solar_iv_5a.sqproj

PV cells (or modules) are typically connected in a series-parallel network in order to increase the voltage and current output. However, if one of the cells has a lower photocurrent I_p (because of shading or dust, for example), there is a possibility that it will conduct in reverse breakdown, an undesirable condition which results in excessive power dissipation or “hot spots.” To prevent this catastrophic situation, bypass diodes are used. It is the purpose of this example to explain the functioning of a bypass diode in a simple case.

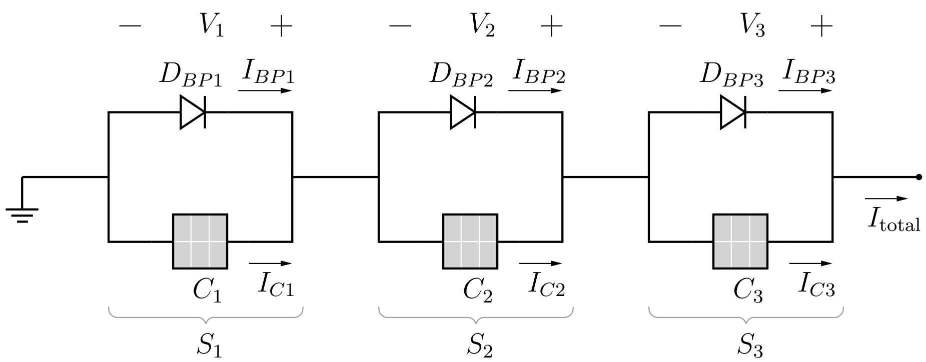


Figure 1: Three solar cells connected in series with a bypass diode connected across each of them.

Fig. 1 shows a series connection of three sub-circuits S_1, S_2, S_3 each consisting of a PV cell and a bypass diode connected in parallel. The I-V relationship for one such sub-circuit is presented in detail in `solar_shade_1.sqproj` and is summarised in Fig. 2. We note the following salient features of the I-V plot of Fig. 2.

(a) When the total current I_{total} is between 0 and I_p, the cell voltage drop is positive (see Fig. 1 for the polarity of the cell voltage), and the bypass diode is off (reverse biased).

(b) The condition $I_{\text{total}} > I_p$ requires the bypass diode to conduct under forward bias which means that the cell voltage is negative. Of the total current, I_p is conducted by the cell, and the difference $(I_{\text{total}} - I_p)$ is conducted by the bypass diode. The cell voltage V_a gets clamped to $-V_{BP}^{\text{on}}$ as seen in the figure.

When three identical cells are connected in series (with the same value of photocurrent I_p), they all carry the same current[1], the voltage drops V_1, V_2, V_3 (see Fig. 1) are identical, and the net voltage drop is simply three times the drop across one of the cells.

Suppose now that Cell 3 is under shade, and as a result its photocurrent has reduced from I_p to $I_p/2$. Consequently, the overall I-V and P-V relationships also change, as shown in Figs. 3 (a) and 3 (b). In order to understand how these changes come about, we have also plotted the voltage across each cell (Fig. 4), current through each cell (Fig. 5 (a)), and current through each bypass diode (Fig. 5 (b)) as a function of the total voltage drop (V_a in Fig. 1).

