Limitation of the magnitude of the ground-fault current
e) Safety

The standard identifies different means of grounding, solidly grounded, inductance grounded, resistance grounded, capacitance grounded and ungrounded systems. In the case of capacitive grounding, main concerns are in the overvoltages. The standard recommends to avoid capacitance grounding and to perform a careful analysis for resonance conditions or increased fault currents, if used.

In multiple-grounded systems, the class of grounding of the system is determined by the cumulative effect of all the grounding points. If most of the major transformer neutrals are grounded by similar means, then the system may loosely be described as being of one class (e.g., an *inductance grounded system*). In general, where there are multiple grounding points of different types of apparatus and different means of apparatus neutral grounding, the class of grounding can only be determined by the zero-sequence to positive-sequence symmetrical component ratios, as viewed from a selected location.

Effectively grounded system is defined as a system grounded through a sufficiently low impedance (inherent or intentionally added, or both) so that the coefficient of grounding (COG) does not exceed 80%. COG is defined as [1]

$$COG = \frac{E_{LG}}{E_{LL}} \cdot 100\%$$

where E_{LG} is the highest root-mean-square (rms), line-to-ground power-frequency voltage on a sound phase, at a selected location, during a line-to-ground fault affecting one or more phases. E_{LL} is the line-to-line power-frequency voltage that would be obtained, at the selected location, with the fault removed. COG for three-phase systems are calculated from the phase-sequence impedance components, as viewed from the fault location.

This value is obtained approximately when, for all system conditions, the ratio of the zero-sequence reactance to the positive-sequence reactance, (X0/X1) is positive and < 3, and the ratio of zero-sequence resistance to positive-sequence reactance, (R0/X1), is positive and < 1. In addition to the condition that COG < 80%, effecting grounding also expected to ensure that transient line to ground overvoltage is less than 2 pu and the line to ground fault current is more than 60% of the three phase fault current [1].

In systems operating at 115 kV and above, there are strong economic reasons encouraging the use of effective grounding [1]. The most significant factors are insulation costs and the lower cost per kVA of transformers. Neutral grounding affects insulation requirements in two ways. First, the use of effective grounding controls temporary overvoltages due to ground faults at lower levels than those obtained with other classes of grounding. Second, effective grounding permits the use of lower-rated surge arresters, thereby providing better protection of the insulation against surge voltages [2].

Operation of the GIC blocking scheme proposed by Emprimus may result in a situation where HV transformer neutrals are capacitance grounded. The objective of this study is to evaluate the likelihood of such conditions resulting in a non- effectively grounded system. A 500/345 kV test network modeled in an electromagnetic transient simulation program (PSCAD/EMTDC) is used to analyze sequence impedance ratios, temporary overvoltages, ground fault current magnitudes, and transient overvoltages due to capacitive neutral grounding of transformer neutrals. All studies and analyses are conducted with the objective of understanding the impact of the neutral blocking capacitor, and thus involve comparison of various performance indices with and without the neutral grounding capacitors. In the following sections methodologies used and the results are presented.

2.0 Study Methodology

The rest network used for studies is shown in Figure 1. The simulations presented in this report consider neutral grounding circuits of the two 22 kV/500 kV two winding transformers connected to bus-2 (T_1, T_2), and the two 500 lK/345 kV autotransformers connected to bus-1 (T_3), and bus-3 (T_4). In case of capacitance grounding, the relevant capacitor is always connected in series with a 1 Ω resistor, a feature in the GIC blocking scheme proposed by Emprimus, which is shown in Figure 2.

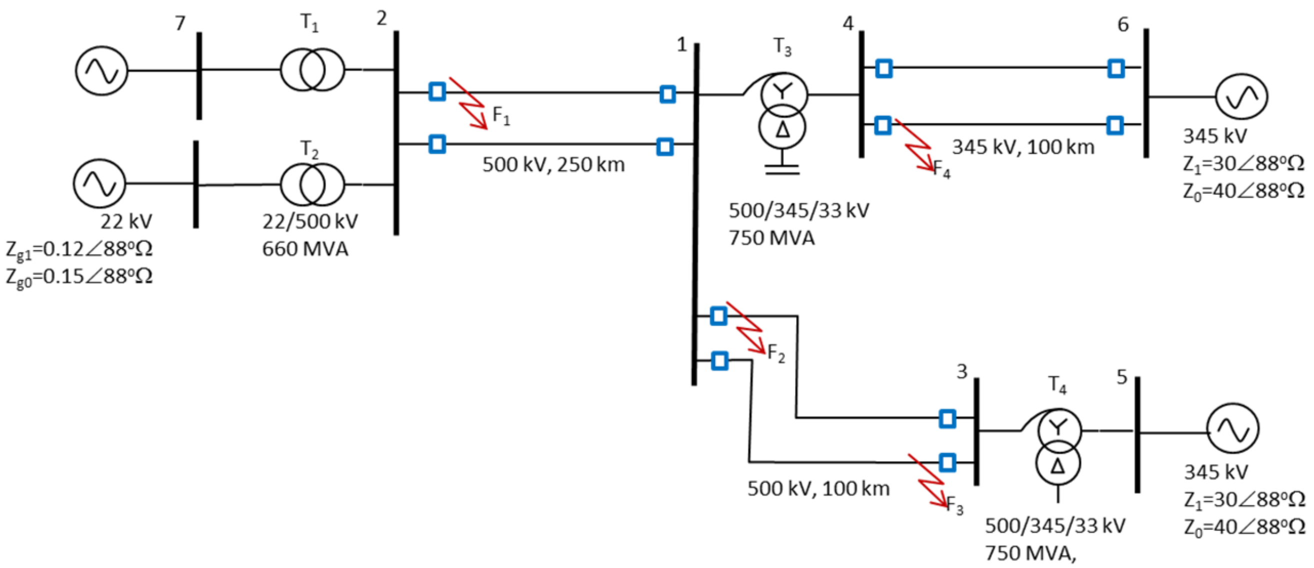

Figure 1: Locations of protection relays and faults

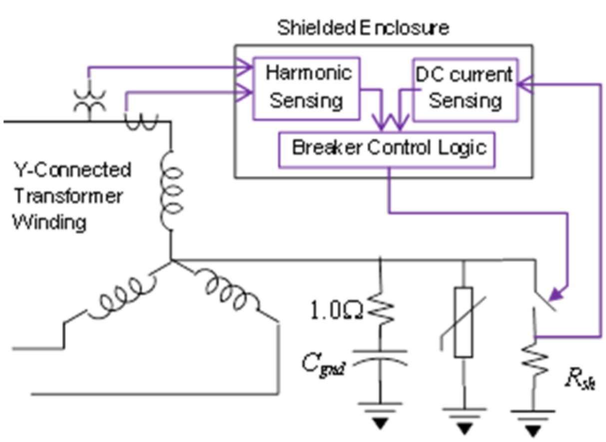

Figure 2 GIC blocking transformer neutral grounding scheme proposed by Emprimus.

The study methodology used has three parts:

a) The first part of the study attempts to determine whether the system X0/X1 ratio and R0/X1 ratio satisfy the criteria defined in IEEE C62.92.1-2000. For this purpose, the test power system is modeled in detail in PSCAD/EMTDC program. The frequency scan tool (Harmonic Impedance Solution module) available in PSCAD/EMTD program is used to obtain X0, X1 and R0 at 60 Hz. These values are then use to determine X0/X1 ratio and R0/X1 ratio of the test network at different locations with and without capacitance neutral grounding.

b) In the second part, the PSCAD/EMTDC simulation model of the power system is used to calculate COG (E_{LG}/E_{LL}) and fault current ratio ($I_{1\phi}/I_{3\phi}$) at different locations in the system, under single-line-to-ground (SLG) faults at selected locations (F_1, F_2, $F_{3,}$ and F_4). COGs and fault current ratios calculated with and without capacitance neutral grounding are comapred.

c) In the third part, PSCAD/EMTDC simulations are used to determine the transient line-to-ground voltages due to SLG faults at different locations. The faults are simulated at several selected locations, and each simulation case is repeated considering different fault initiation time to obtain the maximum transient over voltages. Again transient overvoltages obtained with and without capacitance neutral grounding are compared.

In order to examine the effects of the value of the grounding capacitance, most of the studies were repeated with three different capacitor values (265 μF, 1000 μF, and 2650 μF). Moreover, different system conditions resulting from prior outages of various elements in the test circuit are also considered. These different test conditions are referred to as simulation scenarios in the report.

3.0 Results

The results are presented in three sub-sections. Sub-section 3.1 presents the results of impedance ratio analysis; Sub-section 3.2 presents the analysis of COG and fault current ratios; Sub-section 3.3 presents the analysis of transient over voltages.

3.1 Impedance Ratio Analysis

The values of R0, X0 and X1 (at 60 Hz) at different location of the power system shown in Figure 1 were obtained through frequency scans in PSCAD/EMTDC. Calculations are repeated under six different network conditions named as Scenario-1 to 6. Under each scenario, four different transformer neutral grounding conditions (solidly grounded and capacitance grounding with 2650 μF, 1000 μF, and 265 μF) are considered. A list of scenarios considered and different grounding conditions simulated under each scenario (simulation cases) are given in Table 1.

The values of R0, X0, and X1 measured at bus-1 to bus-7 and the ratios X0/X1 and R0/X1 for different transformer neutral grounding cases under Scenario-1 are listed in Table 2. The same quantities for Scenarios-2-6 are reported in Table 3-Table 7 respectively.

For all cases studied, the ratio X0/X1 remains positive and well below 3. Also, the ratio R0/X1 remains positive and less than 1, for all conditions studied. The highest X0/X1 ratio of 2.165 is reported at bus-7, which is on the Delta side of the 22 kV/500 kV Delta-Wye connected generator step up transformer. Being on the Delta side of the Delta-Wye connected transformer, zero sequence impedance at bus-7 is not affected by the grounding impedance of the Wye connected winding or the grounding impedance of any other transformers in the system. From the results tables, it is clearly seen R0 and X0 at bus-7 have not changed, as expected. However, the ratios X0/X1 and R0/X1 have changed due to changes in X1 in different scenarios.

Decreasing neutral grounding capacitance values reduce the zero sequence reactance (X0) measured at the buses close to the grounding point, thus actually increasing the effectiveness of grounding. However, it is likely that further reduction of grounding capacitances can cause the zero sequence reactance to become zero (or negative) resulting in a power frequency resonance. For the range of capacitances considered in the study (2650-265 μF), X0 remains positive at all buses. Changes in the grounding capacitance values can slightly change the zero sequence resistance (R0) values.

