Technical Bulletin:
Conductor and Overcurrent Device Sizing for CPS 600Vac, 100kW and 125kW Inverters

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1 DC System: Circuits Connected Inverter Input

The following analysis is provided by Brooks Engineering to review the wiring methods and overcurrent protection required for the CPS America 600Vac, 100 kW and 125 kW inverters developed for the U.S. market. Since both the 2017 and 2020 NEC is commonly used, the new 2020 NEC references are placed in brackets where different from the 2017 NEC.

1.1 Bundling of Single String Conductors for Inverter Input

The documentation from CPS indicates that the minimum size of the conductors for home run circuits from PV modules to the inverter is 12 American Wire Gauge (AWG). This is based on the minimum allowable size for the terminals in the inverter. This is a single MPPT inverter so all strings are fused and connected together at the inverter input. The 10 AWG copper conductor size will work on the CPS inverter provided the bundling limitations discussed later are followed. The 12 AWG copper conductor size will only work for special bundling conditions discussed later in this document. If the module short circuit current is rated at 12.8 amps (higher than the highest Isc PV module currently available on the market), then the maximum current is defined by NEC 690.8(A) as 16 amps. As long as the ampacity of the 12 AWG or the 10 AWG remains above 16 amps, either conductor size will work.

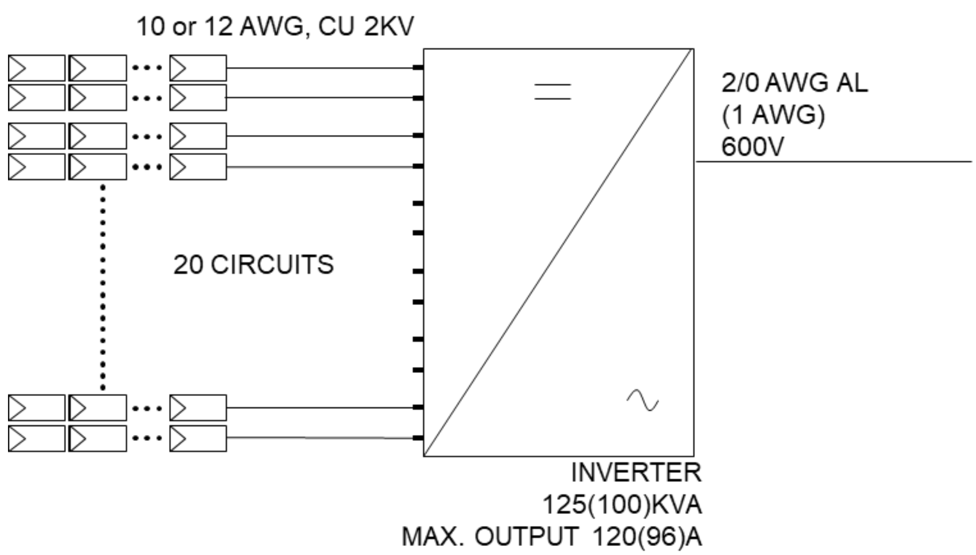

Figure 1.1. Configurations for One String per Input

Bundling limit of 10 AWG, 90°C PV Wire/Cable conductors run as single strings to inverter input is as follows:

Assume highest design temperature for desert locations in the United State is 50°C. Temperature correction factor for this condition is 0.82 according to Table 310.15(B)(2)(a) [Table 310.15(B)(1) in 2020 NEC]. The ampacity of 90°C cables similar to PV Wire/Cable (USE-2) is 40 amps according to Table 310.15(B)(16) [Table 310.16 in 2020 NEC] for 10 AWG copper cable. This results in an ampacity of 32.8 amps before the application of correction factors in Table 310.15(B)(2)(a) [Table 310.15(B)(1) in 2020 NEC]. If all conductors into the 100 kW or 125 kW inverter are run in the same bundle or raceway, the adjustment factor is 0.40 in Table 310.15(B)(3)(a) [Table 310.15(C)(1) in 2020 NEC]. Taking the quotient of (Isc*1.25)/32.8A = 0.40 yields a maximum Isc of 10.5A. This is the highest module Isc based on the worst-case allowable correction factor to maintain ampacity for the input to the CPS inverters. According to Table 310.15(B)(3)(a) [Table 310.15(C)(1) in 2020 NEC], this translates to allowing a bundle of conductors up to 40 conductors in a raceway or cable tray. This is the maximum number of conductors that either the 100 kW or 125 kW, 600Vac inverter allows. If the maximum of 40 conductors were to be installed on the 125 kW inverter, and there were two even bundles of 20 current carrying conductors each, then the maximum Isc increases to 13.1A which is higher than most crystalline silicon modules on the market. These two bundles would need to be separated by the diameter of the bundle. (example: one bundle is 1.25"—separate two bundles by 1.25"). This method is consistent with the direction provided by the note below Table 310.15(20) [Table 310.20, Note 2 in 2020 NEC] that is also referenced in NEC 392.80(A)(2)(d).

It is important that bundles of conductors supplying a specific inverter not be bundled with conductors that are supplying a different inverter. Also, dc conductors cannot be bundled with ac conductors as required by NEC 690.31(B)(2).

Bundling limit of 12 AWG, 90°C PV Wire/Cable conductors run as single strings to inverter input is as follows:

Assume highest design temperature for desert locations in the United State is 50°C. Temperature correction factor for this condition is 0.82 according to Table 310.15(B)(2)(a) [Table 310.15(B)(1) in 2020 NEC]. The ampacity of 90°C cables similar to PV Wire/Cable (USE-2) is 30 amps according to Table 310.15(B)(16) [Table 310.16 in 2020 NEC] for 12 AWG copper cable. This results in an ampacity of 24.6 amps before the application of correction factors in Table 310.15(B)(3)(a) [Table 310.15(C)(1) in 2020 NEC]. If all conductors into the 100 kW or 125 kW inverter are run in the same bundle or raceway, the adjustment factor is 0.40 in Table 310.15(B)(3)(a). Taking the quotient of (Isc*1.25)/24.6A = 0.40 yields a maximum Isc of 7.9A (less than most crystalline silicon modules on the market). This is the highest module Isc based on the worst-case allowable correction factor to maintain ampacity for the input to the CPS inverters. According to Table 310.15(B)(3)(a), this translates to allowing a bundle of conductors up to 40 conductors in a raceway or cable tray. This is the maximum number of conductors that either the 100 kW or 125 kW, 600Vac inverter allows. If the maximum of 40 conductors were to be installed on the 125 kW inverter, and there were two even bundles of 20 current carrying conductors each, then the maximum Isc increases to 9.8A which is higher than some crystalline silicon modules on the market. These two bundles would need to be separated by the diameter of the bundle. (example: one bundle is 1.25”—separate two bundles by 1.25”). This method is consistent with the direction provided by the note below Table 310.15(20) [Table 310.20, Note 2 in 2020 NEC] that is also referenced in NEC 392.80(A)(2)(d).

