Chapter 11

Electrical Integration

Terminology and Definitions • Circuit Design Requirements • Specifying Electrical Components • Code-Compliant Installation Practices
Overview

- Identifying key sections of the National Electrical Code applicable to PV system installations.

- Classifying typical PV system configurations, their major components and circuits.

- Calculating circuit voltages and currents based on component specifications and system designs.

- Determining appropriate specifications and ratings for conductors, wiring methods, disconnecting means and overcurrent protection.

- Understanding the requirements for PV system grounding.
The National Electrical Code (NEC®) provides for the safety of persons and property relative to the use of electricity.

- Applies to nearly all electrical installations – notable exceptions include most vehicles, boats, trains, and certain utility-controlled properties.

Article 690 Solar Photovoltaic Systems
- Addresses safety standards for the installation of PV systems.
Many articles in the first four chapters of the NEC also apply to PV installations, including but not limited to:

- Article 110 Requirements for Electrical Installations
- Article 230 Services
- Article 240 Overcurrent Protection
- Article 250 Grounding and Bonding
- Article 300 Wiring Methods
- Article 310 Conductors for General Wiring
- Article 705 Interconnected Electric Power Production Sources
Article 690: Solar Photovoltaic Systems

Article 690 Solar Photovoltaic Systems includes nine parts addressing the following areas of PV installations:

I. General
II. Circuit Requirements
III. Disconnecting Means
IV. Wiring Methods
V. Grounding
VI. Marking
VII. Connection to Other Sources
VIII. Storage Batteries
IX. Systems Over 600 Volts
The PV power source consists of the complete PV array DC power generating unit, including PV source circuits, PV output circuits, and overcurrent protection devices as required.
Interactive PV System Components and Circuits

Interactive System

PV Array

Source Circuit Combiner Box

Ground Fault Protection

Inverter

AC Fused Disconnect

Utility Disconnect

Main Service Panel

Electric Utility

Integral components in many small string inverters < 12 kW
The listing, labeling and identification of equipment is a foundational basis for building officials in their approval of PV installations for code compliance [90.7, 110.2, 690.4(D)].

- Listed equipment has been evaluated to applicable standards by a Nationally Recognized Test Laboratory (NRTL).

- Labels provide recognizable markings, ratings and specifications for listed products, and are used to establish circuit requirements.

- Identified equipment is listed and labeled for a specific application, such as for inverters intended for use with utility-interactive systems or with ungrounded PV arrays.
Conductors for PV source circuits and PV output circuits must be installed in separate raceways from other building circuits unless partitioned [690.4(B), 300.3].

The conductors for PV source circuits, PV output circuits, and inverter circuits must be identified at all terminations and connections.

Conductors from multiple PV systems (arrays or inverters) using the same raceways or junction boxes must also be identified, and grouped by securing together at least every 6 feet if the raceways or junction boxes can be opened. PV source and output circuit conductors shall be routed along structural members.
Grounded photovoltaic arrays are required to have ground-fault protection to reduce the potential for arcing and fire hazards [690.5].

- Nearly all listed interactive PV inverters incorporate internal array GFP; when a GF condition is detected, the inverter ceases supplying output power.

- The ground-fault protection system detects ground faults, interrupts the fault current, and provides fault indication.

- Markings are required stating that if a ground-fault is indicated, the normally grounded conductors may be energized and ungrounded, presenting a shock hazard.
Lower-voltage system may use DC circuit breakers for interrupting ground faults.
Higher-voltage systems typically use a DC-rated fuse for interrupting ground-fault currents, either externally accessible or located within the inverter.
PV systems with DC circuits over 80 volts entering a building are now required to have DC arc-fault protection for the PV array and DC circuits per the 2011 NEC [690.11].

- Arc-faults must be detected for any continuity failures between PV modules, conductors, connectors or terminations.

Arc-fault protection may be provided by disconnecting inverters or charge controllers from the PV array and DC circuits (open-circuit the array), or by using other components in the circuit to interrupt the flow of arcing current.

- Requires disconnected equipment or the system to be manually restarted after the arc fault has been cleared.
- A visual indicator of an arc-fault condition is also required and must be manually reset.
The conductors, overcurrent devices, disconnect means and other equipment used in PV system circuits are selected and sized based on the maximum circuit voltages and currents.