Table 1 Scenarios and test conditions for impedance ratio analysis

Scenario	Condition	Neutral grounding	Case No.
Scenario-1	System intact	Solidly grounded	Case (1)
		Capacitor grounded, C = 265 μF	Case (2)
		Capacitor grounded, C = 1000 μF	Case (3)
		Capacitor grounded, C = 2650 μF	Case (4)
Scenario-2	One of the 660 MVA, 22/500 kV transformers out of service	Solidly grounded	Case (5)
		Capacitor grounded, C = 265 μF	Case (6)
		Capacitor grounded, C = 1000 μF	Case (7)
		Capacitor grounded, C = 2650 μF	Case (8)
Scenario-3	One of the 500 kV circuits between bus-1 and bus-2 out of service	Solidly grounded	Case (9)
		Capacitor grounded, C = 265 μF	Case (10)
		Capacitor grounded, C = 1000 μF	Case (11)
		Capacitor grounded, C = 2650 μF	Case (12)
Scenario-4	750 MVA, 500/345 kV autotransformer between bus-1 and bus-4 out of service	Solidly grounded	Case (13)
		Capacitor grounded, C = 265 μF	Case (14)
		Capacitor grounded, C = 1000 μF	Case (15)
		Capacitor grounded, C = 2650 μF	Case (16)
Scenario-5	One of 500 kV circuits between bus-1 and bus-3 out of service	Solidly grounded	Case (17)
		Capacitor grounded, C = 265 μF	Case (18)
		Capacitor grounded, C = 1000 μF	Case (19)
		Capacitor grounded, C = 2650 μF	Case (20)
Scenario-6	System intact, two winding transformer neutral grounding capacitors bypassed	T_1,T_2 solidly grounded in all cases	
		T_3, T_4 capacitor grounded, C=265 μF	Case (21)
		T_3, T_4 Capacitor grounded, C=1000 μF	Case (22)
		T_3, T_4 Capacitor grounded, C=2650 μF	Case (23)

Table 2 Sequence reactance/resistance values, and X0/X1 and R0/X1 ratios for Scenario-1

Bus-1					
Grounding	R0 Ω	X0 Ω	X1 Ω	X0/X1	R0/X1
Zgnd = 0 Ω	2.778	28.630	37.205	0.770	0.075
C_{gnd} = 2650 µF	3.541	27.530	37.205	0.740	0.095
C_{gnd} = 1000 µF	3.310	25.865	37.205	0.695	0.089
C_{gnd} = 265 µF	2.556	15.710	37.205	0.422	0.069
Bus-2					
Grounding	R0 Ω	X0 Ω	X1 Ω	X0/X1	R0/X1
Zgnd = 0 Ω	2.658	15.928	33.091	0.481	0.080
C_{gnd} = 2650 µF	3.985	14.616	33.091	0.442	0.120
C_{gnd} = 1000 µF	4.017	12.409	33.091	0.375	0.121
C_{gnd} = 265 µF	4.264	2.074	33.091	0.063	0.129
Bus-3					
Grounding	R0 Ω	X0 Ω	X1 Ω	X0/X1	R0/X1
Zgnd = 0 Ω	1.431	27.380	41.286	0.663	0.035
C_{gnd} = 2650 µF	2.061	26.683	41.286	0.646	0.050
C_{gnd} = 1000 µF	2.056	25.462	41.286	0.617	0.050
C_{gnd} = 265 µF	2.387	16.765	41.286	0.406	0.058
Bus-4					
Grounding	R0 Ω	X0 Ω	X1 Ω	X0/X1	R0/X1
Zgnd = 0 Ω	2.217	23.989	21.129	1.135	0.105
C_{gnd} = 2650 µF	3.224	22.621	21.129	1.071	0.153
C_{gnd} = 1000 µF	2.997	20.494	21.129	0.970	0.142
C_{gnd} = 265 µF	2.573	7.332	21.129	0.347	0.122
Bus-5					
Grounding	R0 Ω	X0 Ω	X1 Ω	X0/X1	R0/X1
Zgnd = 0 Ω	0.636	17.647	18.621	0.948	0.034
C_{gnd} = 2650 µF	1.285	16.959	18.621	0.911	0.069
C_{gnd} = 1000 µF	1.313	15.722	18.621	0.844	0.071
C_{gnd} = 265 µF	1.997	6.649	18.621	0.357	0.107
Bus-6					
Grounding	R0 Ω	X0 Ω	X1 Ω	X0/X1	R0/X1
Zgnd = 0 Ω	2.652	31.190	19.622	1.590	0.135
C_{gnd} = 2650 µF	2.760	31.124	19.622	1.586	0.141
C_{gnd} = 1000 µF	2.805	30.970	19.622	1.578	0.143
C_{gnd} = 265 µF	3.150	30.048	19.622	1.531	0.161
Bus-7					
Grounding	R0 Ω	X0 Ω	X1 Ω	X0/X1	R0/X1
Zgnd = 0 Ω	0.005	0.150	0.069	2.165	0.076
C_{gnd} = 2650 µF	0.005	0.150	0.069	2.165	0.076
C_{gnd} = 1000 µF	0.005	0.150	0.069	2.165	0.076
C_{gnd} = 265 µF	0.005	0.150	0.069	2.165	0.076

Table 3 Sequence reactance/resistance values, and X0/X1 and R0/X1 ratios for Scenario-2

Bus-1					
Grounding	R0 Ω	X0 Ω	X1 Ω	X0/X1	R0/X1
Zgnd = 0 Ω	2.769	28.789	42.922	0.671	0.065
C_{gnd} = 2650 μF	3.554	27.670	42.922	0.645	0.083
C_{gnd} = 1000 μF	3.324	25.973	42.922	0.605	0.077
C_{gnd} = 265 μF	2.570	15.719	42.922	0.366	0.060
Bus-2					
Grounding	R0 Ω	X0 Ω	X1 Ω	X0/X1	R0/X1
Zgnd = 0 Ω	4.983	29.904	50.512	0.592	0.099
C_{gnd} = 2650 μF	7.350	27.590	50.512	0.546	0.146
C_{gnd} = 1000 μF	7.456	23.632	50.512	0.468	0.148
C_{gnd} = 265 μF	8.362	4.234	50.512	0.084	0.166
Bus-3					
Grounding	R0 Ω	X0 Ω	X1 Ω	X0/X1	R0/X1
Zgnd = 0 Ω	1.426	27.389	45.288	0.605	0.031
C_{gnd} = 2650 μF	2.059	26.691	45.288	0.589	0.045
C_{gnd} = 1000 μF	2.054	25.468	45.288	0.562	0.045
C_{gnd} = 265 μF	2.387	16.765	45.288	0.370	0.053
Bus-4					
Grounding	R0 Ω	X0 Ω	X1 Ω	X0/X1	R0/X1
Zgnd = 0 Ω	2.217	24.057	22.830	1.054	0.097
C_{gnd} = 2650 μF	3.235	22.678	22.830	0.993	0.142
C_{gnd} = 1000 μF	3.008	20.534	22.830	0.899	0.132
C_{gnd} = 265 μF	2.574	7.332	22.830	0.321	0.113
Bus-5					
Grounding	R0 Ω	X0 Ω	X1 Ω	X0/X1	R0/X1
Zgnd = 0 Ω	0.634	17.650	19.561	0.902	0.032
C_{gnd} = 2650 μF	1.285	16.962	19.561	0.867	0.066
C_{gnd} = 1000 μF	1.313	15.724	19.561	0.804	0.067
C_{gnd} = 265 μF	1.997	6.649	19.561	0.340	0.102
Bus-6					
Grounding	R0 Ω	X0 Ω	X1 Ω	X0/X1	R0/X1
Zgnd = 0 Ω	2.650	31.195	20.310	1.536	0.130
C_{gnd} = 2650 μF	2.760	31.128	20.310	1.533	0.136
C_{gnd} = 1000 μF	2.805	30.973	20.310	1.525	0.138
C_{gnd} = 265 μF	3.150	30.048	20.310	1.479	0.155
Bus-7					
Grounding	R0 Ω	X0 Ω	X1 Ω	X0/X1	R0/X1
Zgnd = 0 Ω	0.005	0.150	0.083	1.800	0.063
C_{gnd} = 2650 μF	0.005	0.150	0.083	1.800	0.063
C_{gnd} = 1000 μF	0.005	0.150	0.083	1.800	0.063
C_{gnd} = 265 μF	0.005	0.150	0.083	1.800	0.063

Table 4 Sequence reactance/resistance values, and X0/X1 and R0/X1 ratios for Scenario-3

Bus-1					
Grounding	R0 Ω	X0 Ω	X1 Ω	X0/X1	R0/X1
Zgnd = 0 Ω	2.764	29.426	42.887	0.686	0.064
C_{gnd} = 2650 μF	3.571	28.271	42.887	0.659	0.083
C_{gnd} = 1000 μF	3.333	26.521	42.887	0.618	0.078
C_{gnd} = 265 μF	2.578	15.958	42.887	0.372	0.060
Bus-2					
Grounding	R0 Ω	X0 Ω	X1 Ω	X0/X1	R0/X1
Zgnd = 0 Ω	2.691	16.166	36.511	0.443	0.074
C_{gnd} = 2650 μF	4.056	14.816	36.511	0.406	0.111
C_{gnd} = 1000 μF	4.083	12.551	36.511	0.344	0.112
C_{gnd} = 265 μF	4.283	2.064	36.511	0.057	0.117
Bus-3					
Grounding	R0 Ω	X0 Ω	X1 Ω	X0/X1	R0/X1
Zgnd = 0 Ω	1.410	27.424	45.263	0.606	0.031
C_{gnd} = 2650 μF	2.046	26.724	45.263	0.590	0.045
C_{gnd} = 1000 μF	2.044	25.496	45.263	0.563	0.045
C_{gnd} = 265 μF	2.385	16.771	45.263	0.371	0.053
Bus-4					
Grounding	R0 Ω	X0 Ω	X1 Ω	X0/X1	R0/X1
Zgnd = 0 Ω	2.230	24.333	22.821	1.066	0.098
C_{gnd} = 2650 μF	3.269	22.924	22.821	1.005	0.143
C_{gnd} = 1000 μF	3.036	20.737	22.821	0.909	0.133
C_{gnd} = 265 μF	2.589	7.348	22.821	0.322	0.113
Bus-5					
Grounding	R0 Ω	X0 Ω	X1 Ω	X0/X1	R0/X1
Zgnd = 0 Ω	0.630	17.660	19.555	0.903	0.032
C_{gnd} = 2650 μF	1.282	16.971	19.555	0.868	0.066
C_{gnd} = 1000 μF	1.310	15.731	19.555	0.804	0.067
C_{gnd} = 265 μF	1.997	6.650	19.555	0.340	0.102
Bus-6					
Grounding	R0 Ω	X0 Ω	X1 Ω	X0/X1	R0/X1
Zgnd = 0 Ω	2.643	31.214	20.307	1.537	0.130
C_{gnd} = 2650 μF	2.755	31.146	20.307	1.534	0.136
C_{gnd} = 1000 μF	2.801	30.988	20.307	1.526	0.138
C_{gnd} = 265 μF	3.150	30.049	20.307	1.480	0.155
Bus-7					
Grounding	R0 Ω	X0 Ω	X1 Ω	X0/X1	R0/X1
Zgnd = 0 Ω	0.005	0.150	0.072	2.080	0.073
C_{gnd} = 2650 μF	0.005	0.150	0.072	2.080	0.073
C_{gnd} = 1000 μF	0.005	0.150	0.072	2.080	0.073
C_{gnd} = 265 μF	0.005	0.150	0.072	2.080	0.073

Table 5 Sequence reactance/resistance values, and X0/X1 and R0/X1 ratios for Scenario-4