Since two bundles rules out many higher-powered modules on the market today, to include the available module products up to an Isc of 12.8A requires more bundling. Using the same equation above with a Max Isc of 12.8A yields a quotient of 0.65. This limits the maximum bundle to nine conductors according to Table 310.15(B)(3)(a) [Table 310.15(C)(1) in 2020 NEC]. Since conductors come in pairs, the maximum number of module strings per bundle is four (8 conductors), this corresponds to four bundles for the 100 kW inverter and five bundles for the 125 kW inverter. The drawbacks to using 12 AWG conductors are difficult to justify. This is the worst-case allowable correction factor to maintain ampacity for the input to the CPS inverters.

1.2 Bundling of Two String Conductors for Inverter Input

If the conductor is being used for the combined output of two strings, as with a Y-comb connector installation, then the conductor must have sufficient ampacity for the output of both strings. As the following assessment shows, two-string conductors for standard crystalline silicon modules must be fed into dual 15-amp or dual 20-amp fuses using the Y-comb connector in the distributed CPS wiring enclosure. For the application of the Y-comb connector, it is essential that fuses be installed in the cable assemblies going to each series string of crystalline silicon modules. These “fused Y-connectors” are available from several suppliers of cable assemblies. The inverter installation documentation needs to be very clear that these fused Y-connectors are essential to the safe operation of the PV array and for compliance with the NEC.

Since the starting ampacity of 10 AWG cables is 32.8A as established above, the question is whether a bundle of 10 AWG cables can carry the current of two strings in parallel into an inverter input. If all conductors into the 100 kW or 125 kW inverter are run in the same bundle or raceway (20 conductors), the adjustment factor is 0.50 in Table 310.15(B)(3)(a) [Table

310.15(C)(1) in 2020 NEC]. Taking the quotient of (Isc*1.25)/32.8A = 0.50 yields a maximum Isc of 13.1A. This is the highest module Isc based on the worst-case allowable correction factor to maintain ampacity for the input to the CPS inverters. According to Table 310.15(B)(3)(a) [Table 310.15(C)(1) in 2020 NEC], this translates to allowing a bundle of conductors up to 20 conductors in a raceway or cable tray. This is the maximum number of conductors that either the 100 kW or 125 kW, 600Vac inverter allows using the Y-comb connector.

Paralleling multiple series strings prior to any fuse

More strings could be connected to lower current modules such as cadmium-telluride products. When paralleling two strings prior to a fuse, the max series fuse rating of the module must be nearly four times the Isc of the module. Since this is only true of low-current modules such as cadmium-telluride products,

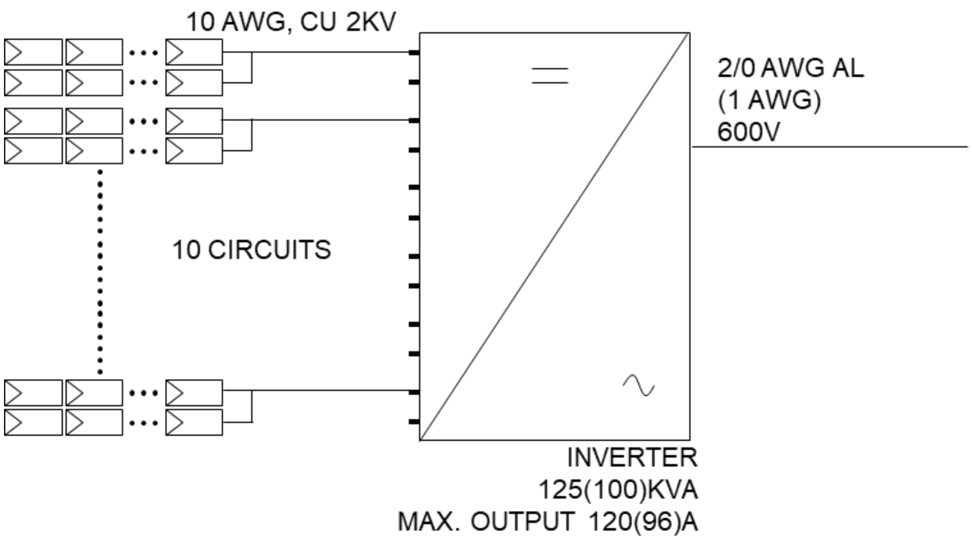

Figure 1.1. Configurations for Two-Strings per Input

Table 1 summarizes the results of the various configurations discussed.

Table 1: Maximum Number of Conductors in Raceway or Bundle in Cable Tray

Max Number of Copper PV Wire Cables in Raceways or Bundles in Cable Trays				
Number of Circuits	1 Circuit Per Fuse			2 Circuits Per Y
Conductor		10 AWG	12 AWG	10 AWG
Module Fuse Rating	Max Isc			
15A	9.6A	30	20	Any
20A	12.8A	Any	8	Any

2 AC System: Circuits Connected To Inverter Output

2.1 Circuits from Inverter to First Overcurrent Device

2.1.1 One inverter connected to one breaker/fuse

The option of connecting one inverter to a single breaker of fuse is the simplest case. The 100 kW and 125 kW inverters have maximum continuous current outputs of 96A and 120A respectively. Therefore, the ampacity of the conductor must be at least 96A or 120A, depending on inverter, after adjustment and correction factors are applied [690.8(B)]. Since these conductors are likely to be installed in bundles of various numbers of conductors, we must establish the minimum conductor size and work our way up based on the bundling.

