A Grounding Bank Design Guideline To Meet The Effective Grounding Requirements Per IEEE P1547.8 Sizing Methodology Using Solectria Inverters

1. Background

Solectria prepared this document to aid the PV developers with the design of grounding bank in order to be compliant with the effective grounding requirements of utilities that accept the IEEE P1547.8 sizing methodology using Solectria inverters. The expectation is that once a project follows this guideline, the design evaluation process by the utility can be expedited and the PV plant can be commissioned sooner. This guideline follows industry standards and recommended practices, which are listed in section 7 especially the latest IEEE P1547.8™ has been used extensively.

Solectria provides a spreadsheet 'Effective Grounding Design Tool for Solectria Inverters', which conveniently calculates parameters involved in effective grounding projects using Solectria inverters. A sample case study using this spreadsheet is included as a reference which is similar to the example provided in IEEEE P1547.8. Currently, this tool is available on our website at

http://www.solectria.com/support/effective-grounding-design-tool/

Please contact Solectria for technical questions or to request the 'Effective Grounding Design Tool'.

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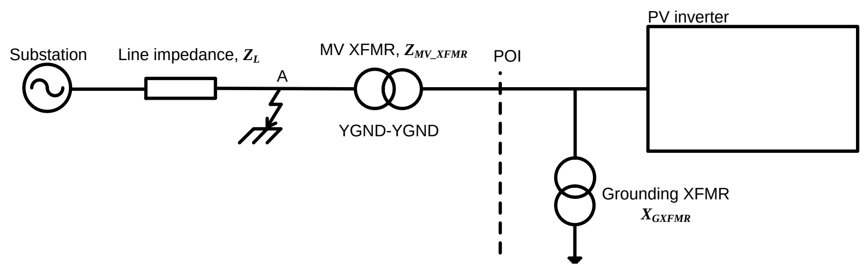
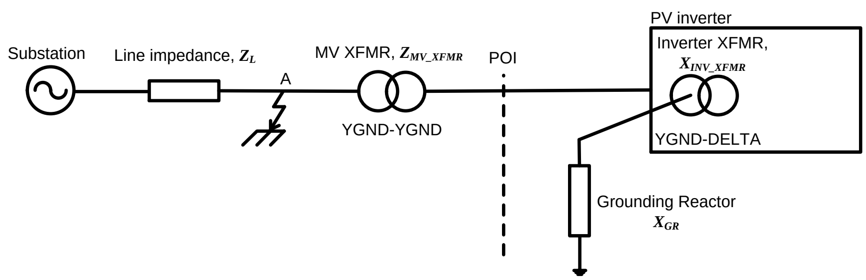
2. Introduction

To illustrate the design of the grounding bank, the following single line diagram is used. The substation is assumed to be an infinite voltage source connected to a 4 wire multi-grounded distribution line and a feeder medium voltage transformer with Ygnd-Ygnd configuration. The line impedance may include the substation transformer impedance if needed.



(a) PV Inverter effective grounding using a grounding transformer



(b) PV Inverter effective grounding using a grounding reactor

Figure 1. Single Line Diagrams of a PV plant with Different Grounding Bank Options
$V_{Substation} = 13.2\text{kV}, Z_{L1} = Z_{L2}$ = 0.1 + j0.2 pu, Z_{L0} = 0.2+ j0.5 pu

In general, effective grounding can be achieved with a grounding transformer as shown in Figure 1 (a). If the PV inverter has an internal transformer with the grounded wye to delta configuration, a grounding reactor can be used instead by accessing the neutral point of the inverter transformer. In this case, it should be guaranteed that the internal transformer is rated for the additional neutral current due to the grounding reactor during the steady state as well as fault conditions. The parameters used for analysis in this document will be referred through their notations as given below:

Z_L : Line impedance of the distribution feeder. With the sequence network decomposition, it is represented by $Z_{L1} = R_{L1} + L_{L1}$, $Z_{L2} = R_{L2} + L_{L2}$ and $Z_{L0} = R_{L0} + L_{L0}$.

Z_{MV_XFMR} : Leakage impedance of the medium voltage interconnection transformer. It will be used with the X/R ratio to calculate the resistive and reactive component of the impedance.