Grounding	R0 Ω	X0 Ω	X1 Ω	X0/X1	R0/X1
Bus-1					
Zgnd = 0 Ω	16.998	83.784	50.842	1.648	0.334
C_{gnd} = 2650 μF	17.515	83.309	50.842	1.639	0.345
C_{gnd} = 1000 μF	17.586	82.424	50.842	1.621	0.346
C_{gnd} = 265 μF	18.251	76.755	50.842	1.510	0.359
Bus-2					
Grounding	R0 Ω	X0 Ω	X1 Ω	X0/X1	R0/X1
Zgnd = 0 Ω	2.691	16.127	36.632	0.440	0.073
C_{gnd} = 2650 μF	4.048	14.784	36.632	0.404	0.111
C_{gnd} = 1000 μF	4.076	12.530	36.632	0.342	0.111
C_{gnd} = 265 μF	4.281	2.064	36.632	0.056	0.117
Bus-3					
Grounding	R0 Ω	X0 Ω	X1 Ω	X0/X1	R0/X1
Zgnd = 0 Ω	0.828	30.846	50.832	0.607	0.016
C_{gnd} = 2650 μF	1.593	30.050	50.832	0.591	0.031
C_{gnd} = 1000 μF	1.634	28.612	50.832	0.563	0.032
C_{gnd} = 265 μF	2.334	18.367	50.832	0.361	0.046
Bus-4					
Grounding	R0 Ω	X0 Ω	X1 Ω	X0/X1	R0/X1
Zgnd = 0 Ω	48.497	134.101	48.121	2.787	1.008
C_{gnd} = 2650 μF	48.497	134.101	48.121	2.787	1.008
C_{gnd} = 1000 μF	48.497	134.101	48.121	2.787	1.008
C_{gnd} = 265 μF	48.497	134.101	48.121	2.787	1.008
Bus-5					
Grounding	R0 Ω	X0 Ω	X1 Ω	X0/X1	R0/X1
Zgnd = 0 Ω	0.476	18.667	20.864	0.895	0.023
C_{gnd} = 2650 μF	1.212	17.916	20.864	0.859	0.058
C_{gnd} = 1000 μF	1.266	16.545	20.864	0.793	0.061
C_{gnd} = 265 μF	2.063	6.746	20.864	0.323	0.099
Bus-6					
Grounding	R0 Ω	X0 Ω	X1 Ω	X0/X1	R0/X1
Zgnd = 0 Ω	2.727	40.121	30.550	1.313	0.089
C_{gnd} = 2650 μF	2.727	40.121	30.550	1.313	0.089
C_{gnd} = 1000 μF	2.727	40.121	30.550	1.313	0.089
C_{gnd} = 265 μF	2.727	40.121	30.550	1.313	0.089
Bus-7					
Grounding	R0 Ω	X0 Ω	X1 Ω	X0/X1	R0/X1
Zgnd = 0 Ω	0.005	0.150	0.072	2.077	0.073
C_{gnd} = 2650 μF	0.005	0.150	0.072	2.077	0.073
C_{gnd} = 1000 μF	0.005	0.150	0.072	2.077	0.073
C_{gnd} = 265 μF	0.005	0.150	0.072	2.077	0.073

Table 6 Sequence reactance/resistance values, and X0/X1 and R0/X1 ratios for Scenario-5

Grounding	R0 Ω	X0 Ω	X1 Ω	X0/X1	R0/X1
Bus-1					
Zgnd = 0 Ω	2.778	28.630	37.205	0.770	0.075
C_{gnd} = 2650 μF	2.796	28.619	37.205	0.769	0.075
C_{gnd} = 1000 μF	2.802	28.595	37.205	0.769	0.075
C_{gnd} = 265 μF	2.831	28.482	37.205	0.766	0.076
Bus-2					
Grounding	R0 Ω	X0 Ω	X1 Ω	X0/X1	R0/X1
Zgnd = 0 Ω	2.658	15.928	33.091	0.481	0.080
C_{gnd} = 2650 μF	3.983	14.620	33.091	0.442	0.120
C_{gnd} = 1000 μF	4.017	12.415	33.091	0.375	0.121
C_{gnd} = 265 μF	4.268	2.073	33.091	0.063	0.129
Bus-3					
Grounding	R0 Ω	X0 Ω	X1 Ω	X0/X1	R0/X1
Zgnd = 0 Ω	1.431	27.380	41.286	0.663	0.035
C_{gnd} = 2650 μF	1.432	27.380	41.286	0.663	0.035
C_{gnd} = 1000 μF	1.433	27.379	41.286	0.663	0.035
C_{gnd} = 265 μF	1.438	27.373	41.286	0.663	0.035
Bus-4					
Grounding	R0 Ω	X0 Ω	X1 Ω	X0/X1	R0/X1
Zgnd = 0 Ω	2.217	23.989	21.129	1.135	0.105
C_{gnd} = 2650 μF	2.224	23.983	21.129	1.135	0.105
C_{gnd} = 1000 μF	2.226	23.973	21.129	1.135	0.105
C_{gnd} = 265 μF	2.236	23.923	21.129	1.132	0.106
Bus-5					
Grounding	R0 Ω	X0 Ω	X1 Ω	X0/X1	R0/X1
Zgnd = 0 Ω	0.636	17.647	18.621	0.948	0.034
C_{gnd} = 2650 μF	0.636	17.647	18.621	0.948	0.034
C_{gnd} = 1000 μF	0.636	17.647	18.621	0.948	0.034
C_{gnd} = 265 μF	0.637	17.645	18.621	0.948	0.034
Bus-6					
Grounding	R0 Ω	X0 Ω	X1 Ω	X0/X1	R0/X1
Zgnd = 0 Ω	2.652	31.190	19.622	1.590	0.135
C_{gnd} = 2650 μF	2.653	31.190	19.622	1.590	0.135
C_{gnd} = 1000 μF	2.653	31.189	19.622	1.589	0.135
C_{gnd} = 265 μF	2.655	31.186	19.622	1.589	0.135
Bus-7					
Grounding	R0 Ω	X0 Ω	X1 Ω	R0 Ω	R0/X1
Zgnd = 0 Ω	0.005	0.150	0.069	2.165	0.076
C_{gnd} = 2650 μF	0.005	0.150	0.069	2.165	0.076
C_{gnd} = 1000 μF	0.005	0.150	0.069	2.165	0.076
C_{gnd} = 265 μF	0.005	0.150	0.069	2.165	0.076

Table 7 Sequence reactance/resistance values, and X0/X1 and R0/X1 ratios for Scenario-6

		Bus-1			
T_3, T_4 Grounding*	R0 Ω	X0 Ω	X1 Ω	X0/X1	R0/X1
Zgnd = 0 Ω	2.778	28.630	37.205	0.770	0.075
C_{gnd} = 2650 μF	3.525	27.542	37.205	0.740	0.095
C_{gnd} = 1000 μF	3.292	25.895	37.205	0.696	0.088
C_{gnd} = 265 μF	2.546	15.758	37.205	0.424	0.068
		Bus-2			
T_3, T_4 Grounding*	R0 Ω	X0 Ω	X1 Ω	X0/X1	R0/X1
Zgnd = 0 Ω	2.658	15.928	33.091	0.481	0.080
C_{gnd} = 2650 μF	2.661	15.925	33.091	0.481	0.080
C_{gnd} = 1000 μF	2.660	15.919	33.091	0.481	0.080
C_{gnd} = 265 μF	2.661	15.883	33.091	0.480	0.080
		Bus-3			
T_3, T_4 Grounding*	R0 Ω	X0 Ω	X1 Ω	X0/X1	R0/X1
Zgnd = 0 Ω	1.431	27.380	41.286	0.663	0.035
C_{gnd} = 2650 μF	2.060	26.683	41.286	0.646	0.050
C_{gnd} = 1000 μF	2.054	25.464	41.286	0.617	0.050
C_{gnd} = 265 μF	2.386	16.766	41.286	0.406	0.058
		Bus-4			
T_3, T_4 Grounding*	R0 Ω	X0 Ω	X1 Ω	X0/X1	R0/X1
Zgnd = 0 Ω	2.217	23.989	21.129	1.135	0.105
C_{gnd} = 2650 μF	3.217	22.627	21.129	1.071	0.152
C_{gnd} = 1000 μF	2.992	20.506	21.129	0.971	0.142
C_{gnd} = 265 μF	2.575	7.336	21.129	0.347	0.122
		Bus-5			
T_3, T_4 Grounding*	R0 Ω	X0 Ω	X1 Ω	X0/X1	R0/X1
Zgnd = 0 Ω	0.636	17.647	18.621	0.948	0.034
C_{gnd} = 2650 μF	1.285	16.959	18.621	0.911	0.069
C_{gnd} = 1000 μF	1.312	15.722	18.621	0.844	0.070
C_{gnd} = 265 μF	1.997	6.649	18.621	0.357	0.107
		Bus-6			
T_3, T_4 Grounding*	R0 Ω	X0 Ω	X1 Ω	X0/X1	R0/X1
Zgnd = 0 Ω	2.652	31.190	19.622	1.590	0.135
C_{gnd} = 2650 μF	2.760	31.124	19.622	1.586	0.141
C_{gnd} = 1000 μF	2.805	30.971	19.622	1.578	0.143
C_{gnd} = 265 μF	3.150	30.048	19.622	1.531	0.161
		Bus-7			
T_3, T_4 Grounding*	R0 Ω	X0 Ω	X1 Ω	X0/X1	R0/X1
Zgnd = 0 Ω	0.005	0.150	0.069	2.165	0.076
C_{gnd} = 2650 μF	0.005	0.150	0.069	2.165	0.076
C_{gnd} = 1000 μF	0.005	0.150	0.069	2.165	0.076
C_{gnd} = 265 μF	0.005	0.150	0.069	2.165	0.076

* T_1,T_2 solidly grounded in all cases

3.2 Analysis of COG and Fault Current Ratio

In order to calculate coefficient of grounding, SLG (Phase-A to ground-AG) faults with zero fault impedance were simulated at bus-1, bus-2, bus-3, and bus-4 (F_1, F_2, F_3, and F_4 indicated on Figure 1). In order to obtain COG, the maximum RMS phase-to-ground voltage observed on any of the healthy phases (Phase-B and Phase-C) during the AG fault is divided by the pre-fault RMS line-to-line voltage (Phase-B to Phase-C voltage) measured at the respective bus. All simulations are carried out in PSCAD/EMTDC and the RMS values were calculated by taking one cycle DFT of the time domain waveforms. Generally GOG is calculated for the faulted bus, but in the result tables, for each fault, E_{LG}/E_{LL} ratios calculated at all buses (bus-1 to bus-7) are reported for examination.

In order to calculate the ratio between the SLG fault current and the three-phase (LLL) fault current, three-phase-to-ground faults were simulated at the same locations as SLG faults. Ratios between the RMS values of the SLG and LLL fault currents at steady state (after the decaying of DC components) are reported as the fault current ratio. Again, the RMS values were calculated using one cycle DFT of time domain current waveforms.

Calculations are repeated under different neutral grounding conditions and different network conditions. Various scenarios considered and the different simulation cases performed under each scenario are listed in Table 8.

Fault current ratios for the four faults considered and the corresponding ELG/ELL ratios computed at different locations (bus-1 to bus-7) under Scenario-1 are given in Table 9. Highlighted in yellow are the E_{LG}/E_{LL} ratios at the location of the respective fault. The corresponding results for Scenario-2 to Scenario-6 are presented in Table 10 to Table 14 respectively.

In an effectively grounded system, SLG fault current at a given location is expected to be at least 60% of the three phase fault current at the same location. For all faults considered in the simulations, this condition is satisfied under all four neutral grounding conditions examined. For most of the faults considered, SLG fault current is higher than the three phase fault current, thus the fault current ratio is greater than 1.0. Capacitive neutral grounding actually increases the SLG fault currents compared to solidly grounded case, due to negative reactance in the zero sequence networks. Decreasing capacitor values (in the range of 2650 μF -256 μF) increase the SLG fault currents. If the grounding capacitance is further decreased, power frequency resonance could be formed causing extremely high SLG fault currents, as pointed out earlier.

