

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.

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.

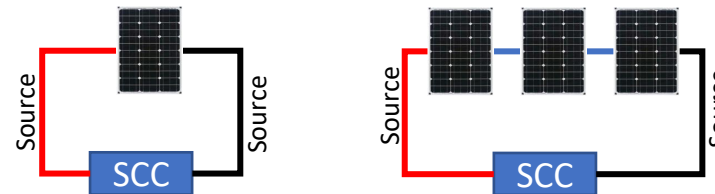
Note: For all of the cases below, the Cable sizing and OCPD rating may need to be adjusted for temperature.

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

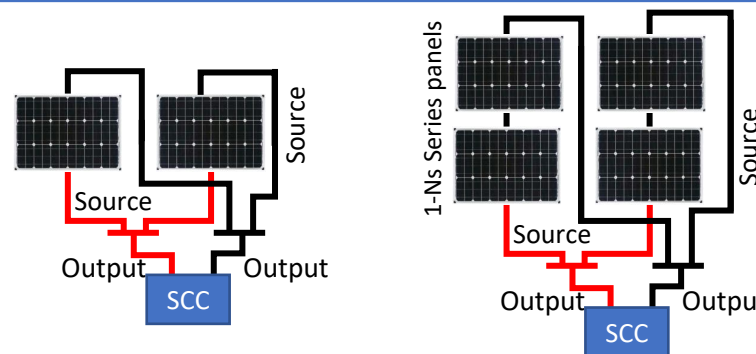
1 string of 1 or more serial panels

- No fuses or breakers required
- Source circuit cables must be rated for at least 156% of I_{sc}



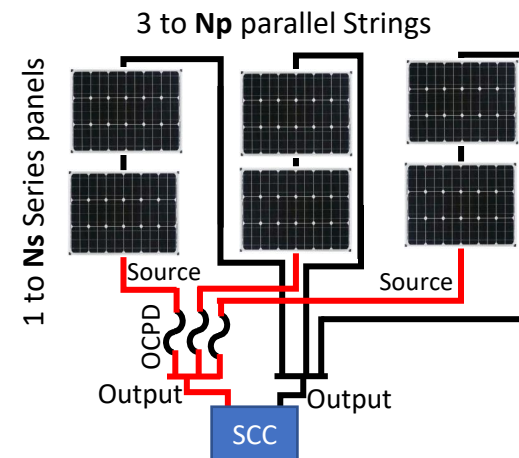
2 Parallel strings of 1 or more series panels

- No fuses or breakers Required
- Source circuit cables must be rated for at least 156% of I_{sc}
- Output circuit cables must be rated for at least $2 \times 156\%$ of I_{sc}



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

- OCPDs (Fuses or breakers) required
- The voltage rating of the OCPDs must be $N_s \times V_{max}$ or greater. (N_s = number of serial panels)
- Each Source circuit must have OCPD rated for at least 156% of I_{sc} .
- Source circuit cables must be rated for at least 156% of I_{sc}
- Source circuit cables must be rated for more current than the OCPD
- Output circuit cables rated for at least $N_p \times 156\%$ of I_{sc} (N_p = 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 (**I_{max}**) from a solar panel.

$$I_{max} = 1.25 I_{sc}$$

- **Min PV cable sizing:** the NEC requires the cable to handle 125% of I_{max}. When this extra 25% is applied you get:
 $1.25 \times I_{max} = 1.25 \times (I_{sc} \times 1.25) = \mathbf{1.56 \times I_{sc}}$ (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 I_{max}. Once again this works out to be:
 $1.25 \times I_{max} = 1.25 \times (I_{sc} \times 1.25) = \mathbf{1.56 \times I_{sc}}$ (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 V_{max} (Not covered here). Otherwise the NEC uses the following table for calculating V_{max}.

