Overcurrent Protection Devices (OCPD) on Solar Arrays

This paper describes when and why PV fuses/breakers are needed and provides high level information on sizing the PV fuse/breakers. There will be some information about sizing the PV wires, but a detailed discussion wire sizing is beyond the scope of this paper.

A more detailed description of NEC compliant fuse sizing can be found here:
https://diysolarforum.com/resources/sizing-fuses-for-photovoltaic-systems-per-the-national-electrical-code.133/download

Disclaimer: Unless otherwise noted, I have tried to keep this document in alignment with the National Electric Code (NEC). However, this document does not address all aspects of the related code.

Rev 0.5

High Level Summary (The short answer):

The following is a summary of the NEC requirements for the Over Current Protection Device (OCPD) and Cabling for a Solar array.

The remainder of this document will examine these requirements in more detail.

Note: For all of the cases below, the Cable sizing and OCPD rating may need to be adjusted for temperature.

Definition: Photovoltaic Source Circuit. *Circuits between solar panels and from solar panels to the common connection point(s) of the DC system.*

Definition: Photovoltaic Output Circuit. *Circuit conductors between the PV Source circuit(s) and the inverter or DC utilization equipment*

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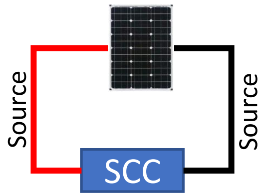
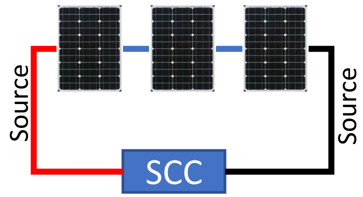
1 string of 1 or more serial panels

- *No fuses or breakers required*
- *Source circuit cables must be rated for at least 156% of Isc*





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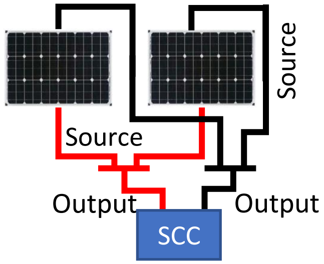
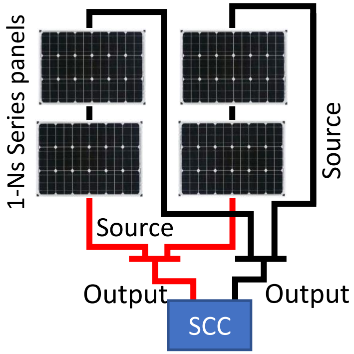
2 Parallel strings of 1 or more series panels

- *No fuses or breakers Required*
- *Source circuit cables must be rated for at least 156% of Isc*
- *Output circuit cables must be rated for at least 2 x 156% of Isc*





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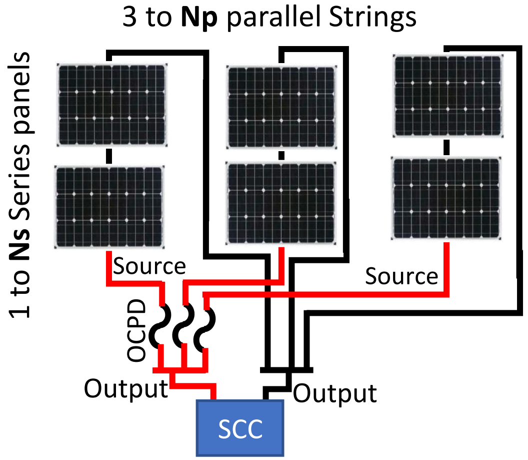
3 or more Parallel Strings of 1 or more series panels:

- *OCPDs (Fuses or breakers) required*
- *The voltage rating of the OCPDs must be Ns x Vmax or greater. (Ns = number of serial panels)*
- *Each Source circuit must have OCPD rated for at least 156% of Isc.*
- *Source circuit cables must be rated for at least 156% of Isc*
- *Source circuit cables must be rated for more current than the OCPD*
- *Output circuit cables rated for at least Np x 156% of Isc (Np = number of parallel strings)*



Max Current and Max Voltage calculations for Solar Panels

Max Current from a panel

Solar panels are current limited devices and the maximum current in their specifications will always be the Short-Circuit Current: **Isc**. However, this is an amount that is determined at very specific light and temperature conditions. Consequently, in some conditions a panel can produce more than the Isc current. Consequently, the NEC considers 125% of **Isc** as the max current (**Imax**) from a solar panel.