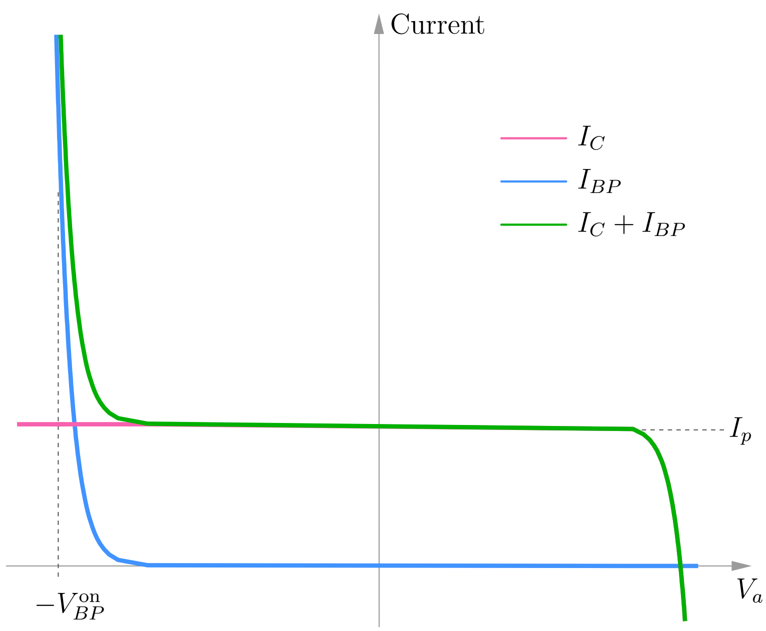


Figure 2: Current-voltage relationship for one of the cell-bypass diode combinations of Fig. 1. The photocurrent is denoted by I_p.

The constraints that the three sub-circuits (S_1, S_2, S_3 in Fig. 1) need to satisfy are shown in Fig. 6. Since S_1, S_2, S_3 are connected in series, the same current (I_{total}) must pass through each of them. Four representative values (denoted by I_1, I_2, I_3, I_4) are shown in Fig. 6. The voltage drops V_1, V_2, V_3 in each case are given by the intersection of the corresponding

[1] Note that the value of the current will depend on how the load is connected. Typically, maximum power point tracking (MPPT) is employed to ensure that the power delivered is maximum, and I_{total} is slightly less than I_p in that case.