Lowest Ambient Temp		Factor (F _t)	Lowest Ambient Temp		Factor (F _t)
°C	°F		°C	°F	
25 or more	77 or more	1	-6 to -10	22 to 14	1.14
24 to 20	76 to 68	1.02	-11 to -15	13 to 5	1.16
19 to 15	67 to 59	1.04	-16 to -20	4 to -4	1.18
14 to 10	58 to 50	1.08	-21 to -25	-5 to -13	1.20
9 to 5	49 to 41	1.08	-26 to -30	-14 to -22	1.21
4 to 0	40 to 32	1.10	-31 to -35	-23 to -31	1.23
-1 to -5	31 to 23	1.12	-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 V_{max} is:

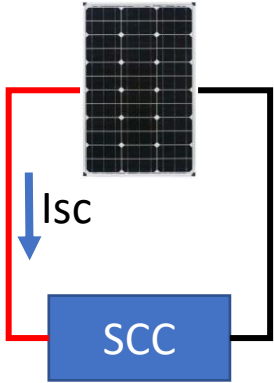
$$V_{max} = \mathbf{1.2} \times 39.9V = 47.9V$$

For simplicity, this paper will always use a temperature factor of 1.2 for determining V_{max}

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

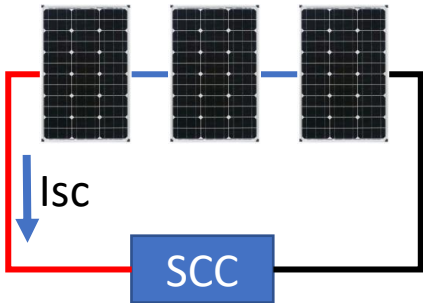
Single Panel and Series Panels

One Panel



Solar panels have a maximum current (I_{sc} : 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.

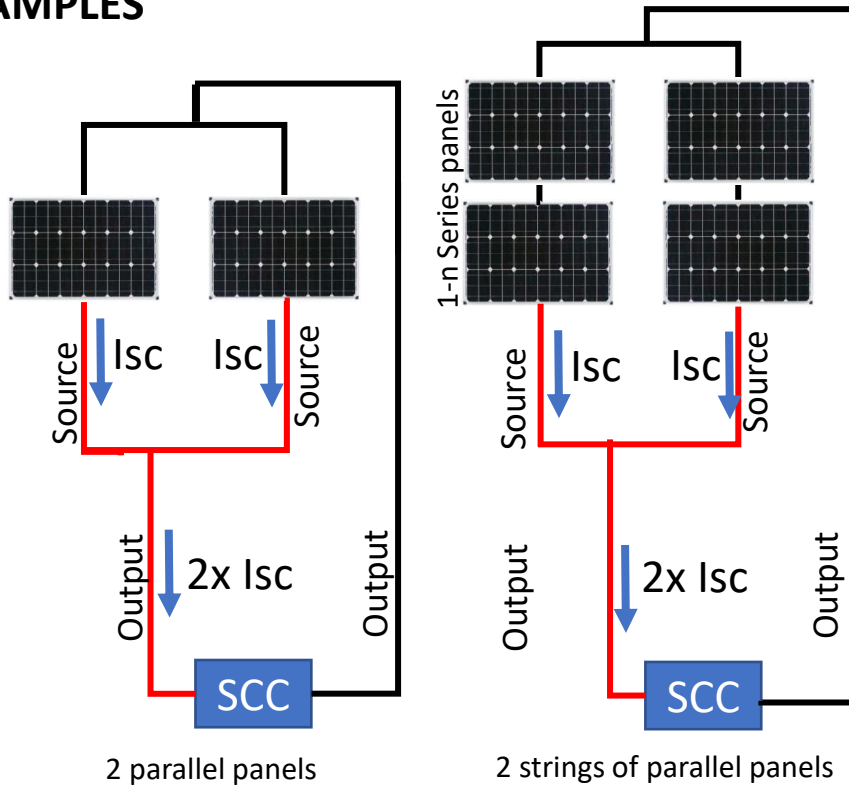
However, to ensure there is no issue with a short, the cable for the solar panels must be sized to handle 156% or more of the I_{sc} of the panels. (Temperature adjustments may be needed when sizing the cable)

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



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:**

$$10.00 \times 1.56 = 15.6 \text{ A.}$$

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:**

$$2 \times 10.00 \text{ A} \times 1.56 = 31.20 \text{ A}$$

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 I_{sc} 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 I_{sc} and therefor is not usually a factor.) The minimum Voltage rating of the OCPD must be the $V_{oc} \times \text{Temp-factor}$ 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 I_{sc} (whichever is larger). The cable for the Output circuit must be able to handle 156% of the combined I_{sc} of all the parallel panels or strings of panels. (Temperature adjustments may be needed when sizing the cables)