X_{INV_XFMR} : Leakage impedance of the internal inverter transformer. As the inverter transformer resistance is low, the resistive component is ignored in the transformer impedance.

X_{GB} : Grounding bank impedance. A grounding bank can be a grounding transformer or a grounding reactor.

R_{GB}: Grounding bank resistance.

X_{GXFMR} : Grounding transformer leakage impedance.

X_{GR} : Grounding reactor impedance.

3. Impedance calculation

The grounding bank impedance is designed according to the following formula.

$$X_{GB} = 0.6 \pm 10\%\, pu \text{ and } X_{GB} / R_{GB} \geq 4$$

where

$$1\, pu\ impedance = Z_{base} = \frac{(kV)^2}{MVA}\ \Omega$$

This formula is independent of the positive sequence reactance X_1 as compared to the conventional effective grounding definition that is used for the synchronous generators. The X_1 component does not represent the physical impedance in a PV inverter. Therefore, this form of effective grounding eliminates the uncertainty of using sequence components in the grounding bank design associated with inverter based distributed generators. This form of impedance X_{GB} can be applied to individual inverters or a PV plant when one grounding bank is designed for a PV plant with multiple inverters.

When a zig-zag or delta-wye transformer is used for the grounding bank, the impedance calculation is straight forward. For example, when a 480VAC, 500kVA rated SGI500 inverter requires effective grounding, the grounding transformer impedance is calculated as follows:

$$1\, pu\ impedance = Z_{base} = \frac{(kV)^2}{MVA}\ \Omega = \frac{(0.48kV)^2}{0.5MVA}\ \Omega = 0.461\ \Omega$$

$$X_{GXFMR} = 0.6 \times 0.461\Omega \pm 10\% = 0.277\ \Omega \pm 10\%$$

In most cases, the leakage impedance of the grounding transformer can be adjusted to achieve the desired grounding impedance. If the leakage impedance is insufficient, additional grounding inductor can be added in series with the grounding transformer's neutral connection to meet the requirement.

The grounding reactor impedance calculation follows the same concept but the leakage impedance of the internal transformer in the PV inverter is added to meet the required grounding impedance requirement. If we consider the same example using 480V 500kVA rated SGI500 inverter, the required X_{GB} is still 0.277 ohm.

$$X_{GB} = 3 \cdot X_{GR} + X_{INV\_XFMR}$$

The internal transformer leakage impedance of SGI500 inverter from Solectria, X_{INV_XFMR} is typically 3% (14mohms) and the required reactance of the grounding reactor X_{GR} is calculated as

$$X_{GR} = \frac{X_{GB} - X_{INV\_XFMR}}{3} = \frac{0.277 - 0.014}{3} = 0.088\ \Omega$$

4. Current handling capacity design

Figure 1 (a) is used to explain the design of the current handling capacity of a grounding bank. In an ideal three phase four-wire grounded wye balanced condition, the current flowing through the grounding bank is zero. However, three phase line to neutral distribution voltages are not perfectly balanced and the voltage imbalance generates zero sequence current to flow in the grounding bank. This imbalance current is limited by the grounding bank impedance as determined in the previous section. The zero sequence current due to the feeder voltage imbalance is steady state current. Hence the grounding bank should be rated for this current continuously.

Also, when an unbalanced fault involving ground is applied on the distribution line, the grounding bank will draw fault currents generated by the grid. The fault currents are cleared by the protective device relatively quickly, so that the grounding banks are rated for the fault current for a short duration in order to practically size and price the grounding bank.

The individual current components in the grounding bank need to be evaluated to determine the current handling capacity of the grounding bank and protection design as provided in the following sections. The same concept can be applied for the grounding reactor current capacity design. When an iron core type is used for the grounding reactor, extra care should be taken to avoid the reactor saturation during the fault condition.

4.1 Neutral current due to voltage imbalance

The zero sequence voltage V_0 = 4% for feeder voltage imbalance is used here to estimate the worst case steady state imbalance current in the distribution feeder according to P1547.8™/D8 draft recommended practice. Usually, the zero sequence voltage in a distribution line is less than 2% so that 4% zero sequence voltage provides enough safety margins for the current rating of the grounding bank.