Imax = 1.25 Isc

- **Min PV cable sizing:** the NEC requires the cable to handle 125% of Imax. When this extra 25% is applied you get:
  1.25 x Imax = 1.25 x (Isc x 1.25) = **1.56 x Isc**. (For a single panel or set of panels in series)
- **Min OCPD Sizing:** PV Fuses and breakers should not be run at greater than 80% of their rated value. Consequently, the NEC requires the fuse or breaker to be a minimum of 125% of Imax. Once again this works out to be:
  1.25 x Imax = 1.25 x (Isc x 1.25) = **1.56 x Isc**. (For a single panel or set of panels in series)

Max Voltage from a panel

The highest voltage on a solar panel's specification will always be the Open Circuit Voltage: **Voc** As with Isc, Voc is determined under very specific conditions and therefor can be higher than the Voc specification in some situations. If the panel spec provides a temp coefficient for Voc, the NEC requires you to calculate Vmax (Not covered here). Otherwise the NEC uses the following table for calculating Vmax .

Lowest Ambient Temp		Factor (F_t)
°C	°F	
25 or more	77 or more	1
24 to 20	76 to 68	1.02
19 to 15	67 to 59	1.04
14 to 10	58 to 50	1.08
9 to 5	49 to 41	1.08
4 to 0	40 to 32	1.10
-1 to -5	31 to 23	1.12

Lowest Ambient Temp		Factor (F_t)
°C	°F	
-6 to -10	22 to 14	1.14
-11 to -15	13 to 5	1.16
-16 to -20	4 to -4	1.18
-21 to -25	-5 to -13	1.20
-26 to -30	-14 to -22	1.21
-31 to -35	-23 to -31	1.23
-36 to -40	-32 to -40	1.25

Example use of table

If the lowest ambient temperature will be -22°C and your panels have a Voc of 39.9V, the calculation for Vmax is:

Vmax = 1.2 x 39.9V = 47.9V

For simplicity, this paper will always use a temperature factor of 1.2 for determining Vmax

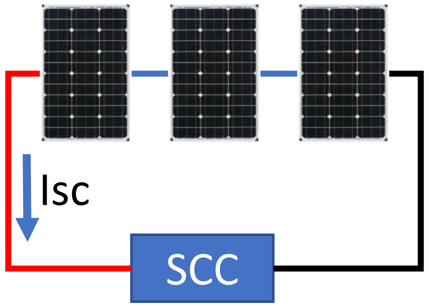
(Some professional installers just use a factor of 1.25 and call it good. This may be overkill in warmer climates)

Single Panel and Series Panels

One Panel

Solar panels have a maximum current (Isc: Short Circuit Current) that is low enough that even a short circuit will not damage the solar panel. Furthermore, the normal operating current is so close to the short circuit current that it would be very difficult to select a fuse or breaker that would blow on a short circuit but not blow in normal operation. Consequently, there is no need to put a fuse or breaker on a single panel.

Between 1 and N series panels



When adding panels in series, the voltage increases, but the current does not. Consequently, even a large string of series panels can be treated the same as a single panel…. And there is no need for a fuse or breaker.

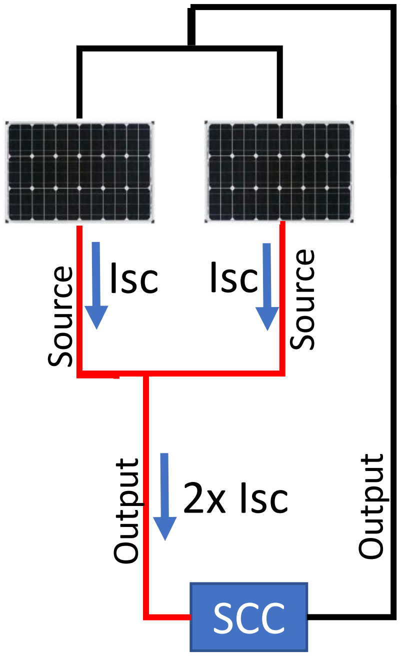
However, to ensure there is no issue with a short, the cable for the solar panels must be sized to handle 156% or more of the Isc of the panels. (Temperature adjustments may be needed when sizing the cable)