Also, in an effectively grounded system, temporary overvoltages due SLG faults are expected to be less than 80% of the pre-fault line-to-line voltages. This condition is indicated by COG < 0.8. For all cases simulated, this condition was satisfied, even when the transformer neutrals are grounded through a 265 μF capacitance. It is also notable that in some cases, for a given fault, the highest E_{LG}/E_{LL} ratio may occur in a location other than the faulted bus. As expected, E_{LG}/E_{LL} ratio at bus-7 is not affected by the transformer grounding method.

Table 8 Scenarios, test locations, and test conditions

Scenario	Condition	Neutral grounding	Case No.
Scenario-1	System intact	Solidly grounded	Case (1)
		Capacitor grounded, C = 265 μF	Case (2)
		Capacitor grounded, C = 1000 μF	Case (3)
		Capacitor grounded, C = 2650 μF	Case (4)
Scenario-2	One of the 660 MVA, 22/500 kV transformers out of service	Solidly grounded	Case (5)
		Capacitor grounded, C = 265 μF	Case (6)
		Capacitor grounded, C = 1000 μF	Case (7)
		Capacitor grounded, C = 2650 μF	Case (8)
Scenario-3	One of the 500 kV circuits between bus-1 and bus-2 out of service	Solidly grounded	Case (9)
		Capacitor grounded, C = 265 μF	Case (10)
		Capacitor grounded, C = 1000 μF	Case (11)
		Capacitor grounded, C = 2650 μF	Case (12)
Scenario-4	750 MVA, 500/345 kV autotransformer between bus-1 and bus-4 out of service	Solidly grounded	Case (13)
		Capacitor grounded, C = 265 μF	Case (14)
		Capacitor grounded, C = 1000 μF	Case (15)
		Capacitor grounded, C = 2650 μF	Case (16)
Scenario-5	One of 500 kV circuits between bus-1 and bus-3 out of service	Solidly grounded	Case (17)
		Capacitor grounded, C = 265 μF	Case (18)
		Capacitor grounded, C = 1000 μF	Case (19)
		Capacitor grounded, C = 2650 μF	Case (20)
Scenario-6	System intact, two winding transformer neutral grounding capacitors bypassed	T_1,T_2 solidly grounded in all cases	
		T_3, T_4 capacitor grounded, C=265 μF	Case (21)
		T_3, T_4 Capacitor grounded, C=1000 μF	Case (22)
		T_3, T_4 Capacitor grounded, C=2650 μF	Case (23)

Table 9 Coefficient of grounding and fault current ratios for Scenario-1

Parameter	Location	Grounding	F_1	F_2	F_3	F_4
$I_{F1\Phi}/I_{F3\Phi}$	Fault point	Zgnd = 0 Ω	1.207	1.081	1.127	0.990
		C_{gnd} = 2650 μF	1.225	1.092	1.134	0.996
		C_{gnd} = 1000 μF	1.259	1.114	1.147	1.031
		C_{gnd} = 265 μF	1.446	1.235	1.247	1.338
$E_{LG(max)}/E_{LL}$ (COG)	Bus-1	Zgnd = 0 Ω	0.557	0.562	0.539	0.578
		C_{gnd} = 2650 μF	0.560	0.564	0.536	0.580
		C_{gnd} = 1000 μF	0.561	0.560	0.534	0.573
		C_{gnd} = 265 μF	0.564	0.536	0.523	0.538
	Bus-2	Zgnd = 0 Ω	0.540	0.558	0.566	0.568
		C_{gnd} = 2650 μF	0.550	0.556	0.565	0.566
		C_{gnd} = 1000 μF	0.547	0.556	0.565	0.565
		C_{gnd} = 265 μF	0.551	0.553	0.563	0.562
	Bus-3	Zgnd = 0 Ω	0.564	0.526	0.546	0.548
		C_{gnd} = 2650 μF	0.566	0.529	0.548	0.543
		C_{gnd} = 1000 μF	0.567	0.528	0.545	0.541
		C_{gnd} = 265 μF	0.570	0.525	0.532	0.531
	Bus-4	Zgnd = 0 Ω	0.562	0.579	0.544	0.597
		C_{gnd} = 2650 μF	0.566	0.583	0.540	0.600
		C_{gnd} = 1000 μF	0.566	0.576	0.538	0.591
		C_{gnd} = 265 μF	0.567	0.546	0.523	0.549
	Bus-5	Zgnd = 0 Ω	0.571	0.545	0.562	0.554
		C_{gnd} = 2650 μF	0.573	0.548	0.565	0.556
		C_{gnd} = 1000 μF	0.573	0.547	0.562	0.555
		C_{gnd} = 265 μF	0.576	0.545	0.550	0.548
	Bus-6	Zgnd = 0 Ω	0.569	0.550	0.546	0.554
		C_{gnd} = 2650 μF	0.570	0.552	0.545	0.548
		C_{gnd} = 1000 μF	0.570	0.550	0.545	0.547
		C_{gnd} = 265 μF	0.572	0.547	0.543	0.540
	Bus-7	Zgnd = 0 Ω	0.578	0.578	0.578	0.578
		C_{gnd} = 2650 μF	0.579	0.578	0.578	0.578
		C_{gnd} = 1000 μF	0.578	0.578	0.578	0.578
		C_{gnd} = 265 μF	0.578	0.578	0.578	0.578

Table 10 Coefficient of grounding and fault current ratios for Scenario-2

Parameter	Location	Grounding	F_1	F_2	F_3	F_4
$I_{F1\Phi}/I_{F3\Phi}$	Fault point	Zgnd = 0 Ω	1.156	1.124	1.152	1.021
		C_{gnd} = 2650 μF	1.174	1.134	1.159	1.023
		C_{gnd} = 1000 μF	1.211	1.152	1.171	1.057
		C_{gnd} = 265 μF	1.428	1.268	1.266	1.355
$E_{LG(max)}/E_{LL}$ (COG)	Bus-1	Zgnd = 0 Ω	0.552	0.552	0.534	0.569
		C_{gnd} = 2650 μF	0.556	0.554	0.530	0.571
		C_{gnd} = 1000 μF	0.556	0.550	0.529	0.565
		C_{gnd} = 265 μF	0.559	0.530	0.518	0.534
	Bus-2	Zgnd = 0 Ω	0.553	0.548	0.557	0.560
		C_{gnd} = 2650 μF	0.562	0.544	0.555	0.556
		C_{gnd} = 1000 μF	0.559	0.544	0.555	0.555
		C_{gnd} = 265 μF	0.565	0.541	0.553	0.550
	Bus-3	Zgnd = 0 Ω	0.558	0.523	0.540	0.543
		C_{gnd} = 2650 μF	0.560	0.525	0.542	0.539
		C_{gnd} = 1000 μF	0.560	0.524	0.540	0.537
		C_{gnd} = 265 μF	0.564	0.522	0.529	0.528
	Bus-4	Zgnd = 0 Ω	0.558	0.569	0.541	0.589
		C_{gnd} = 2650 μF	0.561	0.573	0.536	0.592
		C_{gnd} = 1000 μF	0.561	0.566	0.534	0.583
		C_{gnd} = 265 μF	0.561	0.539	0.521	0.545
	Bus-5	Zgnd = 0 Ω	0.565	0.541	0.557	0.551
		C_{gnd} = 2650 μF	0.567	0.543	0.560	0.553
		C_{gnd} = 1000 μF	0.568	0.542	0.557	0.552
		C_{gnd} = 265 μF	0.570	0.540	0.545	0.544
	Bus-6	Zgnd = 0 Ω	0.564	0.546	0.544	0.552
		C_{gnd} = 2650 μF	0.566	0.547	0.543	0.547
		C_{gnd} = 1000 μF	0.566	0.546	0.542	0.543
		C_{gnd} = 265 μF	0.567	0.541	0.539	0.536
	Bus-7	Zgnd = 0 Ω	0.578	0.578	0.578	0.578
		C_{gnd} = 2650 μF	0.578	0.578	0.578	0.578
		C_{gnd} = 1000 μF	0.578	0.578	0.578	0.578
		C_{gnd} = 265 μF	0.578	0.578	0.578	0.578

Table 11 Coefficient of grounding and fault current ratios for Scenario-3

Parameter	Location	Grounding	F_1	F_2	F_3	F_4
$I_{F1\Phi}/I_{F3\Phi}$	Fault point	Zgnd = 0 Ω	1.227	1.115	1.152	1.028
		C_{gnd} = 2650 μF	1.243	1.129	1.158	1.029
		C_{gnd} = 1000 μF	1.276	1.146	1.171	1.066
		C_{gnd} = 265 μF	1.451	1.266	1.266	1.386
$E_{LG(max)}/E_{LL}$ (COG)	Bus-1	Zgnd = 0 Ω	0.571	0.553	0.534	0.571
		C_{gnd} = 2650 μF	0.573	0.556	0.530	0.573
		C_{gnd} = 1000 μF	0.574	0.551	0.529	0.567
		C_{gnd} = 265 μF	0.577	0.531	0.518	0.535
	Bus-2	Zgnd = 0 Ω	0.536	0.571	0.575	0.574
		C_{gnd} = 2650 μF	0.545	0.569	0.574	0.573
		C_{gnd} = 1000 μF	0.543	0.569	0.574	0.573
		C_{gnd} = 265 μF	0.547	0.569	0.574	0.572
	Bus-3	Zgnd = 0 Ω	0.574	0.523	0.540	0.543
		C_{gnd} = 2650 μF	0.576	0.526	0.542	0.539
		C_{gnd} = 1000 μF	0.576	0.525	0.540	0.538
		C_{gnd} = 265 μF	0.579	0.522	0.529	0.529
	Bus-4	Zgnd = 0 Ω	0.572	0.571	0.541	0.590
		C_{gnd} = 2650 μF	0.575	0.574	0.537	0.593
		C_{gnd} = 1000 μF	0.575	0.567	0.534	0.584
		C_{gnd} = 265 μF	0.576	0.539	0.520	0.545
	Bus-5	Zgnd = 0 Ω	0.577	0.541	0.557	0.551
		C_{gnd} = 2650 μF	0.578	0.543	0.560	0.553
		C_{gnd} = 1000 μF	0.579	0.543	0.557	0.552
		C_{gnd} = 265 μF	0.581	0.540	0.545	0.545
	Bus-6	Zgnd = 0 Ω	0.575	0.546	0.544	0.552
		C_{gnd} = 2650 μF	0.576	0.547	0.543	0.547
		C_{gnd} = 1000 μF	0.576	0.546	0.541	0.544
		C_{gnd} = 265 μF	0.577	0.541	0.539	0.536
	Bus-7	Zgnd = 0 Ω	0.578	0.578	0.578	0.578
		C_{gnd} = 2650 μF	0.578	0.578	0.578	0.578
		C_{gnd} = 1000 μF	0.578	0.578	0.578	0.578
		C_{gnd} = 265 μF	0.578	0.578	0.578	0.578