When a grounding bank or a grounding reactor is used to meet the impedance guideline in the previous section, $\mathrm{X_{GB}}$ = 0.6pu, the steady state zero sequence current is 0.04/0.6 = 0.067pu. Therefore, the expected phase current generated by the grid voltage imbalance will be about 6.7% of the PV plant rated current. For 480V, 500kVA SGI500 inverter, the minimum rating of the phase current is 6.7% x 601A = 40A. If a grounding reactor is considered, it should be rated for 3 x 40A =120A as the neutral current will be sum of three phase currents.

4.2 Fault current from the inverter

PV inverter operation during faults is different from that of synchronous generators. Hence fault currents cannot be easily analyzed by conventional equivalent circuit models. For this reason, hardware test results are generally used for short circuit characteristics of the inverter based DGs.

Solectria tested commercial and utility scale inverters by subjecting them to different types of faults. The worst case fault current obtained from these tests is limited to less than 120% of the inverter's rated current and the inverter shuts off within 2 cycles. The fault current from the inverter flows to the grid side mostly not to the grounding bank as the grounding bank impedance is much higher than the feeder line impedance. For this reason, the fault current contribution from an inverter will be ignored in the grounding bank current rating.

As an example, the fault current flowing through the grounding transformer phase windings by the SGI 500 inverter is 21A, which will be ignored for the grounding bank design. The Effective Grounding Design tool by Solectria provides this calculation.

4.3 Fault current from the substation

Figure 2 shows the equivalent sequence network analyzed to calculate the fault current from the feeder when a single line to ground fault is applied at point A in Figure 1. In this case, the PV inverter equivalent circuit is not included in order to calculate the fault current contribution from the grid side only. The following feeder impedance is used to represent typical parameters in a PV plant installation project with a SGI 500 inverter.

Z_{L1} =Z_{L2} = 0.1 + j0.2 pu, Z_{L0} = 0.2+ j0.5 pu, S_{base} = 10MVA, V_{base} = 13.2kV

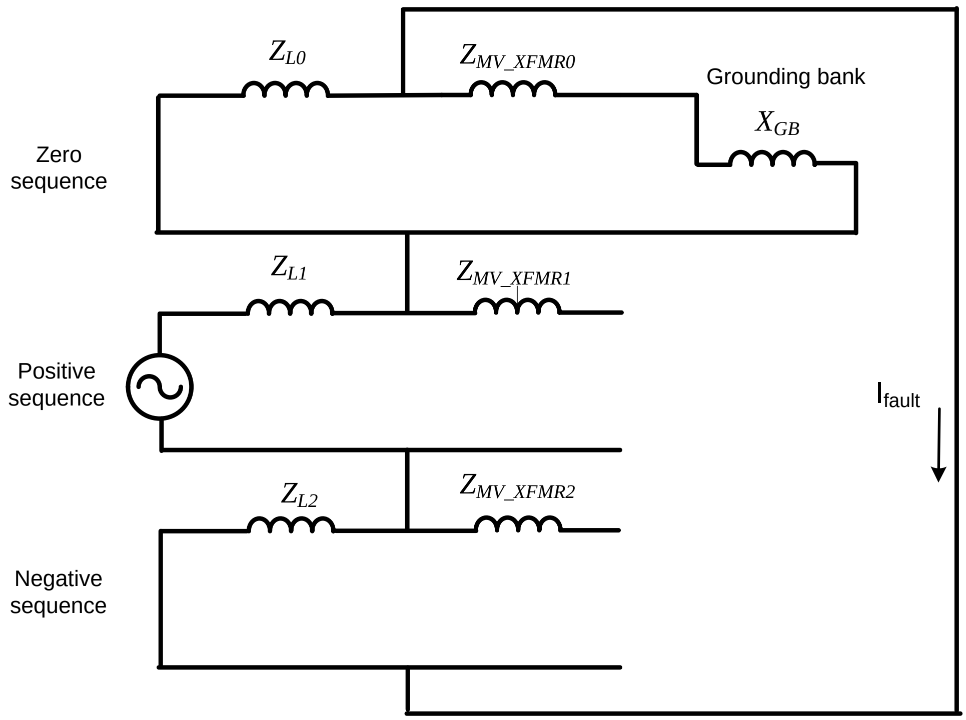


Figure 2. Equivalent Sequence Diagram with a SLG Fault Considering the Grid Side Contribution

The medium voltage transformer impedance is set to 5% to consider a typical value. The grounding bank Impedance (Z = 0.277 ohms) calculated in the section 3 is used to estimate the fault current flowing through the grounding bank. The calculated fault current from the grid at the ground bank is 1552A. It is recommended to use 50% additional margin to consider any changes in the feeder conditions, which corresponds to 1552A x 150% = 2328A.