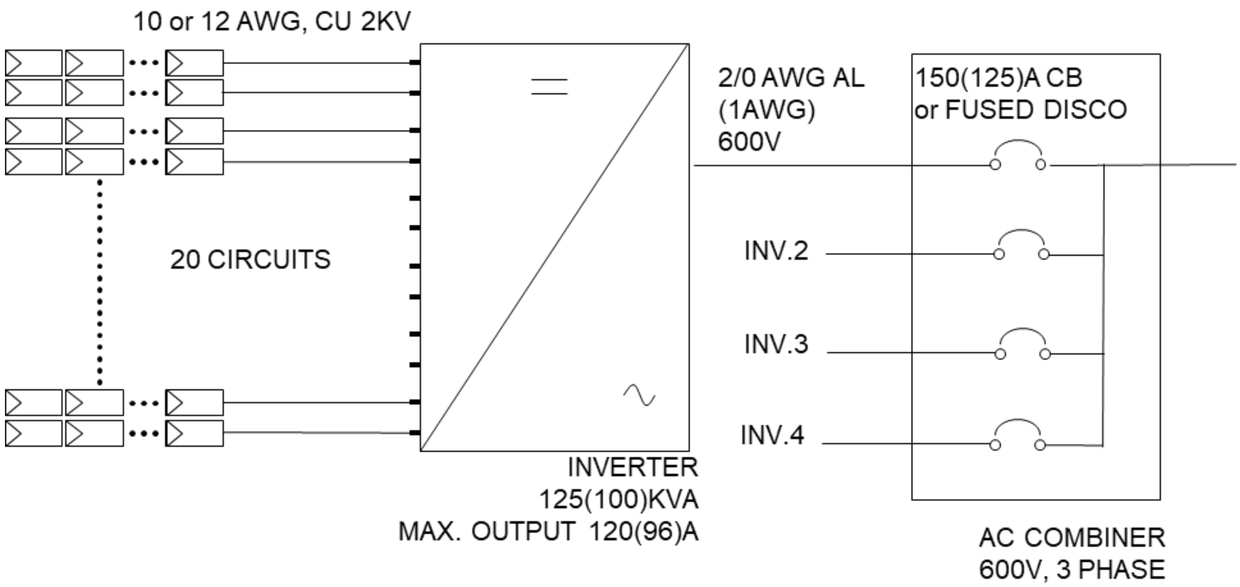

Figure 2.1.1. Configuration with One Inverter per Circuit Breaker or Fuse

The number of conductors in a triplex arrangement in a cable tray will provide for the highest ampacity in the NEC. Also, the availability of 600Vac fuses will dictate the overcurrent device size. In combination, the minimum conductor can be iterated.

<u>100 kW Inverter AC Output</u>

Since the smallest fuse that can be installed on a 96A continuous load is 125 amps [690.9(B)], this circuit breaker fuse will be chosen to determine the smallest allowable conductor size in a 50°C ambient air condition in a triplex cable installed in a ventilated cable tray with no cover. This arrangement allows the use of Table 310.15(B)(20) [Table 310.20 in 2020 NEC] ampacity and the Table 310.15(B)(2)(b) [Table 310.15(B)(2) in 2020 NEC]. correction factors (0.89 for 50°C). Also, the terminal temperature rating of 75°C may need to be observed which becomes the overall limiting factor. Using the 75°C column on Table 310.15(B)(20) to determine the maximum conductor temperature, 2 AWG aluminum or 4 AWG copper (copper expressed in parenthesis from this point onward) conductors meet the requirement. Next, we determine if 90°C rated cables still meet the ampacity requirement in a triplex arrangement in an uncovered cable tray. The ampacity of USE-2, similar in construction to most PV Wire, yields an ampacity of 123A at 40°C for 2 AWG aluminum and 117A at 40°C for 4 AWG copper. Applying the temperature correction factor of 0.89 from Table 310.15(B)(2)(b) yields an overall ampacity of 109A ($104A_{Cu}$)—sufficient for protection by a 125-amp rated fuse according to 240.4(B) but insufficient for the required ampacity of 120A required by the NEC [690.8(B)] (96A x 1.25 = 120A). Therefore, the next size conductor must be used in 50°C environments so that 1 AWG Al has an ampacity of 128A and 3 AWG copper an ampacity of 120A.

The above analysis for the 100 kW inverter is focused on the minimum size conductor based on the requirements of the NEC. In the case where a larger breaker or smaller conductor is desired as part of a listed assembly, other options may be possible. If the next size larger circuit breaker rated at 150-amps is to protect the inverter, larger wire is required for installations that connected directly to the transformer as the total overcurrent protection for the outdoor feeder is now 600-amps rather than 500-amps.

<u>125 kW Inverter AC Output</u>

Since the smallest circuit breaker or fuse that can be installed on a 120A continuous load is 150 amps [690.9(B)], this fuse will be chosen to determine the smallest allowable conductor size in a 50°C ambient air condition in a triplex cable installed in a ventilated cable tray with no cover. Using the 75°C column on Table 310.15(B)(20) [Table 310.20 in 2020 NEC] to determine the maximum conductor temperature, 1/0 AWG Al (1 AWG_{Cu}) conductors meet the requirement. Next, we determine if 90°C rated cables still meet the ampacity requirement in a triplex arrangement in an uncovered cable tray. The ampacity of USE-2, similar in construction to most PV Wire, yields an ampacity of 167A at 40°C for 1/0 AWG aluminum and 185A at 40°C for 1 AWG copper. Applying the temperature correction factor of 0.89 from Table 310.15(B)(2)(b) [Table 310.15(B)(1) in 2020 NEC] yields an overall ampacity of 149A ($165A_{Cu}$)—sufficient for protection by a 150-amp rated circuit breaker or fuse according to 240.4(B) but 1/0 Al just misses the required ampacity of 150A required by the NEC [690.8(B)] (120A x 1.25 = 150A). Therefore, the next size aluminum conductor must be used in 50°C environments so that 2/0 AWG Al has an ampacity of 172A and 1 AWG copper an ampacity of 165A.

The above analysis for the 125 kW inverter is focused on the minimum size conductor based on the requirements of the NEC. In the case where a larger breaker or smaller conductor is desired as part of a listed assembly, other options may be possible. If the next size larger circuit breaker rated at 175-amps is to protect the inverter, larger wire is required for installations that connected directly to the transformer as the total overcurrent protection for the outdoor feeder is now 700-amps rather than 600-amps.

Multiple Conductors in Raceway or Cable Tray

Now that the minimum size conductor is known for each inverter, the next questions to answer are what conductor size increases are necessary for other cable configurations. The minimum ampacity requirement, without adjustment and correction factors is 125% of continuous current as shown above [690.8(B)]. The only caveat to this requirement is if the overcurrent device is rated at 100%. There are other considerations, including the thermal impacts on overcurrent devices, that may require size increases for both conductors and overcurrent devices.

A much more limiting case than uncovered cable tray is for more than three current-carrying conductors to be installed in a raceway. If the conduit is installed above ground, a temperature correction factor is necessary [Table 310.15(B)(2)(a) or Table 310.15(B)(1) in 2020 NEC]. If the conduit is underground, except for distances less than 10' above ground, then the correction factors are unnecessary [310.15(A)(2) Exception].

100 kW Inverter Output Circuits in Raceway

Raceways limit the conductor ampacity to that of Table 310.15(B)(16) [Table 310.16 in 2020 NEC] which results in a conductor size of 2/0 AWG Al for 3 conductors in a raceway underground and for above ground at 50°C (150A x 0.82 = 123A > 120A). However, if two sets of conductors are run in the same raceway (6 current carrying conductors), then the minimum conductor size for underground installations stays the same at 2/0 AWG (150A x 0.8 = 120A = 120A) [Table 310.15(B)(3)(a) or Table 310.15(C)(1) in 2020 NEC]. If the conduit is above ground at 50°C, then the conductor must be increased to 4/0 AWG Al (205A x 0.8 x 0.82 = 134A > 120A). All these minimum sizes assume that a 125-amp breaker or fuse is used to protect the circuit. Additionally, it must be checked to see if the overcurrent device does not have the tendency to nuisance-trip when ambient temperatures reach 50°C. If larger overcurrent devices are required, then the conductor size should also be increased to match the protection of the larger device. For instance, if a 150-amp breaker or fuse is used, the minimum size conductor increases to 3/0 AWG Al for underground raceways with 3 conductors, but the 4/0 AWG Al is still okay for above ground raceways with 3 conductors since it is allowable to round to the next size overcurrent device from 134A without upsizing the wire in accordance with 240.4(B).