Specifications and ratings for major components, including PV modules and inverters, are required to determine the appropriate circuit parameters for sizing the conductors and wiring systems.
The maximum system voltage is the PV array open-circuit voltage adjusted for lowest expected ambient temperatures [690.7].

\[ V_{\text{max}} = V_{oc} \times n_m \times C_T \]

where
- \( V_{\text{max}} \) = maximum system voltage (V)
- \( V_{oc} \) = module rated open-circuit voltage at 25\(^\circ\)C (V)
- \( n_m \) = number of series-connected modules
- \( C_T \) = low-temperature correction factor

This maximum voltage dictates the minimum voltage ratings for cables, disconnects, overcurrent devices, and other equipment used in the PV source circuits and output circuits.
Voltage Correction Factors

- Voltage-temperature correction factors for crystalline silicon PV modules increase with decreasing temperatures.

- Manufacturer’s listed instructions must be used if:
  - The minimum temperatures are below -40°C,
  - Other than crystalline silicon PV modules are used, or
  - Coefficients are provided with listed instructions.

<table>
<thead>
<tr>
<th>Minimum Ambient Temperature (°C)</th>
<th>Correction Factor</th>
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<tbody>
<tr>
<td>24 to 20</td>
<td>1.02</td>
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<tr>
<td>19 to 15</td>
<td>1.04</td>
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<tr>
<td>14 to 10</td>
<td>1.06</td>
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<tr>
<td>9 to 5</td>
<td>1.08</td>
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<td>-31 to -35</td>
<td>1.23</td>
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<tr>
<td>-36 to -40</td>
<td>1.25</td>
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</tbody>
</table>

Adapted from NEC Table 690.7
Maximum System Voltage:  
Example 1

- Assume the following data for a crystalline silicon module and determine the maximum system voltage:
  - Rated open-circuit voltage of each module is 44.4 VDC.
  - 10 series-connected modules per source circuit.
  - The lowest expected ambient temperature is –25°C (-14°F).

- Solution:
  - From Table 690.7, the voltage correction factor is 1.20.
  - Maximum system voltage is \((44.4 \times 10) \times 1.20 = 528 \text{ V}\).
Using the same data from Example 1, calculate the maximum system voltage using a manufacturer-supplied voltage-temperature coefficient of -0.33 \%/°C.

**Solution:**

For each module:

\[
V_{\text{trans}} = V_{\text{ref}} + [V_{\text{ref}} \times C_v \times (T_{\text{cell}} - T_{\text{ref}})]
\]

\[
V_{\text{trans}} = 44.4 \text{ V} + [44.4 \text{ V} \times -0.0033/\text{°C} \times (-25 - 25)\text{°C}] = 51.7 \text{ V}
\]

For the entire array:

\[
V_{\text{max}} = 51.7 \text{ V per module} \times 10 \text{ modules in series} = 517 \text{ V}
\]
Maximum Voltage: Dwellings

- For one- and two-family dwellings [690.7]:
  - Maximum PV system voltage is limited to 600 volts.
  - Live parts in PV circuits over 150 volts to ground must not be accessible to other than qualified persons while energized.
Maximum PV Circuit Currents

- Maximum PV source circuit currents are calculated by multiplying their short-circuit current by 125% [690.8(A)].

  - This 125% factor is in addition to the 125% factor required by 690.8(B), and accounts for higher than rated current output from PV arrays exposed to irradiance levels above 1000 W/m².

- The maximum PV output circuit current is the sum of parallel-connected source circuit currents.
Determine the maximum currents for a PV array consisting of 4 parallel strings of 10 series-connected PV modules each. The PV module rated short-circuit current (Isc) is 5.3 A.

The source circuit maximum currents are:
- $I_{sc} \times 1.25 = 5.3 \, \text{A} \times 1.25 = 6.63 \, \text{A}$

The output circuit maximum current is:
- 4 parallel source circuits $\times 6.63 \, \text{A} = 26.5 \, \text{A}$
For both stand-alone and interactive systems, the maximum inverter output current is the inverter continuous output current rating, and is usually marked on inverter labels.

For unity power factor inverters, the maximum output current can be estimated by dividing the rated AC power output by the nominal AC output voltage.

For example, consider an inverter rated for 6 kW maximum continuous AC power output at 240 V.

- The maximum output current is: \( \frac{6000 \text{ W}}{240 \text{ V}} = 25 \text{ A} \).
For interactive systems, the inverter input circuit is the same as the PV output circuit, and has the same maximum current.