This fault current should be less than the interrupt rating of the disconnect device and the grounding bank should be isolated from the fault within the equipment damage time at the fault current level. Figure 3 shows a typical inverse time current curve used for protection device coordination.

Typically, LV circuit breakers have high interrupt rating, trip out from the fault current in several cycles and do not need external sensing device and hence are very effective for the grounding bank protection. The auxiliary contact in the circuit breaker provides an interlocking option which can be used to trip the inverter whenever the breaker is opened from overcurrent protection. For large PV plants which require coordination accuracy, protective relays can be considered.

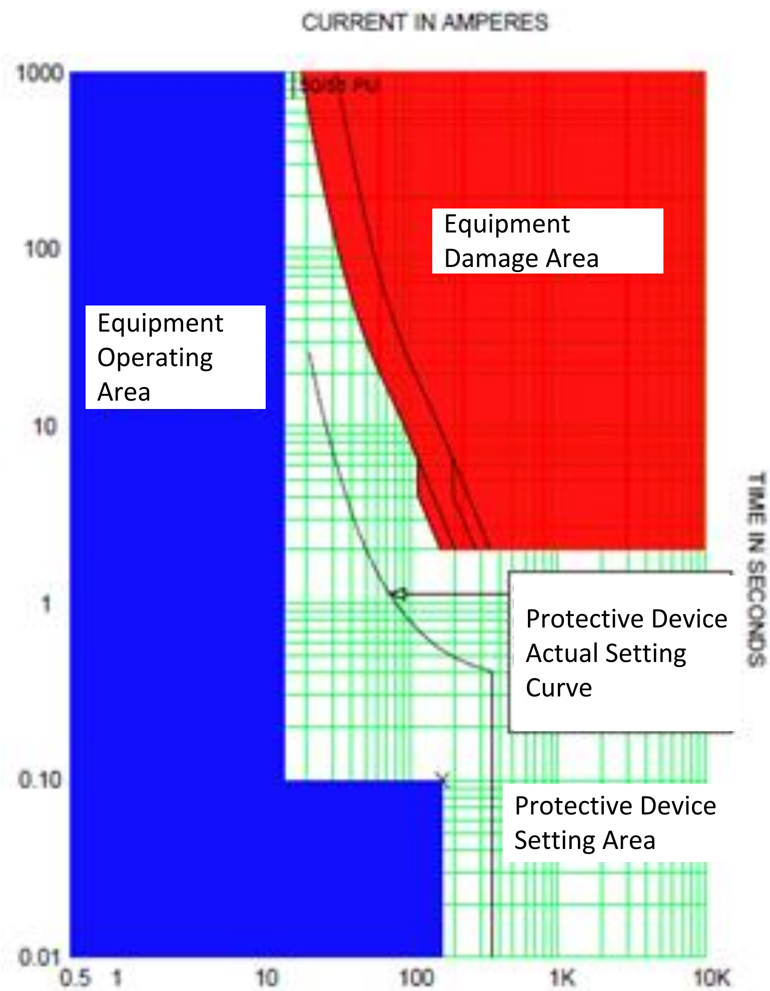


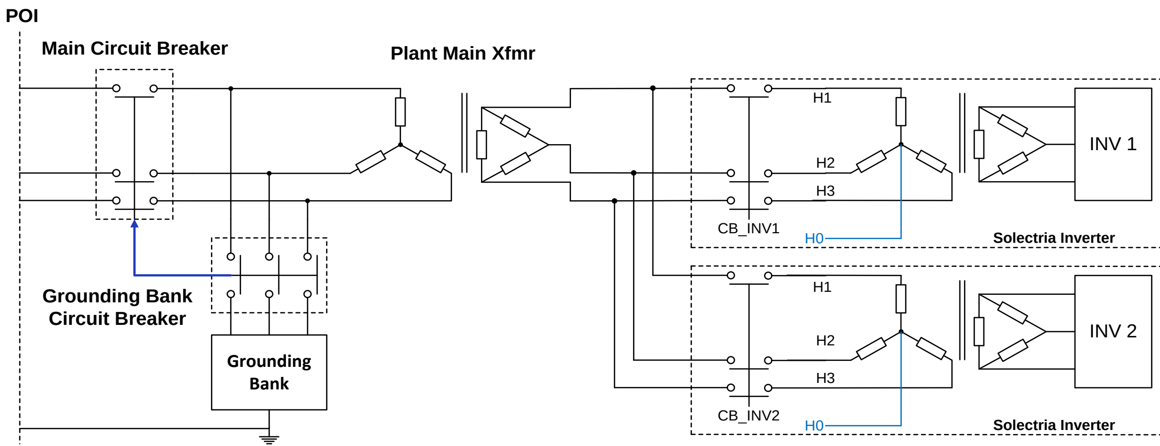
Figure 3. Typical inverse time current curve to coordinate the trip level and time

The trip time should be designed fast to guarantee that the grounding bank will not be damaged but also conservative enough to minimize nuisance trips. Considering the industry standards and recommended practice, the trip time due to fault can range from 10 cycles to 5 sec. (1~2 sec is typical)

The main purpose of the overcurrent protection is to prevent grounding banks from damage during the persistent fault, and isolate the grounding bank. When the grounding bank is disconnected from the grid, the PV inverter should be disabled simultaneously to prevent any overvoltage issue during unbalanced fault conditions. For the same purpose, it is highly recommended to provide a protection scheme that shuts the inverter off when the grounding bank is inadvertently disconnected. This might be achieved when a protective relay is adopted by sensing steady state neutral current or phase under-voltage.