125 kW Inverter Output Circuits in Raceway

Raceways limit the conductor ampacity to that of Table 310.15(B)(16) [Table 310.16 in 2020 NEC] which results in a conductor size of 2/0 AWG Al for 3 conductors in a raceway underground and 4/0 AWG Al for above ground at 50°C (205A x 0.82 = 168A > 150A). However, if two sets of conductors are run in the same raceway (6 current carrying conductors), then the minimum conductor size for underground installations stays the same at 4/0 AWG Al (205A x 0.8=164A > 150A) [Table 310.15(B)(3)(a) or Table 310.15(C)(1) in 2020 NEC]. If the conduit is above ground at 50°C, then the conductor must be increased to 250 kcmil Al (230A x 0.8 x 0.82 = 151A > 150A). All these minimum sizes assume that a 150-amp breaker or fuse is used to protect the circuit. Additionally, it must be checked to see if the overcurrent device does not have the tendency to nuisance-trip when ambient temperatures reach 50°C. If larger overcurrent devices are required, then the conductor size may need to be increased to match the protection of the larger device. However in this instance, if a 175-amp breaker or fuse is used, 4/0 AWG Al is still okay (164A ampacity) for underground raceways with 3 conductors, and 250 kcmil Al is still okay for above ground raceways with 3 conductors since it is allowable to round to the next size overcurrent device from 164A or 151A respectively without upsizing the wire in accordance with 240.4(B).

2.1.2 New recommendations to connect two inverters to one breaker/fuse

The option of connecting two or more inverters to a single breaker or fuse is a more complex case than that of the single inverter. The NEC requires that conductors are protected from overcurrent at the source of the overcurrent unless the circuit complies with 240.21(B). The only other exception to conductors being protected in accordance with 240.21(A) is for the inverters to be listed with a specific cable assembly that has been tested to be protected by a specific overcurrent device size. It is possible that two or more inverters could be paralleled on a single overcurrent device with leads to each inverter that are far smaller than the trunk conductors. This is how microinverters are often configured. This evaluation will only consider the direct installation of inverter units using field wiring methods installed in accordance with the NEC. The CPS 600Vac, 100 and 125 kW inverters should be rated for connection to an overcurrent device provided that device has a trip time of less than 0.020 seconds (one cycle) and an available short circuit current of no greater than 20 kA. With these two parameters, any size 600Vac overcurrent device that can limit the impact to these two conditions is safe. Since the forward current of the inverter is limited, the fault current aspects of the overcurrent device are all that are necessary in an installation.

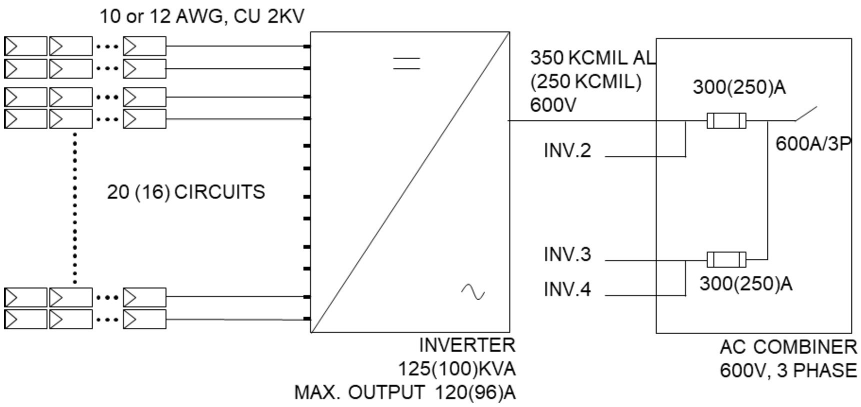

Figure 2.1.2. Configuration with Two Inverters per Circuit Breaker or Fuse

2.1.2.1 Two 100 kW Inverters Connected to a 250-Amp Device

Without a specific listing for a configuration of inverters, overcurrent device, and cable system, the following analysis shows conductor sizing that meets the NEC. With two inverters in parallel, the maximum circuit current is 192 amps. The minimum standard overcurrent device rating is 250-amps (192A x 1.25 = 240A < 250A Fuse). The minimum ampacity of a conductor connected to a 250-amp overcurrent device is 226A—just above the next smaller standard rating size of 225A [NEC 240.4(B)]. The smallest conductor permitted to be connected to a 250-amp overcurrent device is 4/0 aluminum in a triplex arrangement in an uncovered ventilated cable tray (262A x 0.89 = 233A; max for 75°C terminals is 224A > 192A, still okay). For an application using a raceway, the conductor must be increased to 350 kcmil aluminum for a 250-amp overcurrent device in either an underground or above ground installation (280A x 0.82 = 230 A > 226A).

2.1.2.2 Two 100 kW Inverters Connected to a 200-Amp 100% Rated Device

If the overcurrent device is 100% rated, this allows for a slightly smaller conductor to be used. Keep in mind that terminal temperature rating may ultimately limit the ampacity of the circuit. For 100% rated overcurrent devices using 90°C rated assemblies on both ends of the conductor, the minimum size overcurrent device is 200-amps. In this configuration, a 3/0 Al conductor is permitted when installed in a triplex arrangement in an uncovered cable tray. If the terminal temperature rating is reduced to 75°C, then the conductor size in this specific arrangement increases to 4/0 AWG Al.

The next condition to consider is a 100% rated assembly with 75°C terminals where the conductors are installed in a raceway with no more than 3 conductors. This condition requires 4/0 aluminum for underground conduit (205A). For above ground conduit, the size must be increases to 300 kcmil (260A x 0.82 = 213A >192A) based on the conductor ampacity according to Table 310.15(B)(16). If the output conductors of both inverters are run in the same raceway to the overcurrent device, then the conductor must be increased to 300 kcmil (260A x 0.8 = 208A > 192A) for underground conduit and 400 kcmil aluminum for above ground conduit (305A x 0.82 x 0.8 = 200A > 192A). While these are the minimum conductor sizes, larger sized conductors may be necessary for voltage drop or other thermal constraints.

Equipment Ratings Sidebar:

The temperature and capacity ratings of electrical distribution equipment is extremely important for the sizing of circuits within a PV system. Because of the elevated temperatures commonly experienced in outdoor enclosures, particularly those exposed to sunlight, the temperature ratings of the enclosure and devices in the enclosure directly impact circuit sizing. Most typical electrical terminations in the electrical industry are rated at 75°C. This is because the vast majority of electrical equipment is installed indoors in temperature-controlled environments. Moving outdoors to where most PV equipment is located, the ambient temperatures are generally much higher than indoors. For equipment to be certified as a unit for 90°C or higher, all the terminations related to the circuit must be rated at least 90°C or higher. For a circuit to use the 90°C column for ampacity in Article 310, the conductor and the terminations and enclosures at both ends of the circuit must be rated 90°C. Until recently, this has been a rare occurrence in the field.