For stand-alone inverters operating from batteries, the maximum inverter input current must be evaluated at the lowest operating voltage when the inverter is producing rated power:

\[ I_{\text{max}} = \frac{P_{AC}}{V_{\text{min}} \times \eta_{\text{inv}}} \]

where
- \( I_{\text{max}} \) = maximum inverter input current (A)
- \( P_{AC} \) = rated inverter maximum AC power output (W)
- \( V_{\text{min}} \) = minimum inverter operating voltage (V)
- \( \eta_{\text{inv}} \) = inverter efficiency
Consider a nominal 48 V, 4000 W stand-alone inverter that is 90% efficient, and operates to a low voltage cutoff of 44 V.

The maximum inverter input circuit current is:

\[ I_{\text{max}} = \frac{P_{AC}}{V_{\text{min}} \times \eta_{\text{inv}}} = \frac{4000 \text{ W}}{44 \text{ V} \times 0.9} = 101 \text{ A} \]
Overcurrent Device Ratings

- Overcurrent devices in PV system circuits must be sized for at least 125% of the maximum circuit currents [690.8(B)].
  - For PV source circuits and PV output circuits, this 125% factor is in addition to the 125% factor used to calculate maximum circuit currents in 690.8(A), and results in a combined factor of 125% x 125% = 156%.

- The next higher standard size overcurrent protection device may be used.

- Overcurrent devices used in PV source circuits must be no greater than the maximum allowable overcurrent device (or fuse) rating on the module label.
The temperature ratings for terminals and overcurrent devices may limit the ampacity of connected conductors.

- The conductor ampacity is selected at a temperature rating no greater than the temperature ratings of a terminal or device that it is connected to.

- Using terminals rated for 90°C usually avoids this concern, and the 90°C conductor ampacities may be used.
Conductor Ampacity

- Conductors in PV system circuits must be sized for the greater of the following:
  - 125% of the maximum circuit current without adjustments for conditions of use, or
  - The maximum circuit current adjusted for conditions of use.

- Overcurrent devices, where required, must protect the conductors based on their allowable ampacity after adjustments for conditions of use.

- Conditions of use, namely temperature and conduit fill deratings, often account for more than 20% reduction in allowable conductor ampacity.
Consider a PV array with 4 parallel-connected source circuits having a maximum current of 6.6 A for each source circuit.

The minimum required overcurrent device rating for the PV array source circuits is:
- $6.6 \text{ A} \times 1.25 = 8.3 \text{ A}$
- The next higher standard overcurrent device rating is 9 A, or may be as high as the module maximum overcurrent device rating allows.

For the PV output circuit:
- $8.3 \text{ A} \times 4 \text{ parallel source circuits} = 33.1 \text{ A}$
- The next higher standard size overcurrent device is 35 A.
For an inverter with maximum continuous output current of 25 A, the minimum overcurrent device rating must be at least:

- $25 \text{ A} \times 1.25 = 31.3 \text{ A}$

The overcurrent device rating must also be no greater than the maximum overcurrent device rating on the inverter label if marked.
Conductor Ampacity

Allowable conductor ampacity is determined by conductor properties and conditions of use:

- Material type (copper or aluminum)
- Cross sectional area, or gage size (AWG)
- Insulation temperature rating
- Location (ambient temperature, in free air, conduit or buried, on rooftops, or with other conductors)

Ampacity decreases with increasing conductor temperature.

- Rated ampacities at 30°C are adjusted by a derating factor for higher temperatures.
Allowable Ampacities

- Tables 310.15(B)(16) and 310.15(B)(17) in the NEC give allowable ampacities at 30°C for insulated conductors rated up to 2000 volts for insulation temperature ratings of 60°C, 75°C and 90°C.
  - Adjustment factors are applied to derate allowable ampacities for maximum operating temperatures greater than 30°C [Table 310.15(B)(2)(a)].

- Table 310.15(B)(16) applies to no more than three current-carrying conductors in a raceway, cable, or directly buried.
  - Adjustments are applied to derate allowable ampacities when more than three current-carrying conductors are installed in a single conduit or raceway [Table 310.15(B)(3)(a)].