5. A Design Example and Recommended Configurations

Figure 4 (a) shows a sample layout to achieve effective grounding in a PV plant with multiple inverters. The grounding bank can be either a zig-zag or a delta-wye grounding transformer. The main circuit breaker should be rated for the PV plant generation in addition to the steady state zero sequence current resulting from feeder voltage imbalance. When a grid fault is applied, either the main circuit breaker or the grounding bank circuit breaker will trip. If the grounding bank circuit breaker trips first, the auxiliary contact will trip the main circuit breaker using an interlock protection. For the design of the grounding bank, Solectria Effective Grounding Design Tool is used as shown in Figure 4 (b).



(a) Layout of PV plant with the grounding bank

Source voltage (V_S) for fault calculations in pu		1							
Voltage at Inverter POI (V_{INV}) in kV		13.2							
Solectria Inverter model		SGI 500							
Number of inverters		2							
Effective grounding criterion		X_0 pu	0.6			(OR)			
		X_0/X_1							
% Voltage imbalance (%$V_{imbalance}$)						(OR)			
% Zero Sequence Voltage		4							
Grounding Device Option		Grounding Transformer							
Line Impedance of Distribution Feeder	Positive Sequence in pu (Z_{L1})	R_{L1}	0.1	X_{L1}	0.2	MVA base	10	kV base	13.2
	Negative Sequence in pu (Z_{L2})	R_{L2}	0.1	X_{L2}	0.2				
	Zero Sequence in pu (Z_{L0})	R_{L0}	0.2	X_{L0}	0.5				
MV transformer leakage impedance (Z_{MV_XFMR})		0.05				MVA	1	X/R	5

RESET CALCULATE

Grounding Reactor Impedance (X_{GR})	N/A	Ohms
Grounding Transformer Leakage impedance (X_{GXFMR})	104.544	Ohms
Imbalance Ground current ($I_{imbalance}$)	8.75	A
Grid Ground Fault current (I_{f_GRID})	106.86	A
Inverter(s) Ground Fault current (I_{f_INV})	2.87	A
System Voltage Used for calculations at POI	13.2	kV