Be aware that equipment manufacturers may claim that they use 90°C terminals throughout their equipment, but this claim may not be supported in their certification documentation. Ideally, the temperature ratings for all terminations should be placed on the listing label so there is no ambiguity on this subject. Code enforcers and independent engineers are often very aware of this shortcoming in equipment. It is best to be sure of the ratings rather than hoping that nobody checks them closely.

The other rating that can be helpful to reduce the required ampacity of the conductors is the duty rating of the equipment. Overcurrent devices are generally rated to operate continuously at 80% of their current rating (e.g. 100-amp circuit breaker can generally handle 80 amps continuously). However, many devices are now being rated at 100% duty so that a 200-amp circuit breaker would be permitted to operate at 200-amps continuously. However, there are a few very important distinctions that must be followed for a device to be operated continuously at full rating. The first is that the whole assembly that handles this circuit must be rated for 100% duty. The NEC states this in several places including 690.8(B)(1) Exception:

"Exception: Circuits containing an assembly, together with its overcurrent device(s), that is listed for continuous operation at 100 percent of its rating shall be permitted to be used at 100 percent of its rating."

If part of the equipment is rated for continuous operation at 100% and another part in the same circuit is rated at 80%, the circuit must be sized for the more restrictive 80% rating. Additionally, the thermal impacts of the operation at 100% must be considered for the design. Many thermal devices may be rated for continuous operation at 100% in an ambient temperature of 25°C or even 40°C, but when the circuit breaker or fuse reaches 50°C or 60°C, the unit will trip at 100% of its rating. This lack of consideration of thermal impacts on devices has caused several projects in recent years to have significant reliability issues due to tripping overcurrent devices below rated current. To restate this another way, many of these 100% overcurrent devices cannot be run at 100% of their rating at the elevated temperatures typical in most PV systems.

2.1.2.3 Two 125 kW Inverters Connected to a 300-Amp Device

Without a specific listing for a configuration of inverters, overcurrent device, and cable system, the following analysis shows conductor sizing that meets the NEC. With two inverters in parallel, the maximum circuit current is 240 amps. The minimum standard overcurrent device rating is 300-amps (240A x 1.25 = 300A = 300A fuse or breaker). The smallest conductor permitted to be connected to a 300-amp overcurrent device is 250 kcmil aluminum in a triplex arrangement in an uncovered ventilated cable tray (292A x 0.89 = 260A; max for 75°C terminals is 251A > 240A, still okay). For an application using a raceway, the conductor must be increased to 500 kcmil aluminum for a 300-amp overcurrent device in either an underground or above ground installation (350A x 0.82 = 287 A > 251A).

2.1.2.4 Two 125 kW Inverters Connected to a 250-Amp 100% Rated Device

If the overcurrent device is 100% rated, this allows for a slightly smaller conductor to be used. Keep in mind that terminal temperature rating may ultimately limit the ampacity of the circuit. For 100% rated overcurrent devices using 90°C rated assemblies on both ends of the conductor, the minimum size overcurrent device is 250-amps. In this configuration, a 4/0 Al conductor is permitted when installed in a triplex arrangement in an uncovered cable tray. If the terminal temperature rating is reduced to 75°C, then the conductor size in this specific arrangement increases to 250 kcmil Al.

The next condition to consider is a 100% rated assembly with 75°C terminals where the conductors are installed in a raceway with no more than 3 conductors. This condition requires 350 kcmil aluminum for underground conduit (250A @ 75°C). For above ground conduit, the size must be increases to 400 kcmil (305A x 0.82 = 250A > 240A) based on the conductor ampacity according to Table 310.15(B)(16). If the output conductors of both inverters are run in the same raceway to the overcurrent device, then the conductor must be increased to 400 kcmil (305A x 0.8 = 244A > 240A) for underground conduit and 600 kcmil aluminum for above ground conduit (385A x 0.82 x 0.8 = 253A > 240A). While these are the minimum conductor sizes, larger sized conductors may be necessary for voltage drop or other thermal constraints.

Table 2 summarizes the results of the various standard configurations discussed.

Table 2: Minimum Conductor Size for Inverter Output Circuits

Min Size of Al Conductors for AC Inverter Output Circuits to AC Combiner[1]				
	Number of Circuits	75°C Terminals		
	Wiring Method	Open Tray	Underground	Above Gnd
Circuit	Overcurrent Device			
1 100kW Inv	125A	1 AWG	2/0 AWG	4/0 AWG
1 125kW Inv	150A	2/0 AWG	2/0 AWG	4/0 AWG
2 100kW Inv[2]	250A	4/0 AWG	350 kcmil	350 kcmil
2 125kW Inv[2]	300A	250 kcmil	500 kcmil	500 kcmil
3 100kW Inv[3]	400A	1 AWG	2/0 AWG	4/0 AWG
3 125kW Inv[3]	450A	2/0 AWG	2/0 AWG	4/0 AWG
4 100kW Inv[3]	500A	1 AWG	2/0 AWG	4/0 AWG
4 125kW Inv[3]	600A	2/0 AWG	2/0 AWG	4/0 AWG

[1]Larger conductors may be necessary for long circuits and high temperature conditions.

[2]Requires inverters to be listed for the larger overcurrent device

[3]Requires conductors to be listed with inverter and overcurrent device

2.2 Circuits from First Overcurrent Device to Second Overcurrent Device or Transformer

2.2.1 Three 100 kW Inverters Connected to a Single 400-amp Device

The combined output of three 100 kW inverters can be run to a 400-amp fuse or circuit breaker. Even if the 300-amp circuit breaker is rated for 100% duty, and the current is less than 300-amps (288A), thermal limitations on the 300-amp thermal-magnetic breaker may require that the current through the breaker is reduced when the breaker ambient temperature exceeds 40°C. Most locations in the United States will reach or exceed this temperature inside the circuit breaker enclosure particularly if the enclosure is exposed to direct sunlight. Rather than attempting to run a 300-amp circuit breaker at full rating, it may be better to reduce the load on the breaker so that it would be permissible to use an 80% duty circuit breaker in this same application. The only reasonable way to fully utilize a 100%-rated device in a hot climate is to use fully electronic breakers that may not be readily available for this 600 Vac application. Fully electronic breakers do not have thermal elements that can be influenced by temperatures above 40°C.