- Table 310.15(B)(17) applies to conductors installed in free air, not in conduit or raceways.
When more than three current-carrying conductors are installed in a single conduit or raceway, the conductor ampacity must be derated accordingly [310.15(B)(3)(a)].

For example, if 10 to 20 current-carrying conductors are installed in a single conduit, the ampacity for each conductor is reduced by 50 percent.

<table>
<thead>
<tr>
<th>Number of Current-Carrying Conductors</th>
<th>Percentage Adjustment</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-6</td>
<td>80</td>
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<tr>
<td>7-9</td>
<td>70</td>
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<tr>
<td>10-20</td>
<td>50</td>
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<tr>
<td>21-30</td>
<td>45</td>
</tr>
<tr>
<td>31-40</td>
<td>40</td>
</tr>
<tr>
<td>41 and above</td>
<td>35</td>
</tr>
</tbody>
</table>

Adapted from NEC Table 310.15(B)(2)(a)
PV source circuit and PV output circuit conductors installed in conduit on a roof exposed to direct sunlight experience very high operating temperatures, and conductor ampacities must be adjusted accordingly [310.15(B)(3)(c)].

Conductor temperatures in conduits are based on the distance from the bottom of the conduit to the roof surface, and requires adding and specified temperature rise to the maximum expected ambient temperature.

The resulting conductor temperature is then used in conjunction with Table 310.15(B)(2)(a) to determine the allowable conductor ampacity.
Allowable Ampacity: Example

- Consider a 12 AWG 90°C-rated conductor (USE-2 or PV Wire) with a rated ampacity of 30 amps (wet or dry) at ambient temperatures of 26-30°C.

- If eight (8) current-carrying conductors (4 source circuits) are installed in a single conduit, the allowable ampacity for the conductor is reduced to:
  - $30 \text{ A} \times 0.7 = 21 \text{ A}$
If these conductors are installed in conduit mounted flush to a roof surface that is exposed to direct sunlight, the ambient temperature adder is 33°C from Table 310.15(B)(2)(c).

If the maximum ambient temperature is 35°C, the conductor ampacity must be determined at 35 + 33 = 68°C.

For a 90°C conductor, the temperature correction factor is 0.58, which further reduces the allowable ampacity to:

21 A x 0.58 = 12.2 A
All PV system circuits must be protected from overcurrent in accordance with Article 240 [690.9].

- Overcurrent protection for PV source and output circuits is usually not required for small interactive systems using only one or two identical strings.

- Branch-circuit or supplementary-type overcurrent devices are permitted to provide overcurrent protection for PV source circuits, and are required to be accessible, but not required to be readily-accessible.

- A single overcurrent device is used to protect series-connected strings of two or more modules, and must have a DC rating.
Voltage drop should be limited in all PV system circuits to no more than 2 to 3%.

Excessive voltage drop in DC circuits is a particular concern for lower-voltage systems and for PV arrays located long distances from DC utilization equipment.

Excessive voltage drop in AC circuits may cause loads to operate improperly, or hinder an interactive inverter’s ability to remain connected to the grid.
Conductor resistance and voltage drop increase with smaller conductor size, longer conductor lengths, and higher operating currents and temperatures.

Ohm’s law is used to calculate voltage drop:

\[ V_{\text{drop}} = I_{\text{op}} \times R_C \times L \]

where

- \( V_{\text{drop}} \) = voltage drop (V)
- \( I_{\text{op}} \) = operating current (A)
- \( R_C \) = conductor resistance per unit length (Ω/kft.)
- \( L \) = total conductor round-trip length (kft)
Consider a PV array that operates nominally at 500 V with a maximum output current of 20 A. The output circuit used 8 AWG stranded conductors having resistance of 0.8 Ω/kft, and the one-way circuit distance is 350 feet.

The voltage drop is this circuit is:

\[ V_{\text{drop}} = I_{\text{op}} \times R_C \times L \]

\[ V_{\text{drop}} = 20 \text{ A} \times \frac{0.8\Omega}{\text{kft}} \times \frac{(2 \times 350)}{1000} \text{kft} = 11.2 \text{ V} \]

Based on the nominal system operating voltage of 500 V, this voltage drop amounts to:

\[ 11.2 \text{ V} / 500 \text{ V} = 0.0224 \text{ or } 2.2\% \]
All ungrounded current-carrying DC conductors of a PV system require a disconnecting means to isolate these circuits from all other conductors in a building or structure [690.13].