Table 12 Coefficient of grounding and fault current ratios for Scenario-4

Parameter	Location	Grounding	F_1	F_2	F_3	F_4
$I_{F1\Phi}/I_{F3\Phi}$	Fault point	Zgnd = 0 Ω	1.228	0.818	1.151	0.612
		C_{gnd} = 2650 μF	1.244	0.820	1.158	0.612
		C_{gnd} = 1000 μF	1.277	0.823	1.171	0.612
		C_{gnd} = 265 μF	1.451	0.848	1.269	0.612
$E_{LG(max)}/E_{LL}$ (COG)	Bus-1	Zgnd = 0 Ω	0.553	0.663	0.550	0.578
		C_{gnd} = 2650 μF	0.558	0.664	0.546	0.578
		C_{gnd} = 1000 μF	0.559	0.663	0.544	0.578
		C_{gnd} = 265 μF	0.565	0.659	0.527	0.578
	Bus-2	Zgnd = 0 Ω	0.536	0.555	0.564	0.578
		C_{gnd} = 2650 μF	0.545	0.554	0.562	0.578
		C_{gnd} = 1000 μF	0.543	0.553	0.562	0.578
		C_{gnd} = 265 μF	0.547	0.548	0.559	0.578
	Bus-3	Zgnd = 0 Ω	0.560	0.553	0.542	0.578
		C_{gnd} = 2650 μF	0.563	0.555	0.539	0.578
		C_{gnd} = 1000 μF	0.564	0.554	0.537	0.578
		C_{gnd} = 265 μF	0.569	0.552	0.527	0.578
	Bus-4	Zgnd = 0 Ω	0.578	0.578	0.578	0.759
		C_{gnd} = 2650 μF	0.578	0.578	0.578	0.759
		C_{gnd} = 1000 μF	0.578	0.578	0.578	0.759
		C_{gnd} = 265 μF	0.578	0.578	0.578	0.759
	Bus-5	Zgnd = 0 Ω	0.571	0.565	0.557	0.578
		C_{gnd} = 2650 μF	0.574	0.567	0.560	0.578
		C_{gnd} = 1000 μF	0.574	0.567	0.558	0.578
		C_{gnd} = 265 μF	0.578	0.567	0.550	0.578
	Bus-6	Zgnd = 0 Ω	0.578	0.578	0.578	0.592
		C_{gnd} = 2650 μF	0.578	0.578	0.578	0.592
		C_{gnd} = 1000 μF	0.578	0.578	0.578	0.592
		C_{gnd} = 265 μF	0.578	0.578	0.578	0.592
	Bus-7	Zgnd = 0 Ω	0.578	0.578	0.578	0.578
		C_{gnd} = 2650 μF	0.578	0.578	0.578	0.578
		C_{gnd} = 1000 μF	0.578	0.578	0.578	0.578
		C_{gnd} = 265 μF	0.578	0.578	0.578	0.578

Table 13 Coefficient of grounding and fault current ratios for Scenario-5

Parameter	Location	Grounding	F_1	F_2	F_3	F_4
$I_{F1\Phi}/I_{F3\Phi}$	Fault point	Zgnd = 0 Ω	1.210	1.087	1.149	0.990
		C_{gnd} = 2650 μF	1.228	1.098	1.155	0.997
		C_{gnd} = 1000 μF	1.261	1.117	1.168	1.032
		C_{gnd} = 265 μF	1.446	1.243	1.264	1.335
$E_{LG(max)}/E_{LL}$ (COG)	Bus-1	Zgnd = 0 Ω	0.555	0.559	0.549	0.576
		C_{gnd} = 2650 μF	0.559	0.561	0.546	0.578
		C_{gnd} = 1000 μF	0.559	0.557	0.544	0.571
		C_{gnd} = 265 μF	0.563	0.534	0.536	0.536
	Bus-2	Zgnd = 0 Ω	0.540	0.558	0.570	0.568
		C_{gnd} = 2650 μF	0.549	0.556	0.570	0.566
		C_{gnd} = 1000 μF	0.547	0.555	0.569	0.565
		C_{gnd} = 265 μF	0.551	0.553	0.568	0.562
	Bus-3	Zgnd = 0 Ω	0.568	0.537	0.540	0.548
		C_{gnd} = 2650 μF	0.570	0.540	0.542	0.550
		C_{gnd} = 1000 μF	0.571	0.539	0.540	0.548
		C_{gnd} = 265 μF	0.574	0.537	0.529	0.540
	Bus-4	Zgnd = 0 Ω	0.561	0.577	0.552	0.595
		C_{gnd} = 2650 μF	0.565	0.581	0.549	0.598
		C_{gnd} = 1000 μF	0.565	0.574	0.547	0.589
		C_{gnd} = 265 μF	0.566	0.545	0.536	0.548
	Bus-5	Zgnd = 0 Ω	0.574	0.552	0.557	0.559
		C_{gnd} = 2650 μF	0.575	0.555	0.560	0.561
		C_{gnd} = 1000 μF	0.576	0.554	0.558	0.560
		C_{gnd} = 265 μF	0.578	0.552	0.546	0.554
	Bus-6	Zgnd = 0 Ω	0.569	0.549	0.553	0.553
		C_{gnd} = 2650 μF	0.570	0.551	0.552	0.548
		C_{gnd} = 1000 μF	0.571	0.550	0.551	0.547
		C_{gnd} = 265 μF	0.572	0.547	0.546	0.541
	Bus-7	Zgnd = 0 Ω	0.578	0.578	0.578	0.578
		C_{gnd} = 2650 μF	0.578	0.578	0.578	0.578
		C_{gnd} = 1000 μF	0.578	0.578	0.578	0.578
		C_{gnd} = 265 μF	0.578	0.578	0.578	0.578

Table 14 Coefficient of grounding and fault current ratios for Scenario-6

Parameter	Location	Grounding	F_1	F_2	F_3	F_4
$I_{F1\Phi}/I_{F3\Phi}$	Fault point	Zgnd = 0 Ω	1.207	1.081	1.127	0.990
		C_{gnd} = 2650 µF	1.207	1.095	1.134	0.996
		C_{gnd} = 1000 µF	1.207	1.113	1.147	1.031
		C_{gnd} = 265 µF	1.208	1.238	1.246	1.339
$E_{LG(max)}/E_{LL}$ (COG)	Bus-1	Zgnd = 0 Ω	0.557	0.562	0.539	0.578
		C_{gnd} = 2650 µF	0.557	0.564	0.536	0.580
		C_{gnd} = 1000 µF	0.557	0.559	0.534	0.573
		C_{gnd} = 265 µF	0.557	0.536	0.523	0.538
	Bus-2	Zgnd = 0 Ω	0.540	0.558	0.566	0.568
		C_{gnd} = 2650 µF	0.540	0.557	0.566	0.567
		C_{gnd} = 1000 µF	0.540	0.557	0.566	0.566
		C_{gnd} = 265 µF	0.540	0.555	0.564	0.562
	Bus-3	Zgnd = 0 Ω	0.564	0.526	0.546	0.548
		C_{gnd} = 2650 µF	0.564	0.529	0.548	0.543
		C_{gnd} = 1000 µF	0.564	0.528	0.545	0.541
		C_{gnd} = 265 µF	0.564	0.525	0.533	0.531
	Bus-4	Zgnd = 0 Ω	0.562	0.580	0.544	0.597
		C_{gnd} = 2650 µF	0.563	0.583	0.540	0.600
		C_{gnd} = 1000 µF	0.563	0.576	0.538	0.591
		C_{gnd} = 265 µF	0.563	0.546	0.523	0.549
	Bus-5	Zgnd = 0 Ω	0.571	0.545	0.562	0.554
		C_{gnd} = 2650 µF	0.571	0.548	0.565	0.556
		C_{gnd} = 1000 µF	0.571	0.547	0.562	0.555
		C_{gnd} = 265 µF	0.572	0.545	0.550	0.548
	Bus-6	Zgnd = 0 Ω	0.569	0.550	0.546	0.554
		C_{gnd} = 2650 µF	0.569	0.552	0.545	0.548
		C_{gnd} = 1000 µF	0.569	0.550	0.545	0.547
		C_{gnd} = 265 µF	0.570	0.547	0.543	0.540
	Bus-7	Zgnd = 0 Ω	0.578	0.578	0.578	0.578
		C_{gnd} = 2650 µF	0.578	0.578	0.578	0.578
		C_{gnd} = 1000 µF	0.578	0.578	0.578	0.578
		C_{gnd} = 265 µF	0.578	0.578	0.578	0.578

3.3 Analysis of Transient Overvoltages

In this section, electromagnetic transient simulations carried out in PSCAD/EMTDC are used to determine the highest transient overvoltages observed between any of the phases and the ground due to SLG faults. SLG faults are simulated at nine different locations (F_1 to F_9) on the network, and the each SLG fault simulation is repeated 32 times considering different fault inception angles (i.e. fault is initiated at 32 different time points uniformly distributed over one voltage cycle). Voltages at number of different locations on the network are monitored and the highest transient overvoltage observed at each location is reported as a per unit value, based on the nominal phase to ground peak voltage.

$$E_{LG(transient-pu)} = \frac{E_{LG(transient)}}{E_{LG(peak-nominal)}}$$

Calculations are repeated under different transformer neutral grounding conditions and different network conditions (scenarios). The three different grounding conditions simulated include (i) solidly grounded transformer neutrals, (ii) capacitance grounded transformer neutrals, and (iii) capacitance grounded transformer neutrals with MOV in parallel with the capacitance/resistance branch. The neutral grounding capacitance used was 2650 µF, except for Scenario-6 where the grounding capacitance was 265 µF. Descripts of the various scenarios considered and the different simulation cases performed under each scenario are listed in Table 15 .

Table 15 Scenarios and different test conditions considered in transient overvoltage analysis

Scenario	Condition	Neutral grounding	Case No.
Scenario-1	All the elements are in-service	Solidly grounded Capacitor grounded, C = 2650 µF Capacitor grounded with MOV, C = 2650 µF	Case (1) Case (2) Case (3)
Scenario-2	All the lines on bus-1 are disconnected from bus-1	Solidly grounded Capacitor grounded, C = 2650 µF Capacitor grounded with MOV, C = 2650 µF	Case (4) Case (5) Case (6)
Scenario-3	One of the 660 MVA, 22/500 kV transformers out of service	Solidly grounded Capacitor grounded, C = 2650 µF Capacitor grounded with MOV, C = 2650 µF	Case (7) Case (8) Case (9)
Scenario-4	750 MVA, 500/345 kV autotransformer between bus-1 and bus-4 out of service	Solidly grounded Capacitor grounded, C = 2650 µF Capacitor grounded with MOV, C = 2650 µF	Case (10) Case (11) Case (12)
Scenario-5	One of 500 kV, 250 km circuits is out of service	Solidly grounded Capacitor grounded, C = 2650 µF Capacitor grounded with MOV, C = 2650 µF	Case (13) Case (14) Case (15)
Scenario-6	All the elements are in-service	Capacitor grounded, C = 265 µF Capacitor grounded with MOV, C = 265 µF	Case (16) Case (17)

The locations of the faults simulated under Scenario-1 and the monitoring points are shown on Figure 3. The highest transient overvoltages observed at different monitoring points due to each fault are given in Table 16. Highlighted are the observations at fault locations.