2 Parallel or 2 Parallel Strings of 2 or more Series Panels

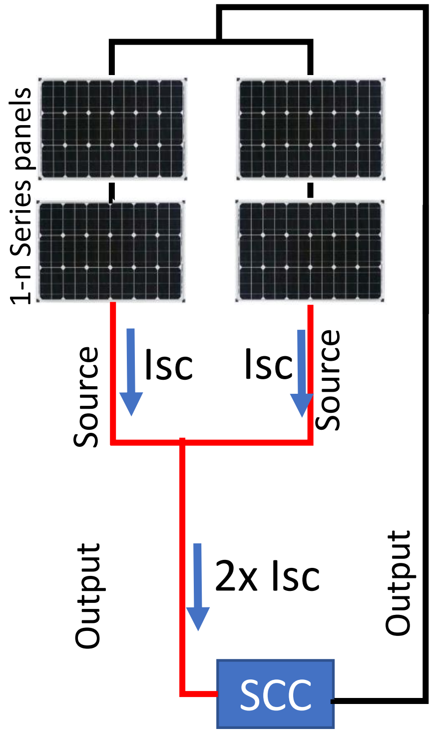
In the case of parallel panels, the current adds as you add panels. Consequently, in the event of a short circuit in one of the panels, that panel would 'see' the combined current of all of the parallel panels.

With **two** parallel panels or strings of panels, the combined current is low enough that **Over-Current Protection(OCP) devices are not needed** (See Appendix B for further explanation). The source circuit cable cabling used must be rated at 156% or more of ISC . The main output circuit cable must also handle 156% of the expected Isc load from both panels or strings. (Temperature adjustments may be needed when sizing the cable)

EXAMPLES



2 parallel panels



2 strings of parallel panels

Panel Specs	
Watts (STC)	315 W
Max Power Voltage (VMPP)	33.1 V
Max Power Current (IMPP)	9.52 A
Open Circuit Voltage (VOC)	39.9 V
Short Circuit Current (ISC)	10.00 A
Max System Voltage (UL)	DC 1000 V

- **Minimum Source circuit cable rating**:
  10.00 x 1.56 = 15.6 A.
  The ampacity charts indicate a minimum of 14AWG wire. (It may need to be larger if it has a long run)
- **Minimum Output circuit cable rating:**
  2x 10.00A x 1.56 = 31.20A
  The ampacity charts indicate a minimum of 10 AWG (It may need to be larger if it has a long run to the SCC)

Notice that additional panels in series does not change the cable sizing requirements.

3 or more Parallel Strings of 1 or more Series Panels

With 3 or more parallel panels, the current due to a short can become a hazard if the current from other strings back-feed into the shorted panel. Consequently, **an OCPD must be placed on each parallel panel or parallel string of series panels**. The OCP devices must be rated for 156% or more of the Isc of the panels. (Many panels have a 'series fuse rating'. This is the *most* current the panel can handle without damage and therefore the OCPD current rating must be less than this value. This value is usually quite high compared to Isc and therefor is not usually a factor.) The minimum Voltage rating of the OCPD must be the Voc x Temp-factor of the of the combined voltage of the number of panels in series. (See page 3 for description of the Temp-factor)

The cable for the Source circuit must be rated to handle at least the current rating of the OCPD selected or 156% of Isc (whichever is larger). The cable for the Output circuit must be able to handle 156% of the combined Isc of all the parallel panels or strings of panels. (Temperature adjustments may be needed when sizing the cables)