A switch must not be installed in the circuit with a grounded conductor, unless:

- The switch is part of an arc-fault or ground-fault protection circuit, or
- The switch is only used for maintenance, accessible only to qualified persons, and rated for the maximum DC voltage and current in the circuit.
The following provisions also apply to the disconnecting means for PV output circuits [690.14]:

- Not required to be service-rated equipment or installed at the array location.

- Source circuit switches and overcurrent devices are permitted on the PV array side of the disconnecting means.

- A maximum of six (6) disconnects are allowed, and they must be grouped, suitable for use, and each marked to identify it as a PV system disconnect.

- Must be installed at a readily-accessible location outside a building or inside a building nearest to the point where the conductors enter the building.
Utility-interactive inverters installed in not-readily-accessible locations, such as in attics or on rooftops, must have AC and DC disconnecting means located within sight of or inside the inverter [690.14(D)].

An additional, readily-accessible AC disconnecting means is also required.

A plaque or directory must be installed at the service entrance denoting the presence of a PV power source and the inverter location.
All PV system equipment must have a means to disconnect from ungrounded conductors from all sources. The disconnecting means must be grouped and identified if equipment can be energized from more than one source [690.15].

- These disconnect requirements apply to PV arrays, charge controllers, batteries, inverters and chargers.
- Single AC disconnecting means are permitted for one or more AC modules or micro inverters.

Switches or circuit breakers used for the disconnecting means must be [690.17]:
- Readily accessible.
- Manually and externally operable, and protected from live parts.
- Plainly indicating an open or closed position.
- Rated for sufficient fault current interrupting and maximum system voltage.
Warning signs are required when both sides of a disconnecting means may be energized in the open position.
This combination DC disconnect and combiner box from SMA mounts to the bottom of the inverter, and allows the connection of up to four fused source circuits. It also includes a partitioned raceway for the inverter AC output conductors.
DC Disconnects

- A maximum of six (6) disconnects are allowed for the PV power source, and they must be grouped and marked as PV disconnects [690.14].
Fuses used in PV source circuits must be able to be disconnected independently of other source circuit fuses [690.16].

Fuses must have disconnects to isolate them from both sides if so energized.
Because PV arrays are always energized when exposed to light, arrays or portions of arrays are disabled for installation or maintenance by open-circuiting, by short-circuiting, or by placing an opaque covering over the array [690.18].

Where covering arrays is impractical, the array may be sectioned into lower-voltage and less hazardous portions by opening series connectors until the installation or maintenance is completed.
Wiring Methods

- Wiring methods used in PV systems include standard types of conductors, raceways and fittings used in building electrical systems, in addition to special cables, connectors and other methods specifically identified for use in PV systems [690.31].

- Environmental exposure requires PV array conductors to have insulation rated for high temperatures, wet locations, and sunlight resistance.
Conductor Properties

Electrical conductor properties are defined by [310]:

- Type of material (aluminum, copper-clad aluminum or copper)
- Size of conductor in AWG or kcmils
- Stranded or single conductor (8 AWG and larger must be stranded)
- Insulation type (single or double-insulated, single-conductor or multi-conductor cable with outer insulation)
- Insulation material (thermoplastic, thermoset, silicone, etc.)
Two types of single-conductor cables are permitted to be used for exposed connections between PV modules within PV array source circuits [690.31]:

- USE-2 is rated for 90°C wet or dry, 600 volts, and is sunlight resistant.

- Photovoltaic (PV) wire is a double-insulated sunlight-resistant conductor rated for 90°C in wet locations, and for 600, 1000 or 2000 volts. PV wire is intended for use with higher voltage and ungrounded PV arrays.

Other standard types of conductors rated for 90°C and wet locations are not sunlight resistant, and must be installed and protected in conduit or other raceways, including types:

- RHW-2, THW-2, THHW-2, THWN-2 and XHHW-2
Single, exposed conductors are not permitted to run distances from PV modules to source circuit combiner boxes. Single conductors must be installed in conduit upon leaving the PV array location.
Photovoltaic (PV) Wire
USE-2 Single Conductor Cables
Conductor Colors

- Grounded current-carrying conductors must be white, gray or have three white stripes or white markings at terminations on conductors larger than 6 AWG.
  - Can not be green colored.

- Equipment grounding conductors (EGC) must be bare, or have insulation colored green or green with yellow stripes.

