Connecting Multiple Sunny Boy Inverters to a Three Phase Utility

Technical Note

Revision 1.5

February 15, 2002
Kent Sheldon

SMA America
20830 Red Dog Road
Grass Valley, CA 95945
530.273.4895

Table of Contents

Abstract

Sunny Boy string inverters are used throughout the world for all sizes of grid tied photovoltaic (PV) installations. Large installations within the United States have historically used central inverters. The interconnection difference between these two approaches is a trade-off between AC or DC circuit collection.

Introduction

This document does not attempt to detail all the National Electrical Code (NEC) or local codes applicable to photovoltaic installations. All of the requirements of the NEC, including those found in Article 690-Solar Photovoltaic Systems, should be followed. These guidelines will include some of those requirements, but by no means all of them. Local electrical and building codes should also be followed and they may dictate additional requirements not found in these guidelines or the NEC.

Connecting a large number of string inverter AC outputs to a utility system is much simpler than combining a similar number of PV DC circuits for connection to a central inverter. Interfacing a central inverter with a large PV array requires a specially designed DC collection center. It must be rated for 600Vdc (in the US), contain over-current protection for each individual PV string circuit, and bus work for the single output circuit to the central inverter. The PV disconnect device required by NEC Article 690 must be load-break rated for 156% of the combined PV array short-circuit current. These large collection centers are typically custom built, very expensive and will not be listed to UL1741. The components necessary for connecting multiple AC inverter outputs to a utility system are readily available, less expensive than similar DC rated components, simple to install, comply with UL and NEC requirements, and are familiar to electricians and inspectors.

Three-phase utility systems are discussed through this document. Typically, PV installations involving more than 10kW will be connected to a three-phase distribution system. However, this document may also be applied to single or split-phase distribution systems as needed.

Dedicated Inverter AC Sub-Panel

The simplest solution to connecting multiple inverter AC outputs to a single point of utility connection is frequently an AC sub-panel dedicated to the PV power system (refer to the single line drawing at end of this document). This sub-panel may be installed near the PV inverters to minimize the distance of the multiple AC wire runs. All components are readily available and simple to install.

Care should be taken to balance the inverters around the three phases of the distribution system. Loading individual inverter output breakers from the top of the panel will minimize the current path through the panel bus bars, while insuring the inverter outputs are balanced around the three phase system. If inverters with various AC output current ratings are combined, install the inverters with the greatest output currents above inverters with lesser output currents. This will minimize the high current path to the main conductors. If any load breakers are installed in the dedicated sub-panel, position them below the inverter breakers.

Connect the output of the sub-panel to the main utility distribution panel with the proper type and size wire for the installation. The main utility distribution panel requires a main circuit breaker properly sized for the combined maximum output current of all the string inverters. NEC Section 690.64(B)(2) dictates: 'The sum of the ampere ratings of overcurrent devices in circuits supplying power to a busbar or conductor shall not exceed the rating of the busbar or conductor.' Therefore the sub-panel bus bars must be rated to carry the combined currents of the main panel breaker as well as the sum of all the individual breakers within the panel.