EXAMPLE

3 parallel panels

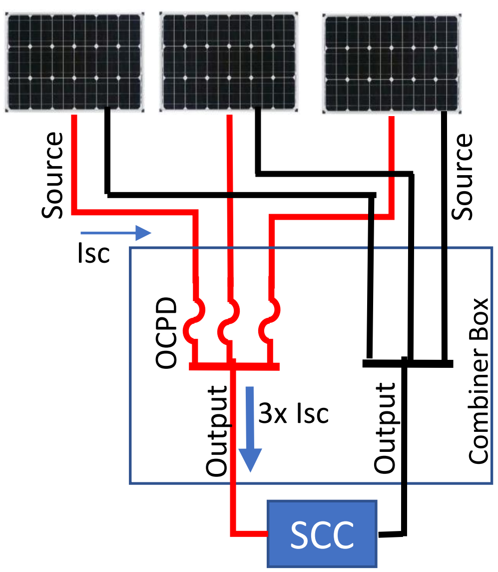


Figure 1

3 parallel strings of series panels

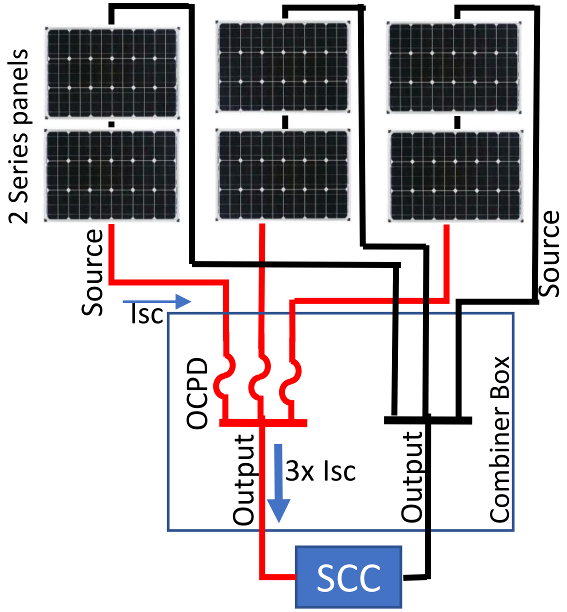


Figure 2

Panel Specs

Watts (STC)	**315 W**
Max Power Voltage (VMPP)	**33.1 V**
Max Power Current (IMPP)	**9.52 A**
Open Circuit Voltage (VOC)	**39.9 V**
Short Circuit Current (ISC)	**10.00 A**
Max System Voltage (UL)	**DC 1000 V**
String Fuse Rating	**32A**

- **OCPD current rating:**
  10 x 1.56 = 15.6A. This will need to be rounded up to **20A** to find an available device
  (This is well under the 32A String Fuse Rating)
- **Minimum OCPD vice voltage rating:**
  For **Figure 1** there is only 1 panel in series, so it is:
  39.9 x 1.20 x 1 = 47.9V
  For **Figure 2** there is 2 panels in series, so it is:
  39.9 x 1.20 x 2 = 95.76V
- **Minimum Source circuit cable current rating:**
  The OCP rating (**20A**) will be used since it is greater than 156% of Isc. This requires a minimum of a 14AWG cable. (It may need to be larger if it has a long run)
- **Minimum Output circuit cable rating:**
  10 x 3 x 1.56 = 46.8A This requires an 8AWG cable.
  (It may need to be larger if it has a long run)

Sizing cables and adjusting for temperature related issues.

When selecting cable size we often just go to our favorite ampacity chart and select the size based on the expected current. However, there are several temperature related considerations that could increase the required cable size, particularly for PV cable that may be in the sun.

Generally speaking, no further adjustments are needed if 1) the ambient temp remains below 105^{o}F (40^{o}C), and 2) the wires are not on the roof, and 3) there are no more than 3 current carrying wires in the same conduit. (Equipment ground is not considered a current carrying wire). If these conditions are met, you can use the current discussed earlier in the paper and the Ampacity table for the wire type you have. See the next page for the NEC Ampacity chart.

However, if any of the following conditions exist, the wire size may need to be larger (sometimes significantly larger):

- Ambient temps above 105^{o}F/40^{o}C.
- More than 3 current carrying conductors in a single conduit or raceway
- Wire on the roof or in the sun (particularly if it is in conduit).

Calculating these adjustments for these conditions is beyond the scope of this paper but will be addressed in a future paper.