(b) A sample calculation chart using Solectria Effective Grounding Design tool

Figure 4. A Simple Effectively Grounded PV Plant

The upper part of the table in Figure 4 (b) is expected to be filled by the user with utility specific design requirements and site plans. For this example, two units of 480V 500kW rated SGI 500 inverters are connected to 13.2kV feeder through a medium voltage transformer. Effective ground impedance requirements, feeder imbalance constraint and feeder line impedance are consistent with the previous sections and Figure 1. As the grounding bank is connected at the primary side of the medium voltage transformer, POI voltage is 13.2kV. The lower part of the table shows calculation results which can be used for grounding bank design. All currents in the table are neutral conductor currents. Hence these values should be divided by three to estimate the phase currents especially for grounding transformer sizing. The following is summary of the calculation results:

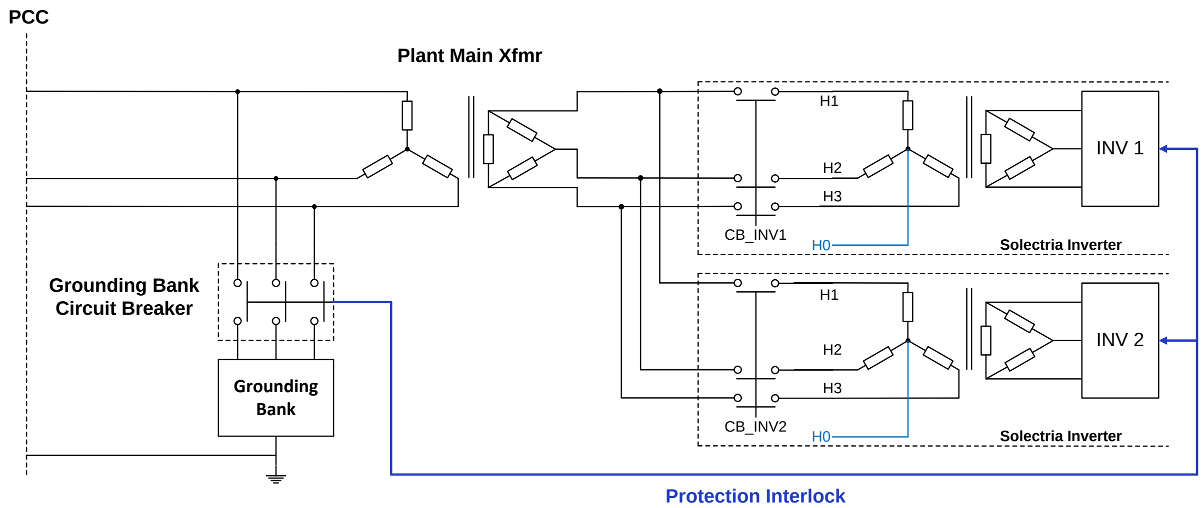
1) The required grounding transformer impedance is about 105 ohms +/- 10%
2) The neutral current due to feeder voltage imbalance is 8.75A. The phase current will be 8.75A/3 =2.91, which will be the minimum current rating of the grounding bank
3) The fault neutral current due to inverters is 2.87A, which can be ignored.
4) The fault current from the grid is 107A. Applying 50% additional margin gives 160.5A. For the phase quantity, it is 53.5A.

The following is the design guide used by IEEE p1547.8 recommended practice to design the grounding bank and associated protection.