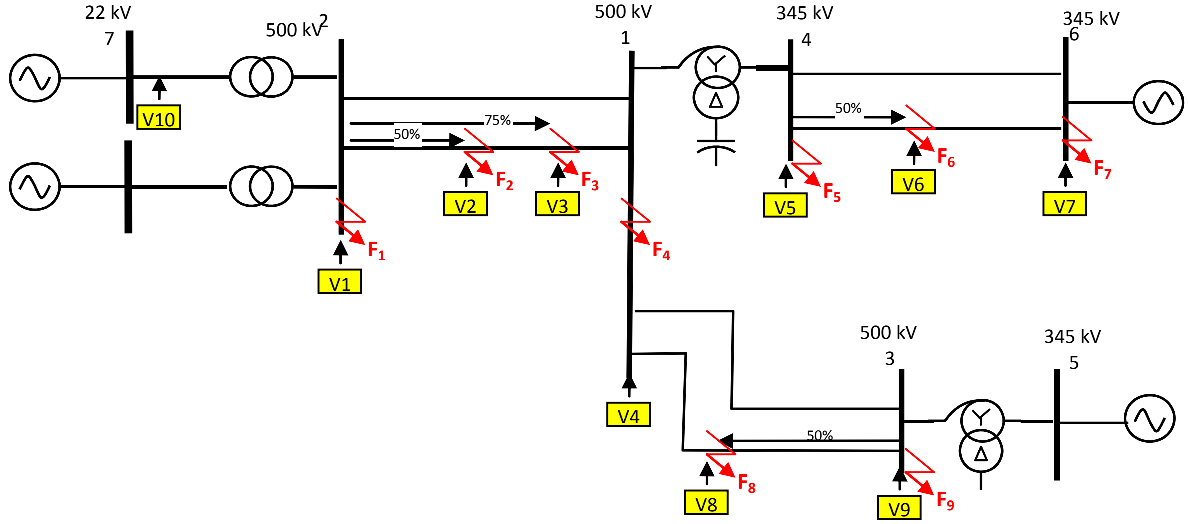

Figure 3: Locations of the faults and monitoring points in Scenario-1

Table 16 Transient overvoltages (pu) in Scenario -1

Fault	Case	Location									
		V1	V2	V3	V4	V5	V6	V7	V8	V9	V10
F1	1	1.24	1.18	1.19	1.19	1.28	1.31	1.25	1.17	1.17	1.03
	2	1.23	1.20	1.22	1.21	1.29	1.31	1.26	1.18	1.18	1.03
	3	1.23	1.19	1.21	1.20	1.29	1.31	1.26	1.18	1.17	1.03
F2	1	1.13	1.32	1.24	1.09	1.09	1.08	1.05	1.07	1.08	1.03
	2	1.13	1.33	1.23	1.09	1.10	1.08	1.05	1.08	1.08	1.03
	3	1.13	1.33	1.23	1.09	1.10	1.08	1.05	1.08	1.08	1.03
F3	1	1.06	1.28	1.35	1.13	1.13	1.11	1.06	1.08	1.09	1.03
	2	1.06	1.28	1.34	1.12	1.12	1.12	1.06	1.09	1.09	1.03
	3	1.06	1.28	1.34	1.12	1.12	1.12	1.06	1.09	1.09	1.03
F4	1	1.14	1.40	1.43	1.33	1.41	1.39	1.23	1.23	1.15	1.08
	2	1.13	1.41	1.44	1.34	1.43	1.40	1.23	1.24	1.16	1.07
	3	1.13	1.41	1.44	1.34	1.43	1.40	1.23	1.24	1.16	1.08
F5	1	1.09	1.16	1.18	1.14	1.17	1.19	1.10	1.14	1.09	1.09
	2	1.09	1.17	1.18	1.16	1.21	1.21	1.11	1.14	1.08	1.07
	3	1.09	1.16	1.18	1.15	1.20	1.21	1.11	1.14	1.08	1.09
F6	1	1.05	1.09	1.08	1.06	1.07	1.24	1.09	1.05	1.03	1.04
	2	1.05	1.08	1.08	1.06	1.07	1.24	1.09	1.05	1.03	1.04
	3	1.05	1.08	1.08	1.06	1.07	1.24	1.09	1.05	1.03	1.04
F7	1	1.07	1.09	1.09	1.06	1.04	1.11	1.17	1.06	1.05	1.04
	2	1.07	1.09	1.09	1.06	1.04	1.11	1.17	1.06	1.05	1.04
	3	1.07	1.09	1.09	1.06	1.04	1.11	1.17	1.06	1.05	1.04
F8	1	1.11	1.18	1.24	1.20	1.16	1.18	1.12	1.33	1.18	1.06
	2	1.10	1.18	1.25	1.21	1.18	1.19	1.12	1.34	1.19	1.06
	3	1.10	1.18	1.25	1.21	1.18	1.19	1.12	1.34	1.19	1.06
F9	1	1.14	1.17	1.16	1.14	1.15	1.16	1.12	1.22	1.29	1.09
	2	1.14	1.16	1.16	1.14	1.14	1.17	1.12	1.23	1.29	1.09
	3	1.14	1.16	1.16	1.14	1.14	1.17	1.12	1.23	1.29	1.09

The locations of the faults simulated under Scenario-2 and the monitoring points are shown on Figure 4. The highest transient overvoltages observed at different monitoring points due to each fault are given in Table 17.

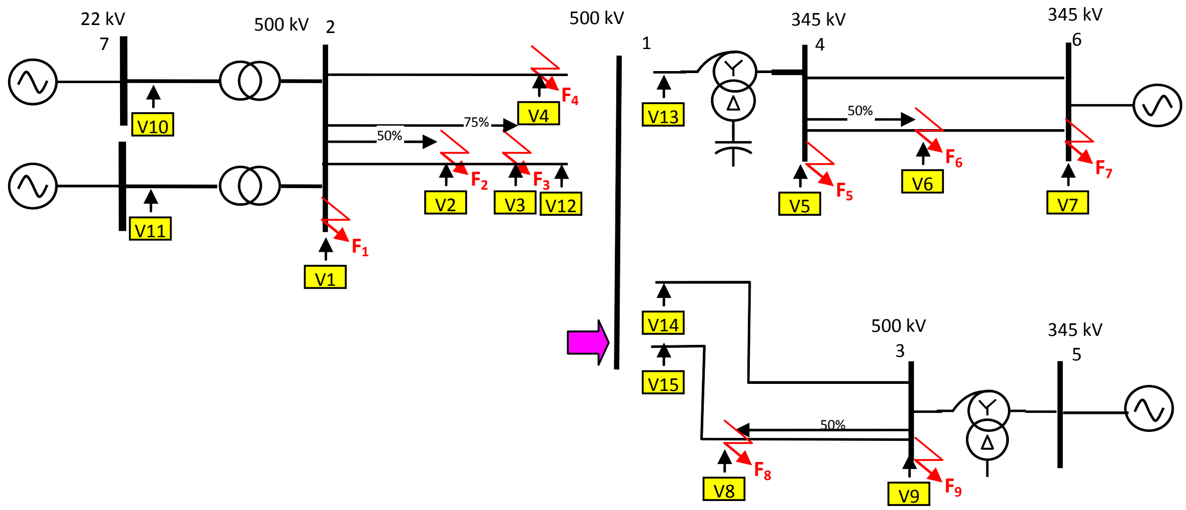

Figure 4: Locations of the faults and monitoring points in Scenario-2

Table 17 Transient overvoltages (pu) in Scenario -2

Fault	Case	Location														
		V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	V11	V12	V13	V14	V15
F1	4	1.42	1.34	1.32	1.26	1.07	1.06	1.04	1.03	1.03	1.09	1.09	1.26	1.09	1.03	1.03
	5	1.42	1.36	1.34	1.29	1.07	1.06	1.04	1.03	1.03	1.09	1.09	1.29	1.09	1.03	1.03
	6	1.42	1.36	1.34	1.29	1.07	1.06	1.04	1.03	1.03	1.09	1.09	1.29	1.09	1.03	1.03
F2	4	1.18	1.37	1.47	1.47	1.07	1.06	1.04	1.03	1.03	1.08	1.08	1.47	1.09	1.03	1.03
	5	1.17	1.37	1.47	1.46	1.07	1.06	1.04	1.03	1.03	1.08	1.08	1.46	1.09	1.03	1.03
	6	1.17	1.37	1.47	1.46	1.07	1.06	1.04	1.03	1.03	1.08	1.08	1.46	1.09	1.03	1.03
F3	4	1.14	1.31	1.39	1.48	1.07	1.06	1.04	1.03	1.03	1.07	1.07	1.46	1.09	1.03	1.03
	5	1.15	1.32	1.38	1.48	1.07	1.06	1.04	1.03	1.03	1.07	1.07	1.46	1.09	1.03	1.03
	6	1.15	1.32	1.38	1.48	1.07	1.06	1.04	1.03	1.03	1.07	1.07	1.46	1.09	1.03	1.03
F4	4	1.16	1.30	1.33	1.46	1.07	1.06	1.04	1.03	1.03	1.07	1.07	1.46	1.09	1.03	1.03
	5	1.16	1.30	1.33	1.46	1.07	1.06	1.04	1.03	1.03	1.07	1.07	1.46	1.09	1.03	1.03
	6	1.16	1.30	1.33	1.46	1.07	1.06	1.04	1.03	1.03	1.07	1.07	1.46	1.09	1.03	1.03
F5	4	1.07	1.08	1.08	1.07	1.53	1.43	1.29	1.03	1.03	1.07	1.07	1.07	1.61	1.03	1.03
	5	1.07	1.08	1.08	1.07	1.33	1.26	1.18	1.03	1.03	1.07	1.07	1.07	1.37	1.03	1.03
	6	1.07	1.08	1.08	1.07	1.52	1.42	1.28	1.03	1.03	1.07	1.07	1.07	1.59	1.03	1.03
F6	4	1.07	1.08	1.08	1.07	1.30	1.35	1.22	1.03	1.03	1.07	1.07	1.07	1.33	1.03	1.03
	5	1.07	1.08	1.08	1.07	1.20	1.29	1.16	1.03	1.03	1.07	1.07	1.07	1.23	1.03	1.03
	6	1.07	1.08	1.08	1.07	1.28	1.34	1.20	1.03	1.03	1.07	1.07	1.07	1.31	1.03	1.03
F7	4	1.07	1.08	1.08	1.07	1.51	1.49	1.42	1.03	1.03	1.07	1.07	1.07	1.60	1.03	1.03
	5	1.07	1.08	1.08	1.07	1.50	1.48	1.42	1.03	1.03	1.07	1.07	1.07	1.59	1.03	1.03
	6	1.07	1.08	1.08	1.07	1.50	1.48	1.42	1.03	1.03	1.07	1.07	1.07	1.59	1.03	1.03
F8	4	1.07	1.08	1.08	1.07	1.07	1.06	1.04	1.32	1.24	1.07	1.07	1.07	1.09	1.38	1.42
	5	1.07	1.08	1.08	1.07	1.07	1.06	1.04	1.32	1.25	1.07	1.07	1.07	1.09	1.37	1.43
	6	1.07	1.08	1.08	1.07	1.07	1.06	1.04	1.32	1.25	1.07	1.07	1.07	1.09	1.37	1.43
F9	4	1.07	1.08	1.08	1.07	1.07	1.06	1.04	1.31	1.29	1.07	1.07	1.07	1.09	1.38	1.38
	5	1.07	1.08	1.08	1.07	1.07	1.06	1.04	1.29	1.29	1.07	1.07	1.07	1.09	1.36	1.36
	6	1.07	1.08	1.08	1.07	1.07	1.06	1.04	1.29	1.29	1.07	1.07	1.07	1.09	1.36	1.36

The locations of the faults simulated under Scenario-3 and the monitoring points are shown on Figure 5. The highest transient overvoltages observed at different monitoring points due to each fault are given in Table 18.