- Ungrounded current-carrying conductors can be any color except for green, white or gray to clearly distinguish them as ungrounded conductors.
The following are basic requirements for terminating electrical conductors [110.3, 110.14]:

- All terminating devices must be listed and identified for the proper conductor material, the conditions of use, and installed according to manufacturer’s instructions.
- Conductors or materials made of dissimilar metals must not be allowed to touch each other, and any solders or corrosion inhibitors used must be suitable for the application.
- The ampacity of any connected conductors must be evaluated at the lowest termination temperature rating.
- Crimped lugs must use the proper crimping tool.
- Terminals using setscrews must be torqued to the proper specifications.
- Fine-stranded cables require special terminals intended for the use.
Conductor Protection

- For PV systems with a maximum system voltage over 30 volts, PV source and output circuit conductors must not be readily accessible for physical protection and to reduce electrical hazards [690.31].
  - Requires conductors to be installed in conduit, enclosures or other raceways.
  - The conductors must be made not readily accessible by elevation, fencing around the array, or guarding of the exposed conductors with barriers.
Conductor Protection

- Ground-mounted PV arrays are often elevated or installed behind fencing to make exposed conductors not readily accessible.
Smaller conductor sizes 16 AWG and 18 AWG are often used on higher-voltage, lower-current thin-film PV modules for source-circuit module connections [690.31(D)].

- These cables must meet the PV source circuit ampacity requirements after temperature derating, and be rated for sunlight resistance and wet locations.

- Normal listing and labeling marks used on conductor sizes 14 AWG and larger are not usually printed on smaller conductor cables.
PV source circuits and PV output circuits inside a building are required to be routed in metal raceways, metal enclosures, or use type MC metal-clad cable prior to the first readily accessible disconnect means [690.31(E)].

Conductors and wiring methods are not permitted within 10 inches under a roof deck unless the location is underneath PV modules or equipment.

Conductors and raceways for PV circuit conductors inside buildings must be marked and routed along structural members where possible.
Metal conduit or cable is not required where the PV disconnect is located outside a building (A) or nearest to the point where the conductors enter a building (B).

Where PV conductors run inside a building before reaching the disconnect, metal conduit or type MC cable must be used.
Flexible Cables

- Flexible cords and cables may be used for tracking PV arrays, and must be identified for hard service, outdoor use, wet locations and sunlight resistance [690.31(C)].

- Temperature correction factors to be used are listed in Table 690.31(C).

- Terminals, lugs, devices, or connectors must be specifically identified and listed for used with fine-stranded flexible cables [690.31(F)].
Concealed fittings and connectors are permitted for module connections that are listed and identified for the use, and properly rated for the circuit requirements and environmental conditions [690.32].

Applies to building-integrated PV products.
Connectors are used in PV systems for PV module connections and other equipment as applicable, and must be [690.33]:

- Polarized and non-interchangeable.
- Guarded against contact with live parts.
- Latching or locking type.
  - Readily accessible connectors operating at over 30 volts require a tool for opening.
- First to make and last to break grounded conductors.
- Load-break rated for interrupting the maximum circuit current, or require a tool for opening and marked “Do Not Disconnect Under Load” or “Not for Current Interrupting.”
Module Connectors

Multi-Contact MC4 connectors with locking sleeve and assembly/opening tool.
Module Connectors

Tyco SOLARLOK connectors on PV module whips.

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Junction Boxes

- Junction boxes and other enclosures are used in PV systems to combine circuit conductors, provide transitions for wiring methods, and to protect electrical equipment and devices from physical damage and the environment [690.34].

- Junction boxes may be installed behind or beneath PV arrays, and requires them to be made accessible by removal of modules connected to a flexible wiring system.

  - PV source circuit combiner boxes must be listed to the UL 1741 standard.
Enclosure Classifications

- Electrical enclosures for non-hazardous are classified for the level of protection they provide from the elements and physical damage [110.20].
  - Enclosure types 1, 2, 5, 12, 12K and 13 are for indoor use only.
  - Enclosure types 3, 3R, 3S, 4, 4X, 6 and 6P are for both indoor and outdoor use and provide varying degrees of protection from dust, water and corrosion.
- Enclosures must be installed according to instructions to maintain its classification.
Source circuit combiner boxes are used to parallel multiple PV source circuits and transition to the PV output circuit wiring [690.34].