EXAMPLE

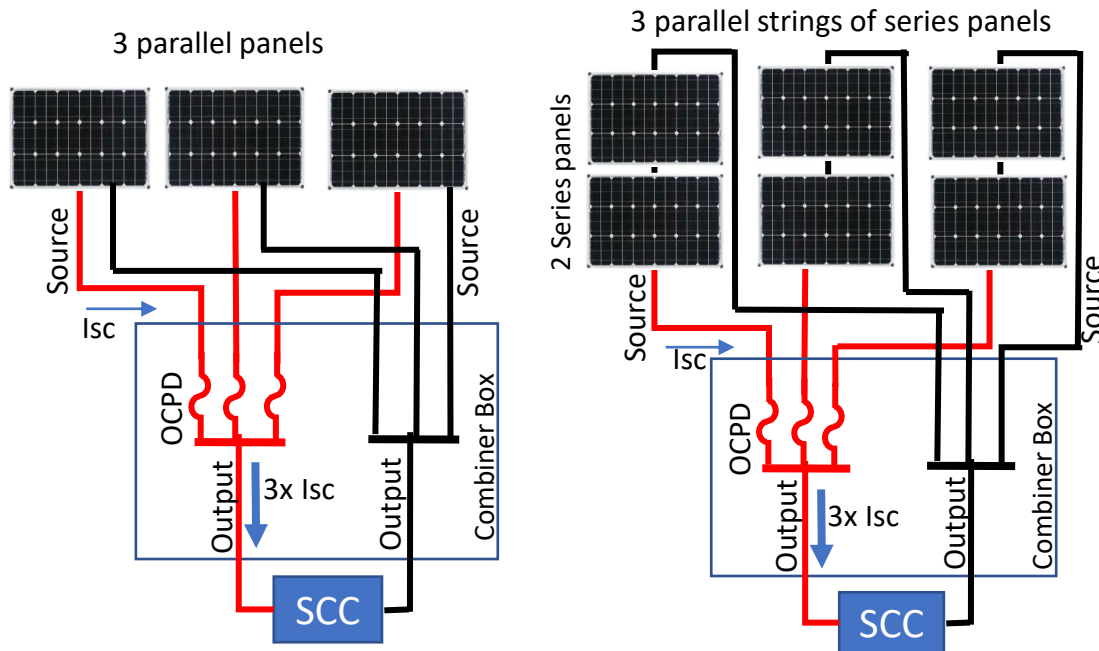


Figure 1

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:**
 $10 \times 1.56 = 15.6A$. 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:
 $39.9 \times 1.20 \times 1 = 47.9V$
For **Figure 2** there is 2 panels in series, so it is:
 $39.9 \times 1.20 \times 2 = 95.76V$
- **Minimum Source circuit cable current rating:**
The OCP rating (**20A**) will be used since it is greater than 156% of I_{sc} . 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:**
 $10 \times 3 \times 1.56 = 46.8A$ 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°F (40°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°F/40°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.