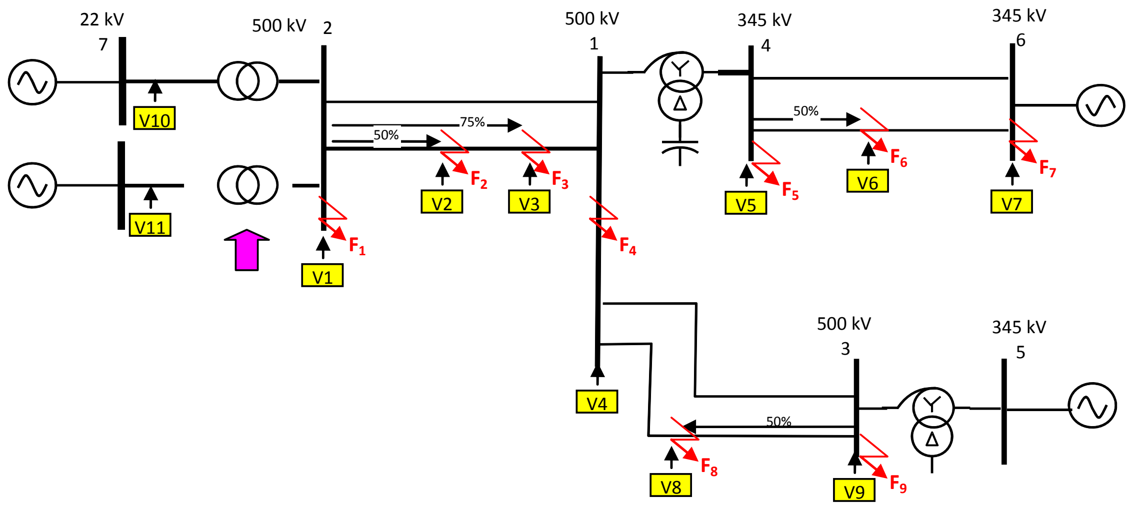

Figure 5: Locations of the faults and monitoring points in Scenario-3

Table 18 Transient overvoltages (pu) in Scenario -3

Fault	Case	Location										
		V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	V11
F1	7	1.24	1.20	1.20	1.17	1.23	1.24	1.18	1.16	1.15	1.01	1.08
	8	1.23	1.21	1.22	1.18	1.24	1.25	1.19	1.17	1.15	1.01	1.08
	9	1.23	1.20	1.21	1.18	1.24	1.25	1.19	1.17	1.15	1.01	1.08
F2	7	1.16	1.33	1.25	1.10	1.10	1.06	1.05	1.08	1.07	1.01	1.08
	8	1.16	1.33	1.26	1.11	1.11	1.07	1.05	1.08	1.08	1.01	1.08
	9	1.16	1.33	1.26	1.11	1.11	1.07	1.05	1.08	1.08	1.01	1.08
F3	7	1.09	1.29	1.33	1.10	1.12	1.11	1.06	1.08	1.09	1.01	1.08
	8	1.08	1.29	1.33	1.10	1.12	1.11	1.06	1.09	1.09	1.01	1.08
	9	1.08	1.29	1.33	1.10	1.12	1.11	1.06	1.09	1.09	1.01	1.08
F4	7	1.21	1.54	1.55	1.38	1.36	1.35	1.21	1.31	1.21	1.03	1.08
	8	1.21	1.55	1.56	1.40	1.38	1.37	1.22	1.32	1.21	1.03	1.08
	9	1.21	1.55	1.56	1.40	1.38	1.37	1.22	1.32	1.21	1.03	1.08
F5	7	1.10	1.21	1.22	1.17	1.19	1.16	1.10	1.16	1.11	1.03	1.08
	8	1.10	1.21	1.21	1.16	1.18	1.18	1.11	1.16	1.11	1.03	1.08
	9	1.10	1.21	1.21	1.16	1.18	1.18	1.11	1.16	1.11	1.03	1.08
F6	7	1.05	1.10	1.10	1.08	1.07	1.26	1.10	1.06	1.04	1.01	1.08
	8	1.05	1.10	1.09	1.08	1.07	1.26	1.10	1.06	1.04	1.02	1.08
	9	1.05	1.10	1.09	1.08	1.07	1.26	1.10	1.06	1.04	1.01	1.08
F7	7	1.07	1.10	1.11	1.08	1.07	1.12	1.18	1.07	1.07	1.03	1.08
	8	1.07	1.10	1.11	1.08	1.06	1.12	1.18	1.07	1.06	1.03	1.08
	9	1.07	1.10	1.11	1.08	1.06	1.12	1.18	1.07	1.06	1.03	1.08
F8	7	1.15	1.25	1.27	1.19	1.16	1.13	1.08	1.32	1.18	1.03	1.08
	8	1.15	1.25	1.28	1.20	1.17	1.14	1.09	1.33	1.19	1.03	1.08
	9	1.15	1.25	1.28	1.20	1.17	1.14	1.09	1.33	1.19	1.03	1.08
F9	7	1.17	1.22	1.21	1.18	1.21	1.11	1.09	1.22	1.34	1.08	1.08
	8	1.17	1.22	1.22	1.18	1.20	1.11	1.09	1.23	1.34	1.07	1.08
	9	1.17	1.22	1.22	1.18	1.20	1.11	1.09	1.23	1.34	1.07	1.08

The locations of the faults simulated under Scenario-4 and the monitoring points are shown on Figure 6. The highest transient overvoltages observed at different monitoring points are given in Table 19Table 18.

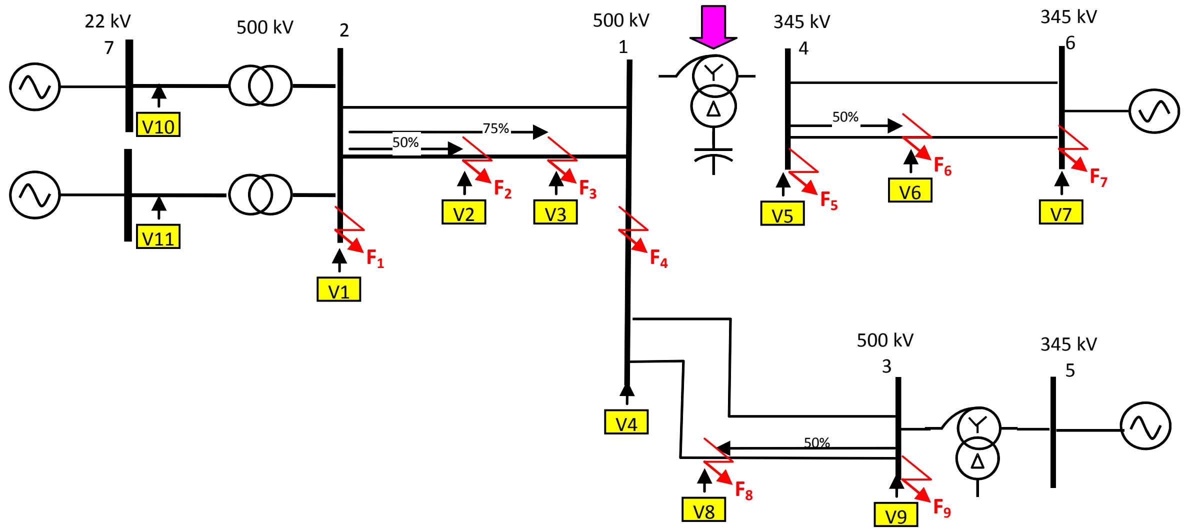

Figure 6: Locations of the faults and monitoring points in Scenario-4

Table 19 Transient overvoltages (pu) in Scenario-4

Fault	Case	Location										
		V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	V11
F1	10	1.33	1.28	1.33	1.35	1.00	1.00	1.00	1.35	1.33	1.04	1.04
	11	1.32	1.31	1.35	1.36	1.00	1.00	1.00	1.36	1.33	1.04	1.04
	12	1.32	1.30	1.34	1.36	1.00	1.00	1.00	1.36	1.33	1.04	1.04
F2	10	1.13	1.41	1.39	1.29	1.00	1.00	1.00	1.21	1.12	1.03	1.03
	11	1.13	1.42	1.39	1.29	1.00	1.00	1.00	1.21	1.13	1.04	1.04
	12	1.13	1.42	1.39	1.29	1.00	1.00	1.00	1.21	1.13	1.04	1.04
F3	10	1.06	1.35	1.37	1.30	1.00	1.00	1.00	1.24	1.09	1.03	1.03
	11	1.05	1.35	1.38	1.30	1.00	1.00	1.00	1.24	1.09	1.04	1.04
	12	1.05	1.35	1.38	1.30	1.00	1.00	1.00	1.24	1.09	1.04	1.04
F4	10	1.07	1.33	1.36	1.29	1.00	1.00	1.00	1.20	1.11	1.04	1.04
	11	1.07	1.34	1.36	1.30	1.00	1.00	1.00	1.20	1.11	1.04	1.04
	12	1.07	1.34	1.36	1.30	1.00	1.00	1.00	1.20	1.11	1.04	1.04
F5	10	1.00	0.99	0.98	0.97	1.40	1.28	1.14	0.97	0.96	1.03	1.03
	11	1.00	0.99	0.98	0.97	1.40	1.28	1.14	0.97	0.96	1.03	1.03
	12	1.00	0.99	0.98	0.97	1.40	1.28	1.14	0.97	0.96	1.03	1.03
F6	10	1.00	0.99	0.98	0.97	1.33	1.27	1.11	0.97	0.96	1.03	1.03
	11	1.00	0.99	0.98	0.97	1.33	1.27	1.11	0.97	0.96	1.03	1.03
	12	1.00	0.99	0.98	0.97	1.33	1.27	1.11	0.97	0.96	1.03	1.03
F7	10	1.00	0.99	0.98	0.97	1.20	1.18	1.15	0.97	0.96	1.03	1.03
	11	1.00	0.99	0.98	0.97	1.20	1.18	1.15	0.97	0.96	1.03	1.03
	12	1.00	0.99	0.98	0.97	1.20	1.18	1.15	0.97	0.96	1.03	1.03
F8	10	1.09	1.30	1.30	1.25	1.00	1.00	1.00	1.27	1.11	1.03	1.03
	11	1.09	1.30	1.31	1.25	1.00	1.00	1.00	1.27	1.11	1.03	1.03
	12	1.09	1.30	1.31	1.25	1.00	1.00	1.00	1.27	1.11	1.03	1.03
F9	10	1.15	1.27	1.33	1.29	1.00	1.00	1.00	1.22	1.29	1.04	1.04
	11	1.15	1.28	1.31	1.27	1.00	1.00	1.00	1.20	1.29	1.04	1.04
	12	1.15	1.28	1.31	1.28	1.00	1.00	1.00	1.21	1.29	1.04	1.04

The locations of the faults simulated under Scenario-5 and the monitoring points are shown on Figure 7. The highest transient overvoltages observed at different monitoring points are given in Table 20Table 18.