- Source circuit combiners include touch-safe fuses for source circuit overcurrent protection and the module listing.

- Load-break rated DC disconnects or circuit breakers at the combiner box level permit isolation of subarrays for maintenance, testing and emergency events.

- Advanced combiner boxes intended for use with specific inverters may include DC-DC converters and maximum power point trackers.

Source circuit combiners must be UL1741 listed and rated for enclosure type, number of poles, conductor sizes and terminal temperatures.
Source Circuit Combiner Boxes
Combiner Boxes

A. DC NEG, POS, GND WIRE LEADS FROM PV ARRAY. WIRE SIZE 14-6 AWG

B. DC POS INPUT WIRE SIZE FROM 6-1/0 AWG

C. DC POS OUTPUT WIRE SIZE FROM 6-1/0 AWG

PV ARRAY

8 & 12 POLE COMBINER BOXES

SQUARE D DISCONNECT OR SIMILAR

INVERTER(S)

Blue Oak PV Products
Source Circuit Combiner Boxes

BCBS Series Standard Box

BCBC Series Compact Box

BCBD Series Integrated Disconnect Box

Cooper Bussmann
PV arrays are permitted to have ungrounded source and output circuits when the following conditions are met [690.35]:

- Both ungrounded conductors (positive and negative) must have a disconnecting means and overcurrent protection.
- Array ground fault-protection for all conductors must be provided.
- All PV source and output circuit conductors must be either:
  - Installed in raceways, or
  - Jacketed multi-conductor cables, or
  - Listed and labeled PV wire where used for single-conductor exposed PV module connections.
Proper grounding of PV systems reduces the risk of electrical shock to personnel and the effects of lightning and surges on equipment.
System vs. Equipment Grounding

- **System grounding** is the intentional connection of a current-carrying conductor in an electrical system to ground (earth).
  - Commonly, this connection is made at the supply source, such as a transformer or at the main service disconnecting means for a premises.

- **Equipment grounding** is the connection of non-current carrying metal parts to ground.
  - Requires electrical bonding and grounding of PV module frames, racks, enclosures, junction boxes, conduit and other metallic components.

- System grounding and equipment grounding conductors are separate and only connected together (bonded) at the source of supply.
System Grounding

- Any PV power source with a maximum voltage over 50 V must have one current-carrying conductor grounded [690.41].
  - Exceptions are permitted for ungrounded systems meeting specific requirements.

- The connection of the grounded DC system conductor must be made at a single point in the PV output circuit [690.42].
  - For interactive systems, the connection for the grounded DC current-carrying conductor is typically made only at the ground-fault protection device internal to the inverter, and may be required for proper operation of the ground-fault protection device.
An equipment grounding conductor (EGC) connects all exposed non-current-carrying metal parts of PV module frames, support structures, enclosures and raceways to ground [690.43].

- Equipment grounding is required for all PV systems operating at any voltage.
- Proper bonding between these metal parts is required whenever there is a transition between different components or equipment.

The EGC can be a conductor, busbar, metallic raceway, or structural component.

EGCs must be installed in the same raceway as the PV circuit conductors upon leaving the vicinity of an array.
PV module frames must be grounded to their support structures using an approved method rated for outdoor use. Splices between separate structural member must be bonded.
Special equipment bonding washers may be used to provide module frame to support structure connections for equipment grounding.
Equipment Grounding

- Special bonding jumpers, stainless-steel bonding washers and lay-in lugs may be used to electrically connect separate components or attach equipment grounding conductors.
The minimum size equipment grounding conductors are based on the rating of the overcurrent device ahead of the equipment [690.45, 250.122].

<table>
<thead>
<tr>
<th>Overcurrent Device Rating</th>
<th>Minimum Size of EGC (Copper, AWG)</th>
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<tbody>
<tr>
<td>15</td>
<td>14</td>
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<td>20</td>
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<td>8</td>
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<td>200</td>
<td>6</td>
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</tbody>
</table>

Adapted from NEC Table 250.122
PV array equipment grounding conductors smaller than 6 AWG must be protected where subjected to physical damage [690.46, 250.120(C)].
A grounding electrode system consists of a rod, pipe, plate, metal water pipe, building steel or concrete-encased electrode, and includes all grounding electrodes at a building or structure that must be bonded together.