Sizing PV cables for length of run

The previous wire sizing calculations in this paper were all for safety (minimizing fire risk). However, The PV array is often a long distance from the Solar Charge controller. Consequently, there could be a significant voltage drop along the cables if they are not sized appropriately.

To determine voltage drop I will use an on-line voltage drop calculator. There are many out there. This one works well for me: https://www.bestboatwire.com/pages/voltage-drop-calculator (Note: Be sure to put in the total round trip length)

When calculating for voltage drop, I use the Array Vmpp and Impp as the inputs to the calculator. (Voc and Isc are not the typical conditions and the 1.56x factor in the previous calculations is significantly higher than typical conditions).

I like to design for 3% voltage drop or less. Higher voltage drops will still work, but it can be a trade off between cost and system efficiency.

Notice that because of the 1.56x current multiplier for safety and the possibility of needing larger wires for voltage drop. There can be a significant advantage to designing the PV array for higher voltage and lower current.

A bit of good news: Because of the 1.56x multiplier for the safety calculations, the safety calculations end up requiring fairly large wires. Consequently, for short to moderate lengths, it is unusual to need to increase the size of the wire.

PV voltage drop Example 1.

In the previous example, we calculated the output circuit needed to be 8AWG for safety reasons. If the array is 100ft from the controller, is 8AWG large enough for a 3% voltage drop?

The ‘normal’ current on the output circuit is 3 x Imp or 3 x 9.52 = 28.56A.

The Voltage on the output circuit is 2 x Vmp or 2 x 33.1V = 66.2V

The round trip conductor length is 2 x 50’ = 100ft

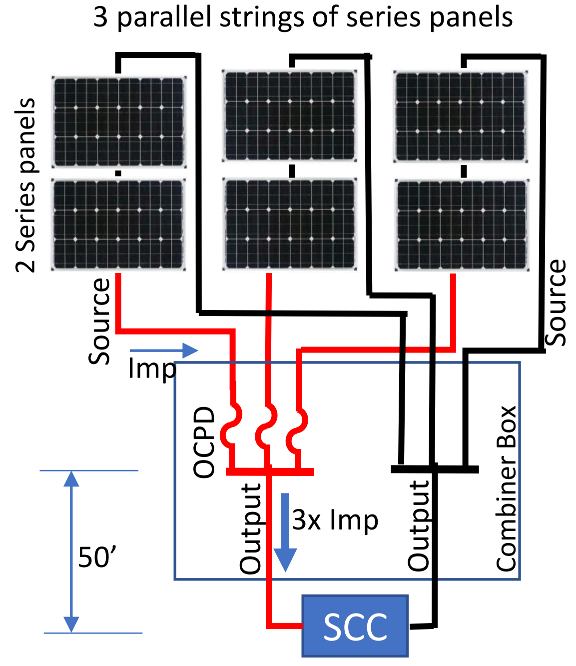
Plugging this into the calculator we get 5.4%.

If we bump the wire size up to 6AWG we get 3.4%

To get to less than 3% we would have to go all the way to 4 AWG.

I would be tempted to call it good with 6AWG and 3.4%

Example 1: Calculate the voltage drop for the output circuit



Panel Specs	
Watts (STC)	315 W
Max Power Voltage (Vmp)	33.1 V
Max Power Current (Imp)	9.52 A
Open Circuit Voltage (VOC)	39.9 V
Short Circuit Current (ISC)	10.00 A
Max System Voltage (UL)	DC 1000 V
String Fuse Rating	32A

PV voltage drop Example 2

For safety purposes, the source cable for example 2 needs to be at least 10AWG. (See previous slides for how that is calculated)

The 'normal' current on the output circuit is 2 x Imp or
2 x 9.52 = 19.04 A.