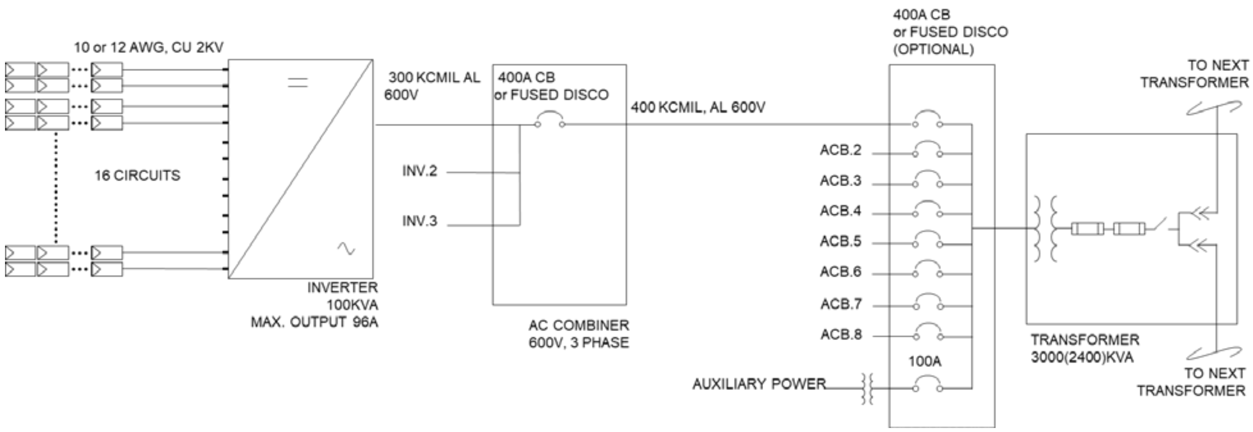

Figure 2.2.1. Configuration with Three Inverters to a 400A Fuse or Circuit Breaker

Due to the ability to round to the nearest higher standard rated overcurrent device [NEC 240.4(B)], the smallest conductor that a 400-amp circuit breaker can protect must have an ampacity of 351 amps (just above the next smaller standard size of 350-amps). A 360-amp conductor is permitted to carry the load of three 100 kW inverters (96A x 1.25 x 3 = 360A). If these conductors are installed in a triplex arrangement in cable tray, the smallest conductor permitted in a 50°C ambient design is 500 kcmil aluminum (458A x 0.89 = 408A > 360A). This smallest conductor assumes that the assembly is rated for 75°C, and is 80% rated, and is based on NEC 392.80(D) which requires specific spacings of triplex conductors in a ventilated, uncovered cable tray. Any variations on this arrangement will increase the required conductor size. If this same circuit is run in a raceway, the minimum conductor size is 700 kcmil aluminum for underground conduit and 700 kcmil for above ground installations. The equipment for the underground installation would have to be 90°C and 100% rated whereas the above ground installation equipment can be 80% rated and 75°C as long as the conductors are at least 90°C for the 600 kcmil conductor size.

2.2.2 Four 125 kW Inverters Connected to a Single 600-amp Device

The combined output of four 125 kW inverters can be run to a 600-amp fuse or circuit breaker. For 600-amp fuses or circuit breakers rated for 80% duty, the maximum allowable continuous current is 80% of 600 amps, or 480 amps. Due to the ability to round to the nearest higher standard rated overcurrent device in 240.4(B), the smallest conductor that a 600-amp circuit breaker can protect must have an ampacity of 501 amps (just above the next smaller standard size of 500-amps). A 600-amp conductor is necessary to carry the load of four 125 kW inverters (120A x 4 x 1.25 = 600A) for 80% equipment. The sizing of a 600-amp conductor also works if the installer decides to use switchgear at the transformer with six, 600-amp circuit breakers.

If these conductors are installed in a triplex arrangement in cable tray, the smallest conductor permitted in a 50°C ambient design is 1000 kcmil aluminum (716A x 0.89 = 637A > 600A). This smallest conductor is based on NEC 392.80(D) which requires specific spacings of triplex conductors in a ventilated, uncovered cable tray. Any variations on this arrangement will increase the required conductor size. If this same circuit is run in a raceway, parallel conductors are required.

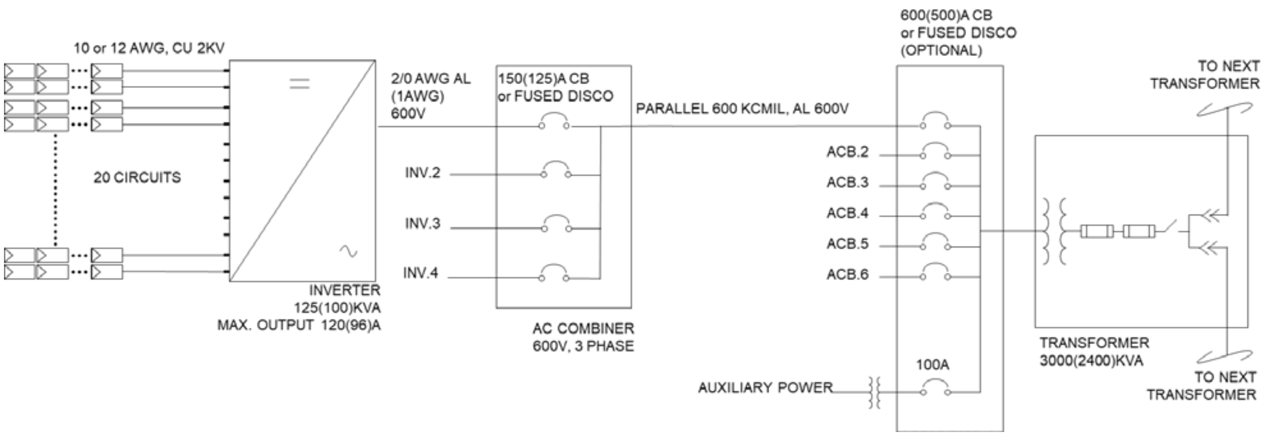

Figure 2.2.2. Configuration with Four Inverter Cluster to Switchgear

Running conductors larger than 600 kcmil in raceways is challenging so parallel sets of conductors should be considered for all raceway circuits requiring larger than 600 kcmil conductors. For ventilated cable tray installations requiring 600-amp conductors, it may be easier to run parallel 350 kcmil conductors in two triplex bundles. These bundles must be separated by 2.15 times the diameter of a single cable in accordance with 392.80(A)(2)(d). For underground circuits in conduit requiring 600-amps, two sets of parallel cables in the same raceway requires parallel 600 kcmil conductors and parallel 700 kcmil for above ground installations. Running the parallel conductors in two separate raceways is permitted provided that the equipment grounding conductor (EGC) required for the overcurrent device is run in each raceway [NEC 310.10(H)] (2/0 AWG Al). This further reduces the conductor size of the current-carrying conductors to parallel 500 kcmil Al for underground conduit and parallel 600 kcmil Al for above ground installations. Smaller conductors ease the issues of conduit sizes, wire bending radii, and physical stress on connections.