NEC Requirement Overview

AC Over-Current Protection

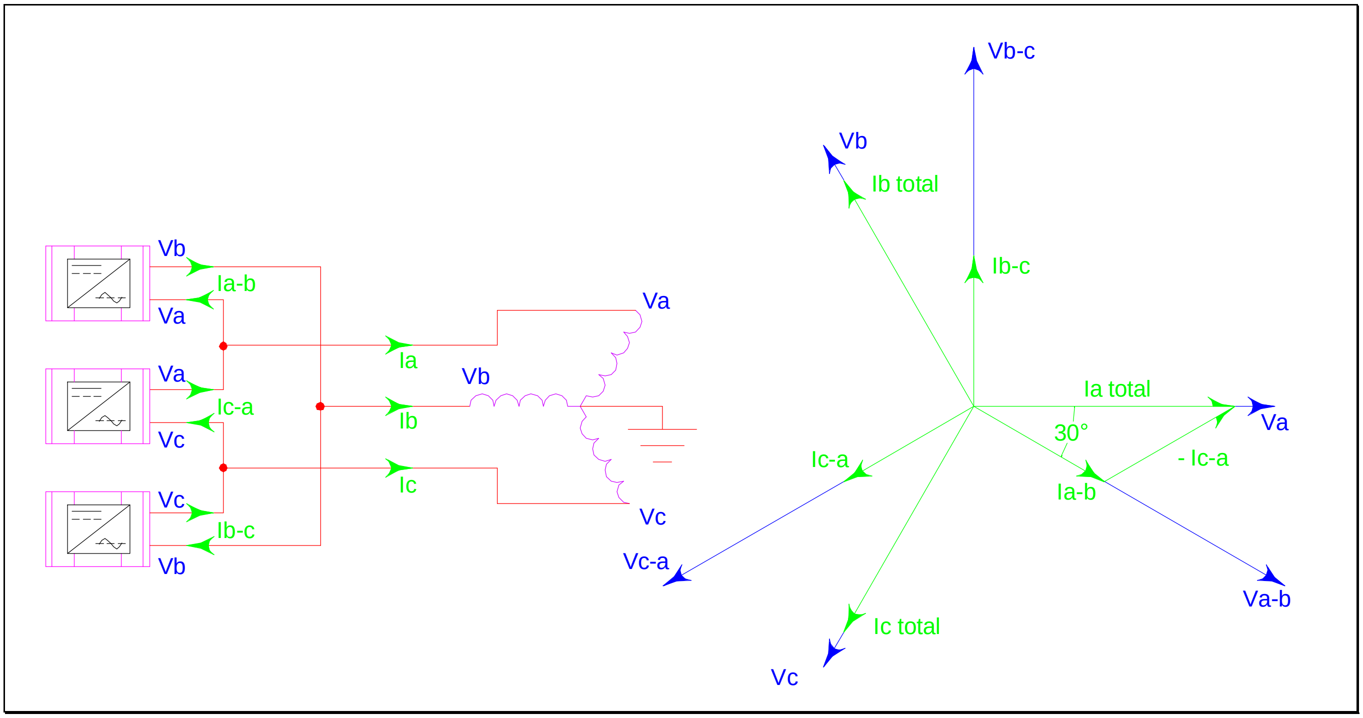
NEC Section 690.9(A) requires each inverter to have individual AC over-current protection. This may be satisfied with a 15A two-pole circuit breaker or fuses installed in both line conductors of the inverter. Circuit breakers should be rated for bi-directional operation. Fuses are typically Class R dual element type, but other types may be used if rated for the application. NEC Section 690.8(B) specifies the over-current protection should be rated at not less than 125% the rated current of the inverter calculated in NEC Section 690.8(B)(3) in accordance with NEC Section 240.3(B) & (C). The Sunny Boy 2500 inverter is AC current limited at 10.4 Amps, so it is not necessary to consider the short circuit current PV array when sizing the AC over-current protection.

Below is an example for sizing the AC protection for one SB2500:

Calculate Protection for One Sunny Boy 2500 Inverter

$10.4 \times 1.25 = 13A$ Use a two-pole 15A breker for each SB2500 inverter

To calculate the size of the three-phase dedicated panel breaker, the single-phase currents must be calculated. To calculate the total phase currents for three Sunny Boy inverters installed around a three phase utility, consider the following diagram:



Calculate the A phase current

From the diagram

$$Ia = Iab - Ica$$

From the phasor diagram

$$Ia_{total} = 2Iab\cos(30)$$

$$or\ Ia_{total} = \sqrt{3}Iab$$

Assuming all inverters can generate equal current, the peak currents on each phase will be

$$10.4 \times \sqrt{3} = 18 \text{ Amps}$$

To calculate phase currents for 9 inverters, 3 across each phase to phase connection

$$3 \times 18 = 54 \text{ Amps per phase}$$

Per NEC690.8(A)

$$54 \times 1.25 = 67.5A$$

NEC 240-3(b) states to use the next standard size protection device, which in this case is an 70A Circuit Breaker from NEC 240.6(A)

From NEC Section 690.64(B)(2): Adding the ampere ratings of all of the circuit breakers per phase in the above example results in a total of 160 amperes [(6 x 15) + 70] of overcurrent protection on the dedicated AC sub-panel. Only six two-pole 15 amp breakers are connected to any one phase, plus the 70 amp main breaker. The NEC requires a 200 Amp load center to be used for this installation.