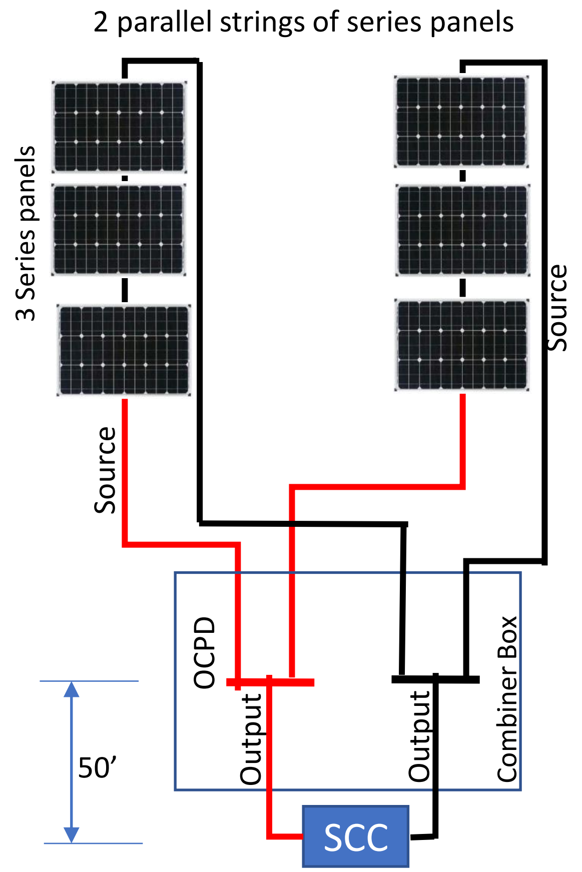
The Voltage on the output circuit is 3 x Vmp or
2 x 33.1V = 99.3V

The round trip conductor length is 2 x 50' = 100ft

Plugging this into the calculator we get 3.82%. A bit high

If we bump the wire size up to 8AWG we get 2.4%. Good!

Example 2: Calculate the voltage drop for the output circuit



Panel Specs	
Watts (STC)	315 W
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Max Power Current (Imp)	9.52 A
Open Circuit Voltage (VOC)	39.9 V
Short Circuit Current (ISC)	10.00 A
Max System Voltage (UL)	DC 1000 V
String Fuse Rating	32A

Notice how a simple rearrangement of the array layout allowed us to significantly reduce the wire size for the PV cables.
In this case, it also allowed us to remove the Source Circuit OCPD devices!

2017 NEC 310.15(B)16 Ampacity Chart

Size (AWG or kcmil)	Temperature Rating of Copper Conductor		
	60°C (140°F)	75°C (167°F)	90°C (194°F)
	Types TW UF	Types RHW THHW THW THWN XHHW USE ZW	Types FEP FEPB MI RHH RHW-2 SA SIS TBS THHN THHW THW-2 THWN-2 USE-2 XHH XHHW XHHW-2 ZW-2
18 AWG	—	—	14
16 AWG	—	—	18
14 AWG*	15	20	25
12 AWG*	20	25	30
10 AWG*	30	35	40
8 AWG	40	50	55
6 AWG	55	65	75
4 AWG	70	85	95
3 AWG	85	100	115
2 AWG	95	115	130
1 AWG	110	130	145
1/0 AWG	125	150	170
2/0 AWG	145	175	195
3/0 AWG	165	200	225
4/0 AWG	195	230	260
250 KCMIL	215	255	290
300 KCMIL	240	285	320
350 KCMIL	260	310	350
400 KCMIL	280	335	380
500 KCMIL	320	380	430
600 KCMIL	350	420	475
700 KCMIL	385	460	520
750 KCMIL	400	475	535
800 KCMIL	410	490	555
900 KCMIL	435	520	585
1000 KCMIL	455	545	615
1250 KCMIL	495	590	665
1500 KCMIL	525	625	705
1750 KCMIL	545	650	735
2000 KCMIL	555	665	750

Fuses vs Breakers

- Either a fuse or a breaker can be safely used to protect parallel strings of panels.
- Breakers and fuses must be DC rated for the voltage of the circuit.
- Fuses are usually significantly less expensive
- There are manufacturer defined temperature deratings for fuses when operated above 104°F/40°C ambient.
- Breakers are resettable, but a well-designed system should not be blowing a breaker or fuse in normal operation.
- Breakers are not generally designed as a switch that can be used regularly. However, a breaker can be use for a disconnect that is rarely used.