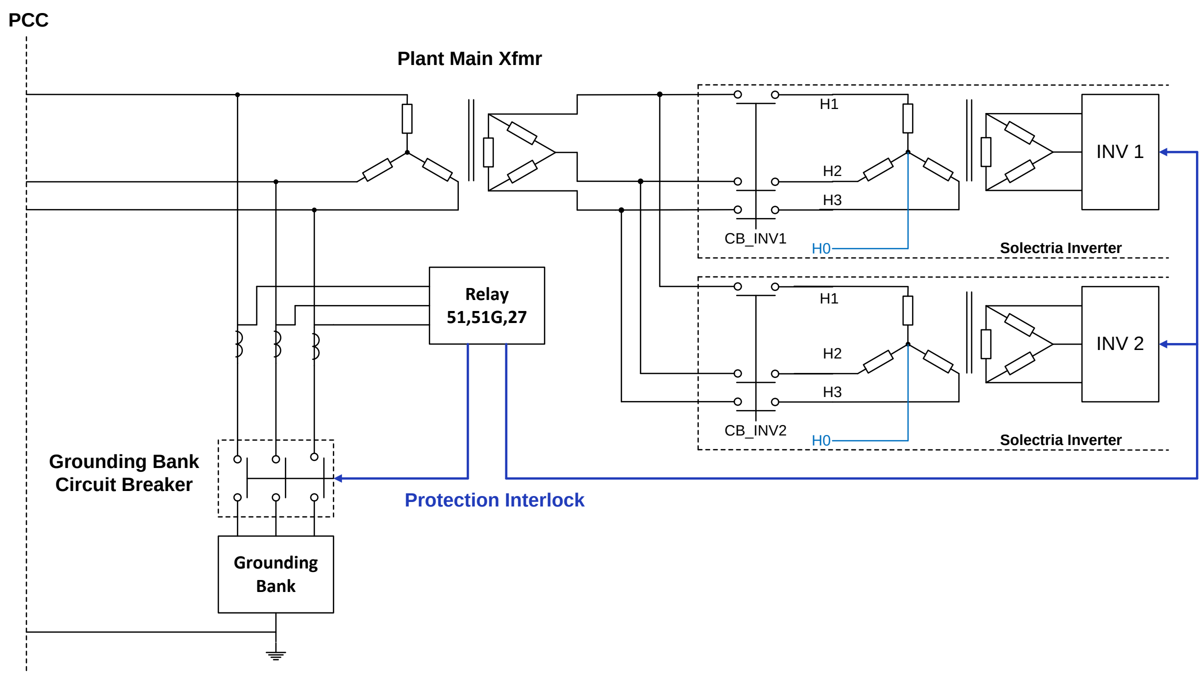
1) As shown in the xls table of Figure 4, the grounding impedance should be 105 ohms.
2) Consider a grounding transformer using 3 x 30kVA standard distribution transformers in a wye-grounded to delta configuration. The full load current will be 30kVA/(13.2kV/$\sqrt{3}$) = 3.93A. Compared with the minimum current rating of 2.91A obtained from the above calculation, it has 35% margin in the current rating.
3) If %Z of the transformer is 5%, the short-circuit current would be 100/5 x 3.93 = 78.7A. At 7.62kV (13.2kV/$\sqrt{3}$), this would give 7.62kV/78.7A = 96.8 ohms for the grounding bank impedance, which is lower than the calculated value. With 5.5%.,the short circuit current will be 100/5.5 x 3.93A = 71.64A. At 7.62kV, this grounding impedance is 7.62kV/71.64A = 106.3 ohms, which is close enough to the impedance requirement.
4) The current flowing in the neutral of the grounding bank is 8.75A, which is $3I_0$. This will be the value of current that would flow if V_0 reached 5.5% of nominal. Set this as the minimum pickup setting for the circuit breaker, which will provide protection against steady state V_0.
5) The calculated fault current from the grid with 50% margin is 160.5A. So, the phase current will be 53.5A, which is about 14pu.
6) Select a circuit breaker and verify that the protection device can be coordinated with the minimum pick up and fault currents with appropriate time delays.
7) In this example, the main circuit breaker should be interlocked with the grounding bank so that inverters are guaranteed to be disabled when the grounding bank circuit breaker is open.

Figure 5 shows a few of possible cases with the floating wye to delta transformer configuration. If there is no separate circuit breaker, the auxiliary contact in the grounding bank circuit breakers can be interlocked to disable the individual inverters. Solectria inverters provide a dry contact that can be used to disconnect from the grid instantaneously.

For more robust and accurate protection, a protective relay can be used especially for large PV plants as shown in Figure 5 (b). With the actual current and voltage measurements, this setup can detect any inadvertent operation of the grounding bank and disable the ground bank and PV inverters.



(a) Effective Grounding and Protection using one circuit breaker



(b) Effective Grounding and protection using a protective relay

Figure 5. Possible effective grounding configurations

Table 1 lists the calculated results of grounding bank design parameters to be used to meet the effective grounding using Solectria inverter models. The table uses 4% zero sequence voltage in order to calculate the ground current resulting from voltage imbalance. The grounding transformer capacity refers to the phase current capacity whereas the grounding reactor capacity refers to the neutral current capacity.