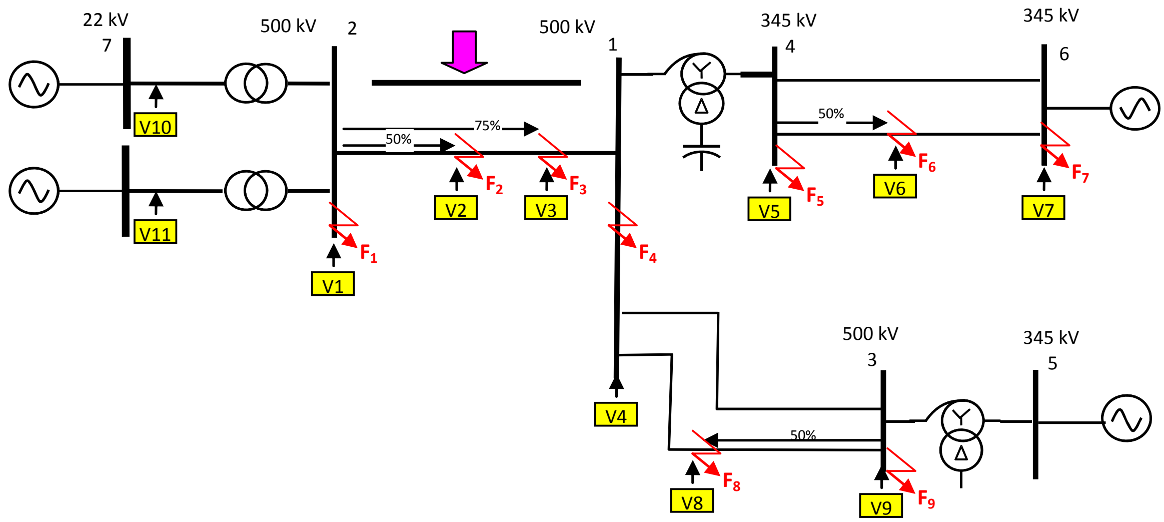

Figure 7: Locations of the faults and monitoring points in Scenario-5

Table 20 Transient overvoltages (pu) in Scenario-5

Fault	Case	Location										
		V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	V11
F1	13	1.15	1.15	1.17	1.15	1.22	1.26	1.22	1.15	1.14	1.04	1.04
	14	1.14	1.18	1.19	1.16	1.23	1.27	1.22	1.16	1.14	1.04	1.04
	15	1.14	1.17	1.18	1.16	1.23	1.27	1.22	1.16	1.14	1.04	1.04
F2	13	1.33	1.29	1.25	1.12	1.13	1.11	1.10	1.13	1.10	1.27	1.27
	14	1.32	1.30	1.25	1.13	1.14	1.11	1.10	1.14	1.11	1.27	1.27
	15	1.32	1.30	1.25	1.13	1.14	1.11	1.10	1.14	1.11	1.27	1.27
F3	13	1.11	1.34	1.38	1.18	1.18	1.14	1.08	1.18	1.13	1.11	1.11
	14	1.10	1.34	1.38	1.19	1.19	1.16	1.08	1.19	1.13	1.11	1.11
	15	1.10	1.34	1.38	1.19	1.19	1.16	1.08	1.19	1.13	1.11	1.11
F4	13	1.20	1.33	1.31	1.31	1.41	1.40	1.24	1.26	1.14	1.12	1.12
	14	1.19	1.32	1.32	1.32	1.44	1.41	1.25	1.27	1.14	1.12	1.12
	15	1.19	1.32	1.32	1.32	1.43	1.41	1.25	1.27	1.14	1.12	1.12
F5	13	1.11	1.17	1.17	1.18	1.23	1.23	1.12	1.15	1.10	1.07	1.07
	14	1.11	1.17	1.18	1.19	1.27	1.25	1.13	1.14	1.08	1.07	1.07
	15	1.11	1.17	1.18	1.19	1.26	1.24	1.13	1.15	1.10	1.07	1.07
F6	13	1.06	1.09	1.09	1.06	1.08	1.27	1.10	1.05	1.03	1.05	1.05
	14	1.06	1.08	1.08	1.06	1.09	1.28	1.10	1.05	1.03	1.05	1.05
	15	1.06	1.08	1.08	1.06	1.09	1.28	1.10	1.05	1.03	1.05	1.05
F7	13	1.09	1.10	1.10	1.06	1.05	1.12	1.18	1.06	1.04	1.06	1.06
	14	1.09	1.09	1.10	1.05	1.05	1.12	1.18	1.06	1.04	1.06	1.06
	15	1.09	1.09	1.10	1.05	1.05	1.12	1.18	1.06	1.04	1.06	1.06
F8	13	1.15	1.16	1.20	1.19	1.19	1.18	1.13	1.33	1.16	1.12	1.12
	14	1.15	1.16	1.19	1.20	1.20	1.19	1.14	1.34	1.17	1.12	1.12
	15	1.15	1.16	1.19	1.20	1.20	1.19	1.14	1.34	1.17	1.12	1.12
F9	13	1.21	1.20	1.21	1.12	1.13	1.20	1.16	1.23	1.27	1.15	1.15
	14	1.21	1.19	1.20	1.13	1.14	1.20	1.16	1.24	1.28	1.15	1.15
	15	1.21	1.19	1.20	1.13	1.14	1.20	1.16	1.24	1.28	1.15	1.15

The locations of the faults simulated under Scenario-6 and the monitoring points are shown on Figure 8. The highest transient overvoltages observed at different monitoring points are given in Table 21.

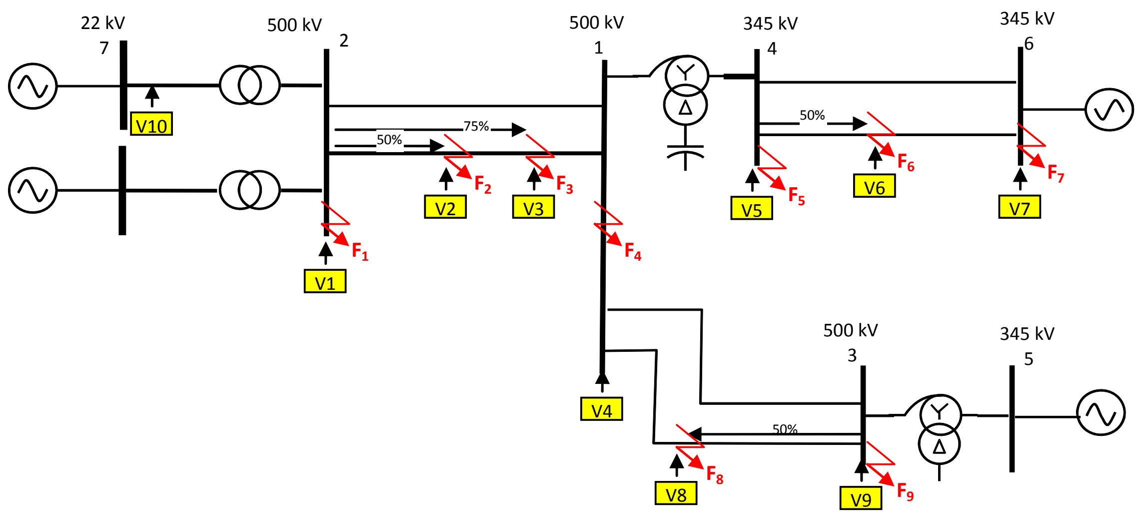

Figure 8: Locations of the faults and monitoring points in Scenario-6

Table 21 Transient overvoltages (pu) in Scenario-6

Fault	Case	Location									
		V1	V2	V3	V4	V5	V6	V7	V8	V9	V10
F1	1	1.24	1.18	1.19	1.19	1.28	1.31	1.25	1.17	1.17	1.03
	16	1.44	1.37	1.32	1.26	1.34	1.35	1.28	1.24	1.22	1.03
	17	1.21	1.17	1.19	1.19	1.28	1.31	1.25	1.17	1.17	1.03
F2	1	1.13	1.32	1.24	1.09	1.09	1.08	1.05	1.07	1.08	1.03
	16	1.13	1.36	1.27	1.13	1.16	1.10	1.07	1.10	1.10	1.03
	17	1.12	1.34	1.24	1.10	1.12	1.10	1.06	1.09	1.09	1.03
F3	1	1.06	1.28	1.35	1.13	1.13	1.11	1.06	1.08	1.09	1.03
	16	1.10	1.29	1.32	1.15	1.20	1.15	1.08	1.13	1.11	1.03
	17	1.08	1.28	1.34	1.13	1.14	1.13	1.07	1.10	1.10	1.03
F4	1	1.14	1.40	1.43	1.33	1.41	1.39	1.23	1.23	1.15	1.08
	16	1.13	1.46	1.50	1.42	1.53	1.47	1.27	1.30	1.20	1.05
	17	1.13	1.41	1.43	1.33	1.43	1.41	1.24	1.24	1.17	1.08
F5	1	1.09	1.16	1.18	1.14	1.17	1.19	1.10	1.14	1.09	1.09
	16	1.09	1.24	1.27	1.26	1.37	1.31	1.16	1.19	1.11	1.06
	17	1.09	1.15	1.16	1.13	1.17	1.19	1.10	1.12	1.07	1.09
F6	1	1.05	1.09	1.08	1.06	1.07	1.24	1.09	1.05	1.03	1.04
	16	1.05	1.08	1.09	1.09	1.15	1.28	1.09	1.07	1.04	1.03
	17	1.05	1.08	1.07	1.05	1.07	1.25	1.09	1.05	1.02	1.04
F7	1	1.07	1.09	1.09	1.06	1.04	1.11	1.17	1.06	1.05	1.04
	16	1.07	1.08	1.08	1.05	1.05	1.11	1.17	1.06	1.05	1.04
	17	1.07	1.08	1.08	1.05	1.04	1.11	1.17	1.06	1.05	1.04
F8	1	1.11	1.18	1.24	1.20	1.16	1.18	1.12	1.33	1.18	1.06
	16	1.10	1.21	1.29	1.25	1.25	1.22	1.14	1.38	1.22	1.05
	17	1.10	1.19	1.26	1.22	1.20	1.20	1.13	1.35	1.20	1.06
F9	1	1.14	1.17	1.16	1.14	1.15	1.16	1.12	1.22	1.29	1.09
	16	1.14	1.18	1.20	1.19	1.16	1.19	1.14	1.28	1.28	1.08
	17	1.14	1.16	1.17	1.15	1.13	1.18	1.13	1.23	1.28	1.10

Results indicate that transient overvoltages are less than 2 pu (the limiting value under effective grounding conditions) for all cases. Furthermore, the results show that capacitance neutral grounding does not significantly alter the transient overvoltages, when the capacitance is 2650 μF. The results of Scenario-6 shows that when the grounding capacitance is decreased to 265 μF, transient overvoltages slightly increase (but still below 2 pu). However, when the parallel MOVs are introduced, the transient overvoltages drop to normal values.

4.0 Concluding Remarks

Based on the three studies conducted, capacitance grounding of transformer neutrals with a capacitance in the range of 265 μF to 2650 μF has no significant impact on effectiveness of the grounding of the 500 kV/345 kV test system considered. Especially with the proposed capacitance value of 2650 μF in the GIC blocking scheme proposed by Emprimus, only a minimum impact is expected on the effective grounding. This conclusion obtained with the test network should be valid for most power systems, but characteristics of a specific power system vary from that analyzed in this study and therefore an appropriate grounding impact analysis for that specific system is recommended when applying the proposed GIC blocking scheme.

5.0 References

[1]IEEE Standard C62.92.5-2000, IEEE Guide for the Application of Neutral Grounding in Electrical Utility Systems-Part 1:Introduction, IEEE Power Engineering Society, September 2000.

[2] IEEE Standard C62.92.5-2009, IEEE Guide for the Application of Neutral Grounding in Electrical Utility Systems-Part V: Transmission Systems and Subtransmission Systems, IEEE Power Engineering Society, 2009.