AC Wire Sizing

The current rating of the AC wiring should be greater than the protection devices in the circuit to insure the over-current device clears before any of the current-carrying components fail during an over-current condition. Considerations should also be made for the wire insulation type, insulation temperature rating, conduit type, and ambient temperature that the wire will experience (within the conduit). This is dependent upon the conditions of the installation. Consider the following example continued from above:

Minimum ampacity requirement : 70 Amps (from breaker rating)

Direct burial or raceway installation, insulation type : THHW, 75°C

Calculate necessary current rating with 50°C temperature derating :

From NEC Table 310-16 correction factors :

$$\frac{54A}{0.75cf} = 72A$$

The wire current rating must be greater than calculated and greater than the current rating of the AC protection device (60A). From NEC Table 310-16, copper wire, 75°C, THHW insulation : Use minimum 4 AWG, rated at 85 Amps. This will also satisfy the main breaker rating.

AC Disconnect

NEC Section 690-14 references Section 230.70 which requires all service entrance conductors be provided with a means to be disconnected from the building or structure. NEC Section 690.17 allows the AC circuit breaker to serve as the over-current protection device as well as the means of AC disconnect. However, many local utilities and electrical inspectors require a ‘Hevi-Duty’ lockable disconnect switch for isolation during system service or maintenance. For multiple inverter installations, only one AC disconnect switch is necessary for all of the inverters. Some utilities require only one AC disconnect for all generation equipment installed at the site. If there is a dedicated AC distribution panel, the disconnect switch may be placed between the dedicated AC sub-panel and the main building distribution panel. NEC Section 230.70 does not specify proximity of the disconnect switch to the PV system, but local inspectors generally require the switch to be placed near the inverters. The switch should have a current rating greater than the ratings of the over-current protection devices in the circuit. From the example above, a three-phase 60 or 100 Amp disconnect switch may be used. Individual inverter AC isolation may be achieved by the 15 Amp, 2-pole circuit breakers located in the dedicated AC distribution sub-panel.

DC Protection

NEC 690.8(B)(2) requires that the PV output source circuit conductors be sized for 156% of the short-circuit current rating of the PV array. For one or two PV strings per inverter, the PV conductors will be large enough not to require any DC protection between the PV array strings and the inverter. In the event of a ground fault at any point in the PV wiring, the string conductors are large enough to handle the full current capacity of the PV array. Fuse protection may be required for more than two PV source circuits per inverter if the circuit and module conductors are not able to carry 156% the short circuit rating of the entire PV array. In this case a fuse rated for 156% of the string short circuit current rating is required between each PV string circuit and the inverter.

DC Disconnect

NEC Section 690.15 requires a means to disable all ungrounded conductors of all sources. Local utilities and inspectors generally require a PV disconnect switch between the inverter and the PV array. The switch must be DC load-break rated for the maximum voltage of the PV array (600Vdc maximum for Sunny Boy 2500 installations), as well as 1.56% of the short-circuit current rating of the PV array. Many disconnect switches require the DC conductor be series through 2 or more poles of the switch for DC applications. NEC Section 690.13 does not allow the grounded conductor to be disconnected unless there is a fault condition. Most PV arrays installed in the United States ground the negative conductor. To satisfy NEC Section 690.13, the negative conductor will pass through the DC disconnect enclosure without being switched, just the positive conductor will pass through the switch poles.

Design Considerations

When planning a large PV installation using string inverters, consider the following:

Utility Interconnection Requirements

Consult with the local utility to understand any specific requirements for interconnecting a PV system to their distribution system. Large PV systems may have unique requirements depending on the existing distribution network. Utility companies may also have an application process that must be completed prior to interconnection.

Local Inspector Requirements

Consult with local building and electrical inspectors, as well as the local utility to understand requirements that may be unique to the installation or service area. For instance: NEC Section 690.17 allows the AC circuit breaker to serve as the over-current protection device as well as the means of AC disconnect. However, many local utilities and electrical inspectors require a ‘Hevi-Duty’ lockable disconnect switch.