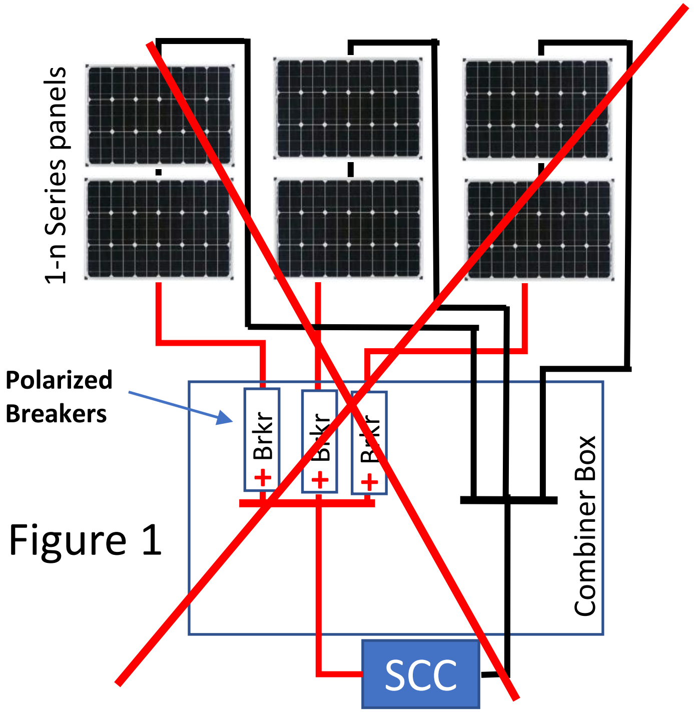


Figure 1

Directional or Polarized DC Breakers – Don't use 'em.

Many DC breakers are designed to trip on excessive current in only one direction. With these breakers, the positive should be on the 'source' side of the circuit the breaker is protecting). These work well as long as the DC current is flowing in the specified direction. However, they do not trip if the current is flowing in the wrong direction. Worse, if you turn them off when the current is flowing in the wrong direction, they may not extinguish the fault and can catch fire. The breakers for solar have the current flowing in one direction when operating normally and must trip when the current is backfed in the other direction. Do not use polarized breakers as over current protection devices on solar strings.

Disconnects Vs OCP on the Output circuit.

All solar installations should have a disconnect on the output circuit, between the solar array and the solar charge controller. This disconnect should disconnect both the positive and the negative line from the array. (This is one of many disconnect requirements that the NEC places on solar installations).

Quite often, the disconnect is implemented using a dual circuit breaker because using a breaker can be a cost-effective way to implement a disconnect. Even some controller manufacturers say to use a breaker. This has created confusion that leads some people to believe breakers are required. However, if the system is installed with proper string OCP (if needed) and properly sized wires, there is not a need for the disconnect on the PV Output circuit to be a breaker. A properly rated dual pole switch is adequate.

If a breaker is used as the disconnect, there are a few things to keep in mind.

- Breakers are not typically designed for frequent use as a switch. Using a breaker as a switch can weaken them over time, and this could result in nuisance trips.
- When used in place of a switch, a breaker's trip rating should be higher than the calculated PV output circuit current (PV output current = Isc x number of parallel stings x 1.56 =)

Appendix A: Additional considerations for NEC compliance

The NEC has additional requirements on PV OCP and PV Disconnect that are not addressed in this paper. Some of the other requirements that are not addressed in this paper include

- Must use Listed components to be NEC compliant.
- Location and Labeling of the OCP devices.
- Derating OCP devices in high temperature climates to avoid nuisance trips.
- Wire and Cabling types.
- Adjusting wire size for temperature, conduit fill and conduit placement.