2.2.3 What Code Section Applies to these Conductors?

The conductors between the first disconnect and overcurrent device to the transformer may be mistakenly called service entrance conductors in applying the NEC. These conductors, while connected to a transformer, never enter a building. The purpose of these conductors is not to supply loads, but to supply the utility distribution system. There is no problem with wiring a set of PV systems into a single transformer without a service disconnecting means on the load side of the transformer. Since a 600Vac PV power production facilities will generally be metered at medium voltages (4kV to 70 kV), the service disconnecting means is actually on the medium voltage side of the transformer. Some transformers have switches that meet the requirements of Part VI of Article 230. Alternatively, remotely activated reclosers are often used that allow for quick and safe shutdown of all the ac power in the power production facility.

Regardless of what method is used for the service disconnecting means on the medium voltage service, the low-voltage side of the transformer does not have to conform to service entrance requirements. The correct set of requirements are found in Article 225, Outside Branch Circuits and Feeders. The conductors connected to the low-voltage side of the transformer are considered outside feeders and are permitted to have overcurrent protection provided in accordance outside secondary conductors in NEC 240.21(C)(4). Outside feeder conductors connected to the secondary of a transformer are permitted to have overcurrent protection at the load end of the circuit provided the disconnect is located with the overcurrent protection. This means that no switch or circuit breaker is required near the transformer as shown in Figure 2.2.3.

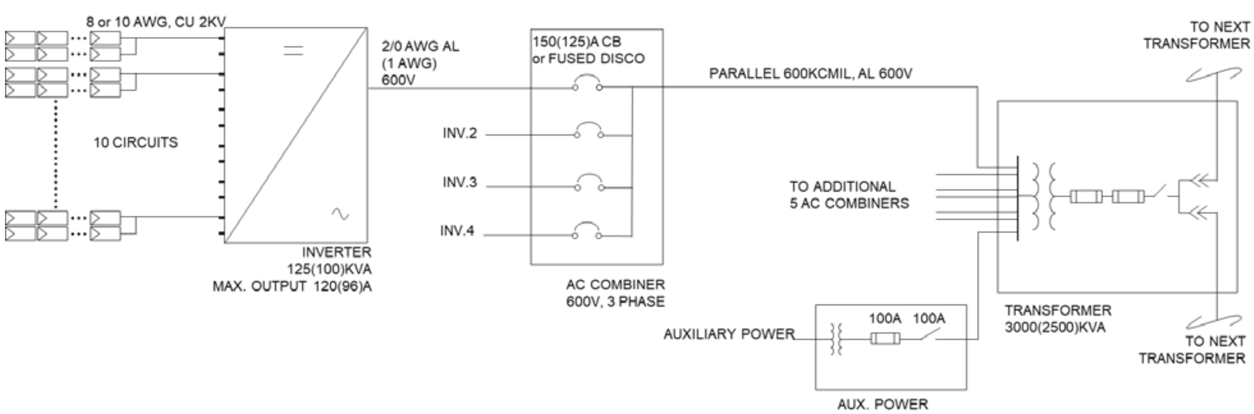

Figure 2.2.3 Configuration with Four Inverter Cluster Directly to Transformer

Table 3 summarizes the size of ac combiner output circuits run from the ac combiner to the transformer or transformer ac combiner. This table takes into consideration two new cases where larger circuit breakers are used at the inverter clusters. If four 175-amp or four 200-amp circuit breakers are installed in the inverter cluster combiner, then the directly connected feeders are required to be increased in size to protect the conductors from the cluster to the transformer. Performing the same conductor sizing calculations as done previously in section 2.2.2, we can see how much larger these feeder conductors must be. Since we can round to the nearest larger overcurrent device up to 800A in accordance with 240.4(B), any conductor with more than 600 amps of ampacity will work for the configuration of four, 175-amp circuit breakers (totaling 700-amps).

Table 3: Minimum Conductor Size for AC Combiner Output Circuits

Min Size of Al Conductors for AC Combiner Output Circuits to Transformer[1]				
	Number of Circuits	75°C Terminals		
	Wiring Method	Open Tray	Underground	Above Gnd
Circuit	Overcurrent Device			
2 100kW Inv	2-125A or 250A	4/0 AWG	350 kcmil	350 kcmil
2 125kW Inv	2-150A or 300 A	250 kcmil	500 kcmil	500 kcmil
3 100kW Inv	3-125A or 400A	500 kcmil	2-350 kcmil	2-400 kcmil
3 125kW Inv	3-150A or 450A	2-4/0 AWG	2-400 kcmil	2-500 kcmil
4 100kW Inv	4-125A, 2-250A, or 500A	500 kcmil	600 kcmil	700 kcmil
4 125 kW Inv	4-150A, 2-300A, or 600A	2-350 kcmil	2-600 kcmil	2-700 kcmil
4 125 kW Inv	4-150A, 2-300A, or 600A	2-350 kcmil	2-500[2] kcmil	2-600[2] kcmil
4 125 kW Inv	4-175A	2-350 kcmil	2-500[2] kcmil	2-600[2] kcmil
4 125 kW Inv	4-200A	2-500 kcmil	2-700[2] kcmil	2-750[2] kcmil

[1]Larger conductors may be necessary for long circuits and high temperature conditions.

[2]These conductors sizes are based on the parallel sets installed in separate raceways

2.3 Recommended Options:

The basic recommendation is to use four 125 kW inverters connected to 600-amp combiner boxes remote from a 3000 kVA transformer on a consolidated inverter/transformer pad. If the terminals on the equipment connected to the 600-amp disconnect are rated for 75°C, then parallel 600 kcmil aluminum conductors in underground conduit meet the ampacity required for a 600-amp disconnect and fuse or circuit breaker. Since these conductors are on the supply-side of the low-voltage overcurrent device, a supply-side bonding jumper, sized in accordance with Table 250.102(C) is required. This requires a minimum size supply-side bonding jumper of 4/0 aluminum to each 600-amp combiner. Table 4 summarizes the minimum ac conductor sizing for the main 600Vac overcurrent device options.

If a transformer has a 3000 kVA rating, it could have multiple sets of conductors feeding separate disconnecting means. The size of the conductors from the transformer to the disconnect and overcurrent device need only be sized based on the size of the overcurrent protection at the disconnect. Therefore, it is possible to run six 600-amp disconnects from a single 3000 kVA transformer. Since the rating on the transformer can be rated for a continuous load of 3000 kVA and the inverters have a continuous current rating of 120A, then it is possible to run a total of up to 24 inverters on a single 3000 kVA transformer (3,000kVA/125kVA = 24). Respecting the thermal ratings of the transformer may require reducing the number of inverters at full capacity in higher temperature applications. Since one 600-amp disconnect can be connected to four 125 kVA (125 kW) inverters, it would be necessary to have a total of six, 600-amp disconnects or circuit breakers to connect the full number of inverters.