Distance From Inverter to AC Sub-panel and PV Array

Long wire runs may require over-sizing of conductors to compensate for voltage drop. Voltage drop is caused by the resistance in the conductors; the smaller the conductor, the larger the resistance. Current passing through the conductor will create voltage per the simple V=IR relationship. As current increases, voltage linearly increases as the resistance is essentially fixed (resistance changes as a function of temperature, but consider it to be fixed at 75°C as assumed by NEC Table 9). The NEC allows for 3% drop on any conductor. Not only is this analogous to a 3% efficiency loss, but it also creates a 3% rise in voltage as the generation device delivers current to the utility. For equipment installed on utility systems with high line voltage, or widely varying voltage, generation equipment may frequently disconnect due to perceived utility over-voltage faults. For this reason it is critical to minimize the AC voltage drop more so than on the DC side. Voltage drop on the DC side will result in efficiency loss; however, this will not cause the inverter to function improperly. We recommend all conductors be sized for less than 1.5% voltage drop. Refer to NEC Chapter 9, Table 9 for information on conductor impedances.

Frequently, actual voltage rise in a distribution system will be greater than calculated due to poor or numerous wiring connections. Always use a minimum amount of quality fastening systems. SMA does not recommend using wire nuts for splicing wires. They are commonly installed improperly and are a notorious cause of high impedance connections.

Consider the following example:

8AWG copper conductor in steel conduit, 1500' wire run (from NEC Chapter 9 - Table 9)

$$Z_e = R \times PF + X_L \sin[\cos^{-1}(PF)]$$

$$Z_e = R, \text{ since PF} = 1$$

$$Z_e = 0.78\Omega \text{ per } 1000', \text{ or } 1.17\Omega \text{ for } 1500'$$

assume: $\mathrm{V_{nominal}} = 250\mathrm{Vac}$ (high line voltage)

Maximum AC current for Sunny Boy 2500 = 10.4A

$$V_{drop} = IR$$

$$V_{drop} = 10.4 \times 1.17 = 12.2$$

Apparent voltage seen at inverter terminals:

$$V_{\mathrm{terminal}} = V_{\mathrm{drop}} + V_{\mathrm{nominal}}$$

$$V_{\mathrm{terminal}} = 12.2 + 250 = 262.2$$

Even though 8AWG wire is capable of carrying the 10 amps of current from the inverter, the wire impedance and run distance will cause significant voltage increase during full inverter output current. The upper voltage limit of the Sunny Boy 2500 is 264V. This inverter will most likely experience frequent utility voltage faults. To minimize the voltage drop, simply increase the wire gauge one or two sizes. Installing 6AWG wire reduces the resistance to 0.49 Ohms per 1000 feet. In this example, 6AWG wire will lower the voltage drop to 7.6Vac, which will help to minimize utility voltage faults.

Another thing to consider is power loss caused by conductor impedance. Continuing with the example from above:

$$W = I^2 R$$

$$W = 10.4^2 \times 1.17$$

$$W = 126$$

This loss equates to about 0.5% of total power output of the system. Similar calculations should be done for the DC conductors. SMA recommends the inverter be located near the PV panels, but some installations may require long DC wire runs.

Termination Techniques

Each inverter should have a dedicated AC wire run to a dedicated circuit breaker. Do not parallel inverters prior to main feed to the utility sub-panel. All connections should be high quality bonds from mechanical devices or crimp devices such as mechanical compression fittings found in circuit breakers or compression lugs for connection to solid bus bar. Do not place multiple wires into any single connection device. Poor quality or improperly installed conductor splicing devices (wire nuts, split nuts, butt connectors, etc.) may create a high impedance bond. This can lead to excessive heating, causing voltage drop and system losses. Extended operation could lead to arcing and fire. Be sure all termination devices are properly installed and meet the environmental requirements for the device.

Some breakers and terminal blocks are listed for use with more than one conductor per contact. These devices will be clearly marked for this application.

AC Point of Interconnection

Photovoltaic inverters may be connected to the AC distribution system on either the load or supply side of the service disconnecting means. NEC Section 230.82 exception 6 specifically allows PV systems to be tied to the supply side; however, protection and disconnecting equipment must be suitable for use as service equipment. NEC Section 690.64(B) explains the requirements for interconnection on the load side of the service disconnecting means. Each inverter must have a dedicated circuit breaker of fusible disconnecting means. Also, the sum of all overcurrent devices is not allowed to exceed the rating of the service busbar or conductor (load center).