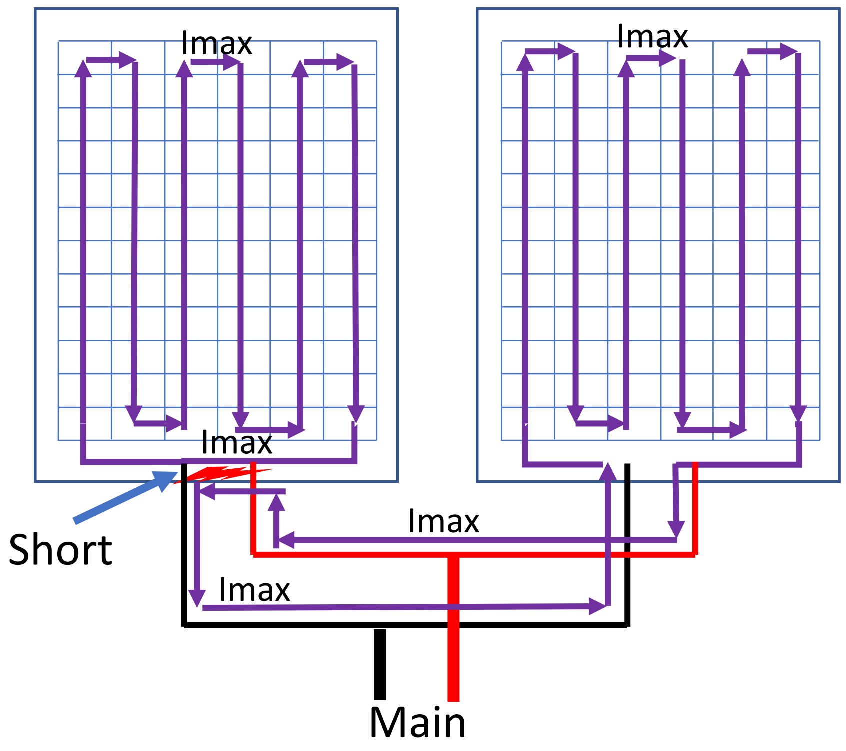
Important related items to consider are

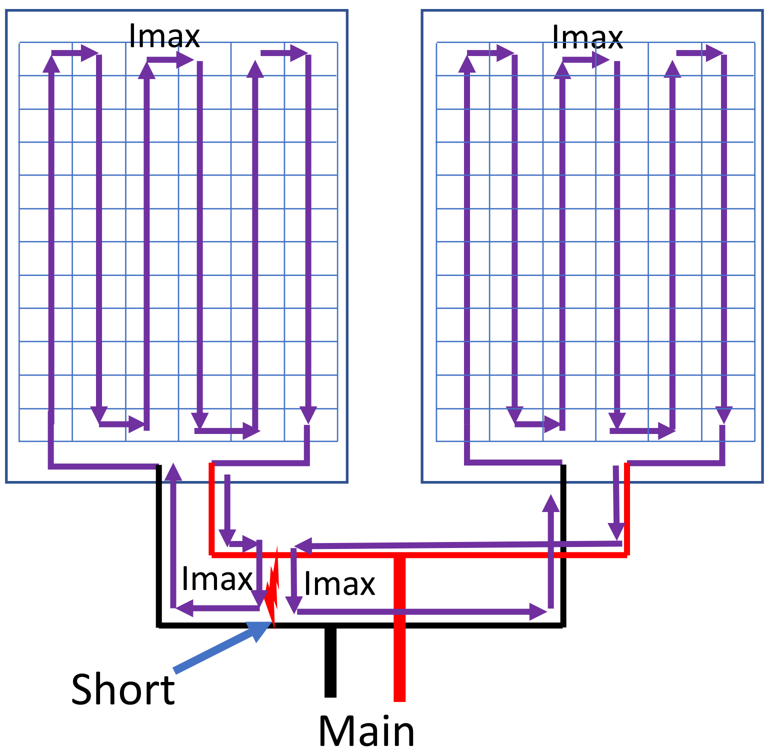
- PV Ground Fault Protection and Arc Fault Protection.
- PV Rapid Disconnect requirements.
- OCPD on the battery side of the SCC

Appendix B: Why 2 parallel panels don't need OCPDs

As stated above, two parallel panels do not need OCP devices on the two strings. However, if both of the panels can produce the Isc current, then we are dealing with twice the current of a single panel…. Why don't you need to put a fuse or breaker on it?

The diagrams below show two parallel panels with shorts in a couple places





Imax = 1.25 x Isc

Notice that the only place that sees the 2xImax is the short itself. Everyplace else in the circuit only sees Imax. Therefor, there is no place you could put an OCP device on the parallel circuits that would see the double current. Furthermore, the main circuit wires must be sized to handle the 2x 1.25 X Imax (2 x 1.25 x 1.25 x Isc) and a short would not be harmful on them.