The grounding electrode conductor (GEC) connects the grounded system conductor or the equipment grounding conductor (EGC) to a grounding electrode system:

- Must be a continuous length without splices except for irreversible connections.
- A 6 AWG GEC may be secured to and run along building surfaces where protected from damage.
- GECs smaller than 6 AWG must be in metal raceways or armored cables.
Rod and pipe grounding electrodes must be installed with 8 feet in contact with the soil, preferably driven vertically to a depth of 8 feet.

- Ground clamps installed above ground must be protected from physical damage, and clamps installed below ground must be listed for direct burial.

- Rod, pipe and plate electrodes must be augmented by an additional grounding electrode if the resistance is not 25 ohms or less.

- The minimum required spacing between ground rods is 6 feet.
The grounding electrode system requirements are specified for the following types of PV systems:

- Alternating-current (AC) systems
- Direct-current (DC) systems
- Systems with AC and DC grounding requirements
PV systems having only AC system grounding requirements include systems using AC modules or module-level micro inverters.

- All other types of PV systems have DC circuits.

A grounding electrode system must be provided or installed as required in 250.50 through 250.60.

The size of the GEC is based on the largest ungrounded system conductor as listed in Table 250.66.

- Must be at least 8 AWG copper, or no larger than 6 AWG copper if connected to a pipe or plate electrode.
Grounding Electrode System:
DC Systems

- PV systems having only DC grounding requirements including stand-alone systems with only DC loads and DC circuits.

- The size of the DC GEC may not be smaller than the largest conductor supplied by the system, and not smaller than 8 AWG copper.

- Where connected to rod, pipe, or plate electrodes the GEC is not required to be larger than 6 AWG copper.
Grounding Electrode System: AC and DC Systems

- PV systems with no direct connection between the DC and AC grounded circuit conductors require a DC grounding system.
  - This applies to most interactive PV systems, except those systems using AC modules.

- Three grounding options are allowed for systems with AC and DC grounding requirements:
  1. A separate DC electrode is used and bonded to the AC grounding electrode.
  2. A common grounding electrode is used for the AC and DC circuits.
  3. The DC grounding electrode conductor (GEC) is combined with the AC equipment grounding conductor (EGC).
When a separate DC electrode is used, it must be bonded to the AC grounding electrode.

Bonding jumpers must be sized based on the larger of the DC GEC and AC GEC size.

The DC GEC or bonding jumpers may not substitute for any required AC equipment grounding conductors.
A common grounding electrode may be used for the AC and DC system grounding requirements, and requires the following:

- The DC GEC must run from a marked DC GEC connecting point to the AC grounding electrode, or the AC GEC if the AC grounding electrode is unavailable.
- The DC GEC may not substitute for any required AC equipment grounding conductors.
The DC grounding electrode conductor (GEC) may be combined with the AC equipment grounding conductor (EGC). This grounding conductor must:

- Run continually without splices (irreversible splices permitted),
- Be connected to the DC GEC at a marked termination point, and
- Be sized for the larger of the size of the equipment grounding conductors (EGCs) and the size of the DC grounding electrode conductor (GEC).
The continuity of the EGC and grounded conductors from PV source circuits and output circuits must be maintained whenever equipment is removed for service or maintenance.

Temporary equipment bonding jumpers may be required if either grounding system is disconnected during maintenance.
Additional grounding electrodes at the PV array location were required in the 690.47(D) of the 2008 NEC, but removed from the 2011 NEC.

If the GEC from a roof-mounted array is dropped vertically and falls within 6 feet of an existing grounding electrode, an additional array grounding electrode is not required.

Where required, the DC grounding electrode conductor usually needs to be a minimum size 6 AWG copper.
Lightning Protection Systems

- The lightning protection systems on buildings must be bonded to the electrical service grounding electrode system.

- Conductive metal parts of PV electrical systems including support structures, raceways, combiner boxes or other metal equipment may require certain spacing from or bonding to the lightning protection system.
Summary

- Article 690 and numerous other sections of the National Electrical Code establish the installation requirements for PV systems.

- The size and ratings for conductors and overcurrent protection devices are determined from the maximum circuit voltages and currents associated with the connected equipment.

- Disconnect means isolate major equipment and circuits for safety and maintenance.

- Grounding and bonding reference equipment and circuits to earth potential to protect equipment from surges and reduce the hazard for electrical shock.
Questions and Discussion