Installing One Inverter on a Three Phase System

Installing one inverter on a three-phase system is quite simple. The inverter may be installed across any two phases that supply 240 or 208Vac (a software retrofit is required to configure the Sunny Boy inverters to operate properly at 208Vac). Sunny Boy inverters are equipped with an internal isolation transformer, which allows connection with any configuration of grounded or floated utility distribution system.

Balancing Inverters on a Three Phase System

Sunny Boy inverters generate line-to-line current, and may be connected to three-phase WYE or delta utility services. The line-to-line connection eliminates imbalanced neutral currents caused by single-phase inverters connected to the AC neutral. Furthermore, the Sunny Boy active island detection will shut down the inverter in the event of significant phase imbalance.

Care should be taken to evenly balance the total number of inverters around the distribution system. This will insure that all system distribution conductors carry an equivalent amount of current. It also insures that no single-phase experiences an excessive voltage imbalance caused by high current on any one phase. It is not necessary to install multiples of three inverters on three phase systems. For Sunny Boy installations there should never be more than 2.5kW of imbalance on properly designed systems. Using a dedicated AC distribution panel described above will simplify balancing multiple inverter installations.

Delta or WYE Utility Interconnection

Sunny Boy inverters may be connected to a grounded or ungrounded delta or WYE utility distribution system. The output of the Sunny Boy inverter is single-phase 240 or 208Vac. The PE connection within the inverter is the point of PV conductor grounding. There is no AC center ground from the inverter to create a 120Vac single-phase reference. Therefore, multiple inverter installations are connected to the utility system phase-to-phase, in a delta manner, regardless of the existing utility configuration. Multiple inverters may be connected to either a grounded or floating WYE system in a phase-to-phase manner. There will be no connection between the inverters and the neutral ground of a WYE or grounded delta system.

Isolation Transformers

Each Sunny Boy inverter is equipped with an internal isolation transformer. This isolates the AC utility system from the inverter and the PV system. This also allows a grounded PV array to be used with a ground referenced AC distribution system. The only case where a transformer may be required is when the available AC voltage is not 240 or 208Vac. The Sunny Boy inverter family requires 240 or 208Vac utility connection (a software retrofit is required to configure the Sunny Boy inverters to operate properly at 208Vac). If for instance, the only available utility voltage is 480Vac, a transformer is necessary to step down the utility voltage to 240Vac to match the required inverter input voltage. It is not necessary to use an isolation transformer for this purpose. An auto-transformer will also work and provide slightly better efficiency. If a three-phase transformer is being considered, any winding configuration may be used. Single-phase transformers on each inverter may also be used.

Check with the utility of jurisdiction regarding the transformer being considered. Some utility companies have specific requirements regarding the type and configuration of transformers installed on their distribution systems. When transformers are added, be sure to reference NEC Article 450 and Section 690.9(B) for appropriate code requirements.

PV Array Conductor Grounding

NEC Section 690.41 & 42 requires the PV array be electrically grounded at any single point on the PV output circuit. In the Sunny Boy inverter family, this is accomplished within the inverter enclosure. The PV array negative conductor is connected to the PE terminal on the AC interface terminal block. No other PV conductor ground may be made for the ground fault detection circuitry to function properly.

A ground bond is required between the PE terminal within the inverter enclosure and the system earth ground. This may be a conductor from PE to the building neutral bus. This ground conductor may not be smaller than the PV circuit conductor (see NEC Section 250.166).

In the event of a PV array ground fault, current will flow through the PV negative ground connection within the inverter and clear a 1 Amp fuse (GFDI fuse) in series with the ground connection. The inverter will shut down and report the GFDI fuse is open. The inverter will not attempt to restart until the ground fault has been corrected and the GFDI fuse replaced.

Equipment Grounding

All equipment ground conductors in the PV system should bond to a single point of earth ground for the entire electrical system. This point is typically the earth ground rod located near the isolation transformer (the same point the WYE neutral conductor is grounded). This includes all PV frame grounds, equipment chassis grounds, conduit, etc. PV frame grounds may be earth grounded at the array, and should also be bonded to the single point of earth ground. Equipment grounding conductors should be sized as required by NEC Section 250.122 (as required by NEC Section 650.45).

Appendix

Drawings:

Three phase distribution system using multiple single phase inverters