2.3.1 Three Recommended Options:

The 125 kW inverter matches well with 150A, 300A, and 600A devices that are plentiful with 600Vac ratings. The options shown below are for the 125 kW inverter. Options 1 is likely the lowest cost, but it requires that the inverter be listed with specifically sized conductors, and lengths of those conductors to define the fault current impact on the inverter and prevent having to run 600-amp conductors to the inverters. Options 2 and 3 have no need for special certifications on the conductors from the overcurrent device to the inverter. A combiner with a 600-amp rated disconnect connected to two, 300-amp fuses, or four, 150-amp fuses. The advantage to the 300-amp fuse option is that there is only one set of fuses for every two inverters. The advantage to the 150-amp fuse option is that the conductors from the fuse to the inverter are much smaller than the 300-amp option.

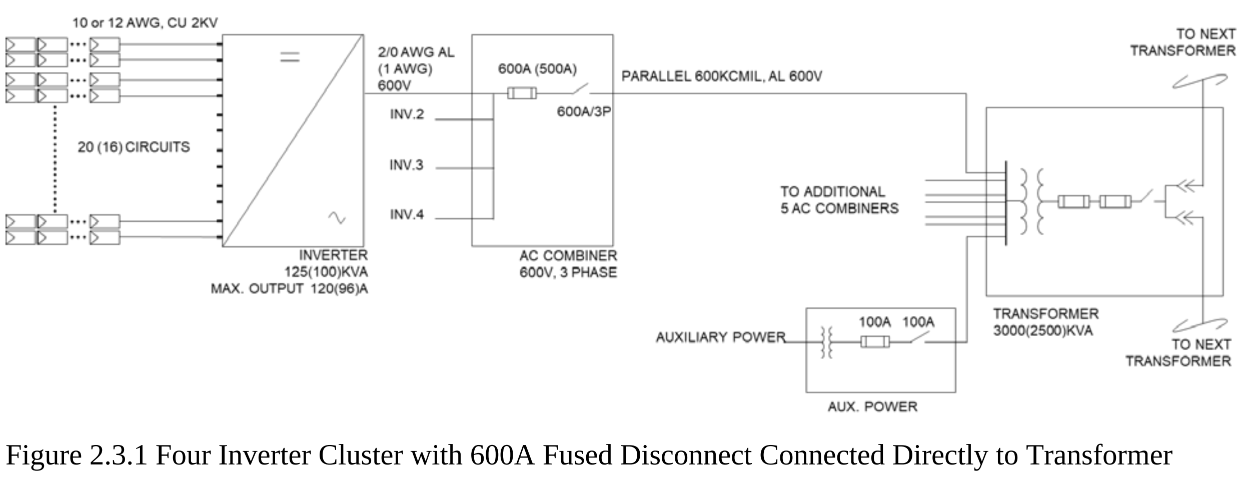

Figure 2.3.1 Four Inverter Cluster with 600A Fused Disconnect Connected Directly to Transformer

Option 1:

For the 600-amp fuse option, the conductor size is based on the certification of the inverter with these fuses (not circuit breakers). With 75°C terminals and fuses operating 80% of rating yields a conductor size of 2/0 AWG Al triplexed in free air or cable tray for the 120 amp continuous output of the 125 kVA inverter. If these conductors are placed in conduit, the conductor size increases to 3/0 AWG Al for underground conduit and 4/0 AWG Al for above ground conduit.

Option 2:

For the 300-amp circuit breaker or fuse option, the conductor size based on 75°C terminals and breakers or fuses operating 80% of rating yields a conductor size of 350 kcmil aluminum triplexed in free air or cable tray. If these conductors are placed in conduit, the conductor size increases to 500 kcmil Al for underground conduit and 600 kcmil Al for above ground conduit.

Option 3:

For the 150-amp circuit breaker or fuse option, the conductor size is the same as for the certified configuration in Option 1. The conductor size is based on 75°C terminals and breakers or fuses operating 80% of rating and yields a conductor size of 2/0 AWG aluminum triplexed in free air or cable tray (193A x 0.89 = 172A > 120A). If these conductors are placed in conduit, the conductor size increases to 3/0 AWG Al for underground conduit and 4/0 AWG Al for above ground installations (205A x 0.82 = 168A > 150A).

Six-Disconnect Discussion Sidebar:

Some options may result in more than six disconnects. Some jurisdictions may try to invoke the six-disconnect rule [NEC 690.13(D)] and claim that only six disconnects can be used. Additionally, they may say that these disconnects must be grouped in the same enclosure or a group of enclosures. The location of several combiners spread out on a large inverter pad would not be considered grouping according to the NEC. This whole six-disconnect discussion misses a critical point on the configuration of this type of PV system.

The whole PV power production facility connected to the 3000 kVA transformer can be considered as a single PV system with the medium voltage disconnect serving as the service disconnect and the PV system disconnect. If the facility is fed through a medium voltage distribution system with multiple transformers, then the service point where the site metering takes place is where the service disconnecting means is located. Conductors from that point to the various site transformers are medium voltage outside feeders. The conductors on the low voltage side of the transformer, as in the single transformer example, are outside secondary conductors and are permitted to follow NEC 240.21(C)(4). There is no limit to the number of feeders that can be run from a transformer outside buildings. Whether the system has two or 20 feeders, the number of disconnects as they relate to 690.13(D) are irrelevant since the single medium voltage PV system disconnect already meets the requirement.

2.4 Thermal estimation review

Since there is only one set of 600-amp fuses or circuit breaker provided in the preferred solution, the heating effects should be negligible. According to the thermal ratings of the fuse holders at 50°C, the maximum current should be reduced to 0.85 times the rating at 35°C. According to the thermal derating curve of the Eaton NH fuse, the fuse has a rating 0.94 times the rating at 30°C. Even if these two deratings are multiplied together, the total derating would be 0.8 times the rating at 30°C. The actual continuous current through the fuse is 480 amps. This corresponds to a ratio of 0.8 which and matches the manufacturer's recommendation of 0.80. This means that the enclosure would be able to get significantly hotter than 50°C before the thermal effects are likely to cause fuse failures. To reach a combined temperature correction factor of 0.8 would require an internal temperature of between 50°C to 65°C depending on how the actual factors combined to impact the fuse link.

Having only one set of fuses in an enclosure is likely to perform better than if two or more sets of fuses or circuit breakers are used in the same enclosure. The lower the fuse rating, the higher the fuse impedance which results in higher heating. If four 150-amp circuit breakers are used for four inverters rather than a single set of 600-amp fuses, it is recommended to keep a spacing of 4" between the breakers to reduce mutual heating of the two circuits. Also, the use of 150-amp breakers does not improve the short circuit exposure of the inverters. The extra cost of four circuit breakers and the larger enclosure versus a single set, combined with the added heat suggests that the optimal configuration is a single set of 600-amp fuses per distribution switch or circuit breaker. In any case, it is recommended that the fuse block or circuit breaker be oriented with the line and load side terminal oriented up and down rather than side-to-side. This allows for better cooling of the breaker or fuse link and prevents a lower breaker or row of fuses from heating breakers or fuses mounted above them. The enclosure would be wide and short to accommodate the breakers or fuses in a long line rather than tall and narrow with the devices mounted vertically.