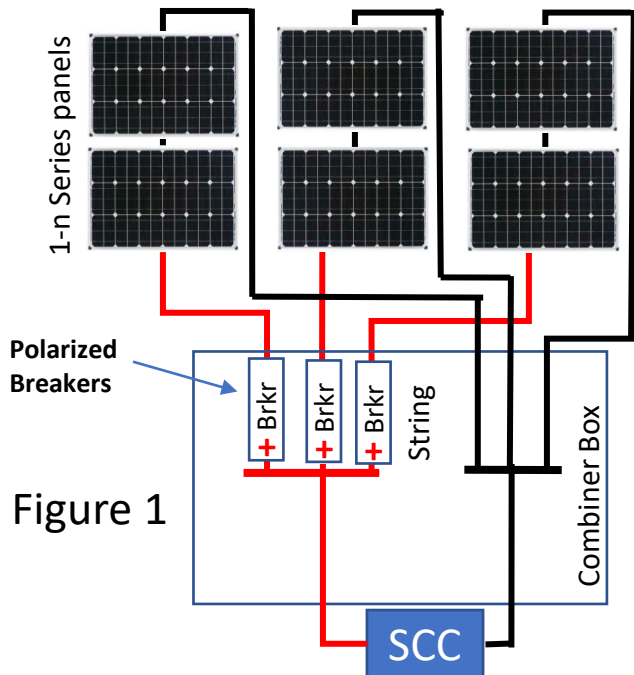
2017 NEC 310.15(B)16

Ampacity Chart

Size (AWG or kcmil)	Temperature Rating of Copper Conductor					
	60°C (140°F)	75°C (167°F)		90°C (194°F)		
	Types	Types		Types		
	TW UF	RHW THHW THW THWN	XHHW USE ZW	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 used for a disconnect that is rarely used.



Directional or Polarized DC Breakers

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).

The String breakers in Figure 1 are there to protect from too much current back-feeding into the panel(s). (The 'source' is the other panels in the array) Consequently, the positive side of the breaker should be toward the SCC (Away from the string being protected)

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 = $I_{sc} \times \text{number of parallel strings} \times 1.56 =$)

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.

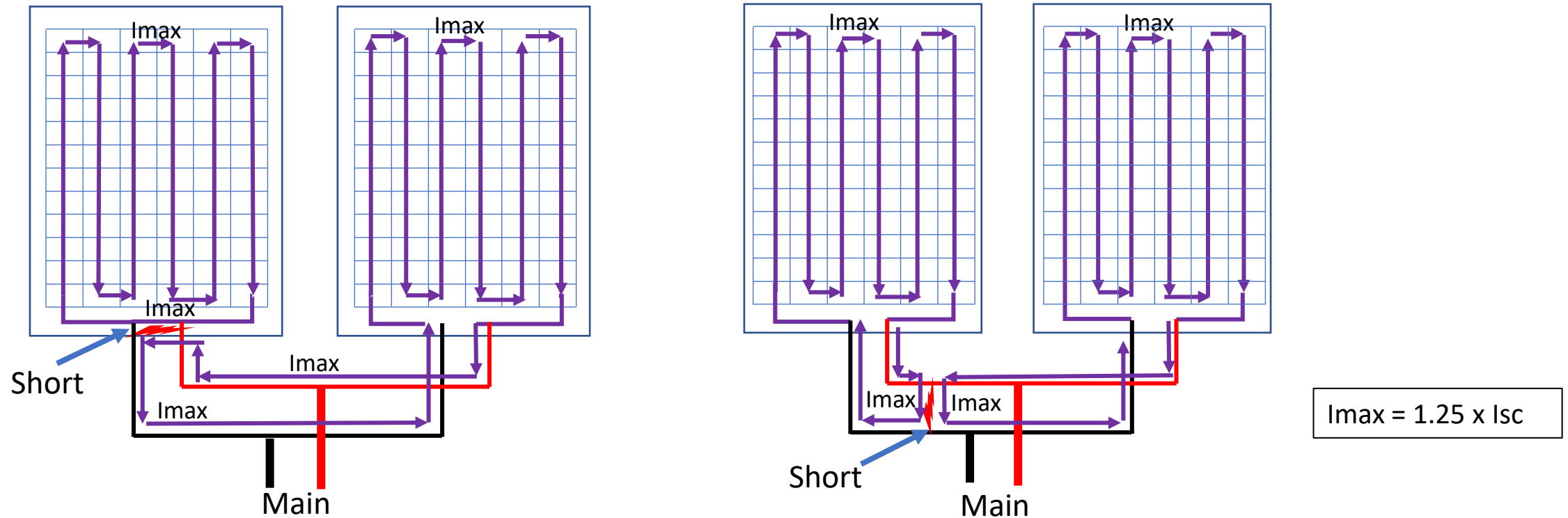
Important related items to consider are

- 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 I_{sc} 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



Notice that the only place that sees the $2 \times I_{max}$ is the short itself. Everyplace else in the circuit only sees I_{max} . Therefore, 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 $2 \times 1.25 \times I_{max}$ ($2 \times 1.25 \times 1.25 \times I_{sc}$) and a short would not be harmful on them.