Model	capacity (kVA)	Voltage (Vrms)	Neutral current continuous rating for V0 = 4% (Arms)	Neutral current rating for ground faults (Arms)	Ground Transformer X_{GB} +/- 10% (ohms)	Ground Reactor* X_{GB} +/- 10% (ohms)	Max. Grounding Resistance R_{GB} (ohms)
PVI14 TL	14	208	7.77	159	1.854	NA	0.464
PVI20 TL	20	480	4.81	98	6.912	NA	1.728
PVI23 TL	23	480	5.53	113	6.010	NA	1.500
PVI28 TL	28	480	6.74	138	4.940	NA	1.260
PVI36 TL	36	480	8.70	178	3.84	NA	0.96
PVI50	50	480	12.03	245	2.765	0.876	0.691
	50	208	27.76	566	0.519	0.164	0.130
PVI60	60	480	14.43	294	2.304	0.730	0.576
	60	208	33.31	678	0.433	0.137	0.108
PVI75	75	480	18.04	367	1.843	0.584	0.461
	75	208	41.64	846	0.346	0.110	0.087
PVI85	85	480	20.45	415	1.626	0.515	0.407
	85	208	47.19	958	0.305	0.097	0.076
PVI100	100	480	24.06	487	1.382	0.438	0.346
	100	208	55.51	1125	0.260	0.082	0.065
SGI225	225	480	54.13	1081	0.614	0.195	0.154
SGI250	250	480	60.14	1198	0.553	0.175	0.138
SGI266	266	480	63.99	1272	0.520	0.165	0.13
SGI300	300	480	72.17	1429	0.461	0.146	0.115
SGI500, 500XT and 500XTM	500	480	120.28	2328	0.277	0.088	0.069
SGI750XTM	750	480	180.45	3396	0.184	0.058	0.046
2 x SGI 500XTM	1000	480	240.64	4409	0.138	0.088	0.035**
3 x SGI 500XTM	1500	480	360.70	6278	0.092	0.088	0.023**
4 x SGI 500XTM	2000	480	481.28	7968	0.069	0.088	0.017**
5 x SGI 500XTM	2500	480	601.38	9502	0.055	0.088	0.014**
6 x SGI 500XTM	3000	480	721.40	10900	0.046	0.088	0.012**

* Application of neutral reactors is based on installation of the neutral at each inerter on utility side of inverter interface transformers that are connected delta on inverter side and grounded wye on utility side. If placed at a plant transformer, this sizing guide cannot be used. Ratings for iron core reactors must provide for fault and continuous ratings without saturation.

** The maximum grounding resistance is based on the effective grounding with a grounding transformer.

Table 1 Grounding equipment Sizing of Solectria Inverters

6. Conclusion

The grounding bank design guideline has been detailed in this document with an example. Given Below is a summary of the effective grounding guideline discussed hitherto:

- The grounding bank design should be compliant to the latest National Electrical Code.
- Grounding bank is generally designed using a grounding transformer. If an interface transformer with grounded wye to delta configuration is available as is the case with Figure 5, a grounding reactor can be connected at the neutral point of the plant main transformer wye side and provide the utility side reference. In this case, the plant main transformer should be rated to accommodate the additional neutral current that the grounding reactor will draw.
- When an iron core type ground reactor is used, fault current saturation should be avoided.
- Usually the grounding bank is rated for short term duty and overcurrent protection is required.
- When the grounding bank is disconnected from the feeder due to overcurrent or inadvertently, the PV inverter should be disabled simultaneously to meet the effective grounding requirement.
- Use of the sizing criteria can be applied to systems where aggregate inverter ratings can be accommodated with the use of a single grounding transformer. (i.e., use specifications of a 500kVA inverter where 5 x 100kW inverter are planned or a multiple string inverters)

7. References

- IEEE Std 142-2007, IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems.
- P1547.8™/D8 Draft Recommended Practice for Establishing Methods and Procedures that Provide Supplemental Support for Implementation Strategies for Expanded Use of IEEE Standard 1547
- IEEE Std C62.92.1-2000, IEEE Guide for the Application of Neutral Grounding in Electrical Utility Systems – Part I: Introduction.
- IEEE Std C62.92.4-2000, IEEE Guide for the Application of Neutral Grounding in Electrical Utility Systems – Part IV: Distribution.
- IEEE Std 32-1972, IEEE Standard Requirements, Terminology, and Test Procedure for Neutral Grounding Devices