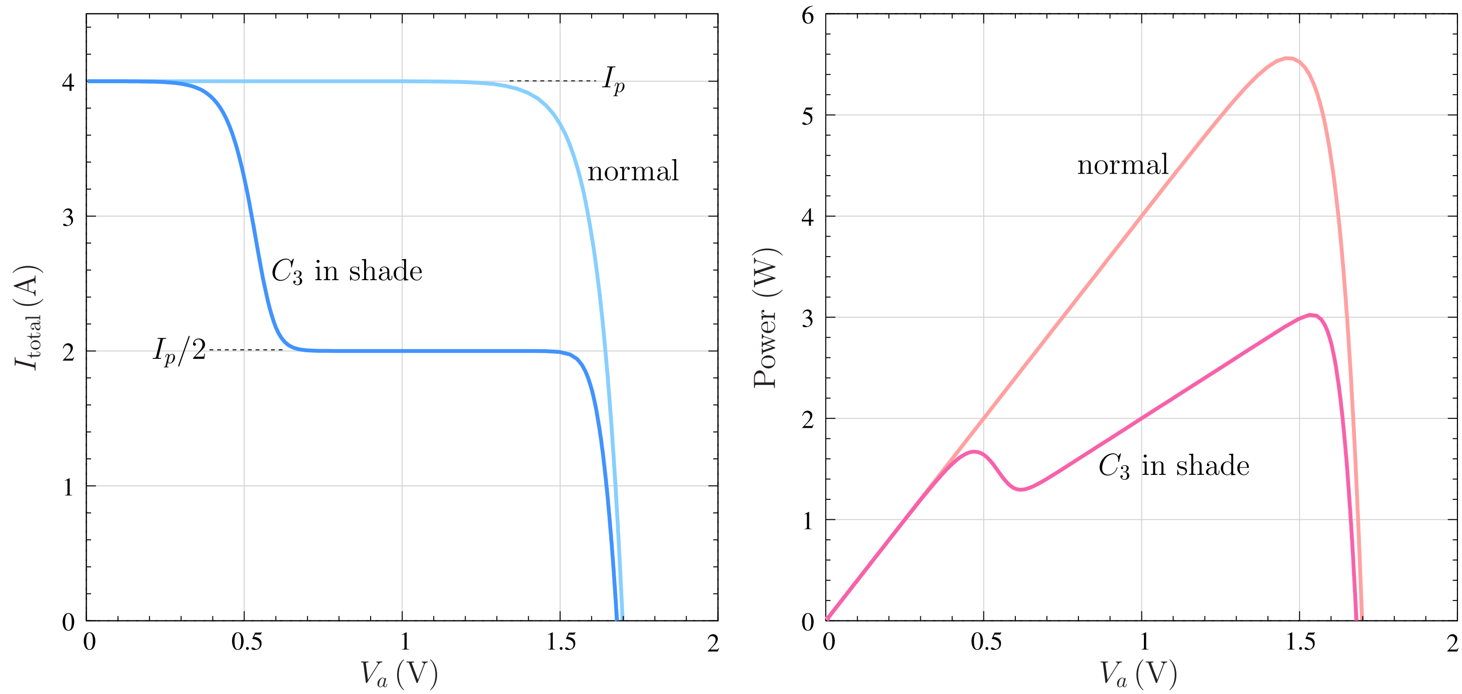


Figure 3: (a) I-V and (b) P-V relationship for the series connection of solar cells shown in Fig. 1, with $I_{p1} = I_{p2} = I_p$, and $I_{p3} = I_p/2$. For comparison, results for $I_{p1} = I_{p2} = I_{p3} = I_p$ are also shown (light colours).

$I_{\text{total}} =$ constant line with the I-V curve for S_1, S_2, S_3, respectively, and the total voltage drop is $V_s = V_1 + V_2 + V_3$. Let us consider the four current values.

* $I_{\text{total}} = I_1$: In this case, $V_1 = V_2 \approx V_3$. Each voltage drop is about 0.55 V, and the total voltage drop V_a is approximately 1.7 V (see Fig. 4). All bypass diodes are off (see Fig. 5 (b)).

* $I_{\text{total}} = I_2 \approx I_p/2$: In this case, $V_1 = V_2$ is nearly constant. However, for $I_{\text{total}} \approx I_p/2$, V_3 can vary over a wide range (see Fig. 6), and therefore the overall I-V relationship (Fig. 3 (a)) shows a large change in V_a at $I_{\text{total}} = I_p/2$. The change in V_3 (from about +0.55 V to about −0.55 V) is also clearly seen in Fig. 4.

* $I_{\text{total}} = I_3$: Since $I_3 > I_p/2$, the sub-circuit S_3 can conduct this current only if D_{BP3} is conducting (see Fig. 6). If I_{total} is increased further, V_3 remains essentially constant since it gets clamped by D_{BP3}.

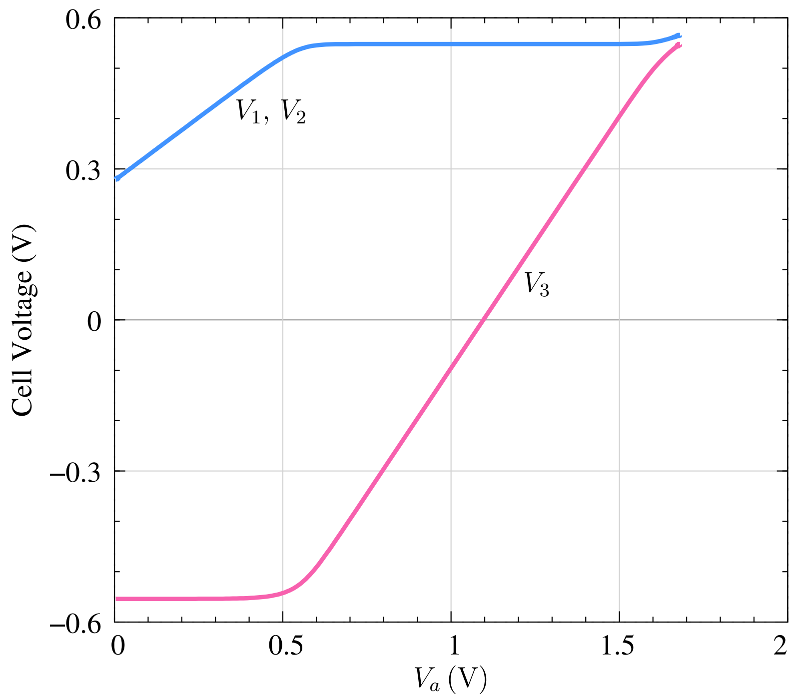


Figure 4: Voltage drops V_1, V_2, V_3 as a function of V_a (see Fig. 1).

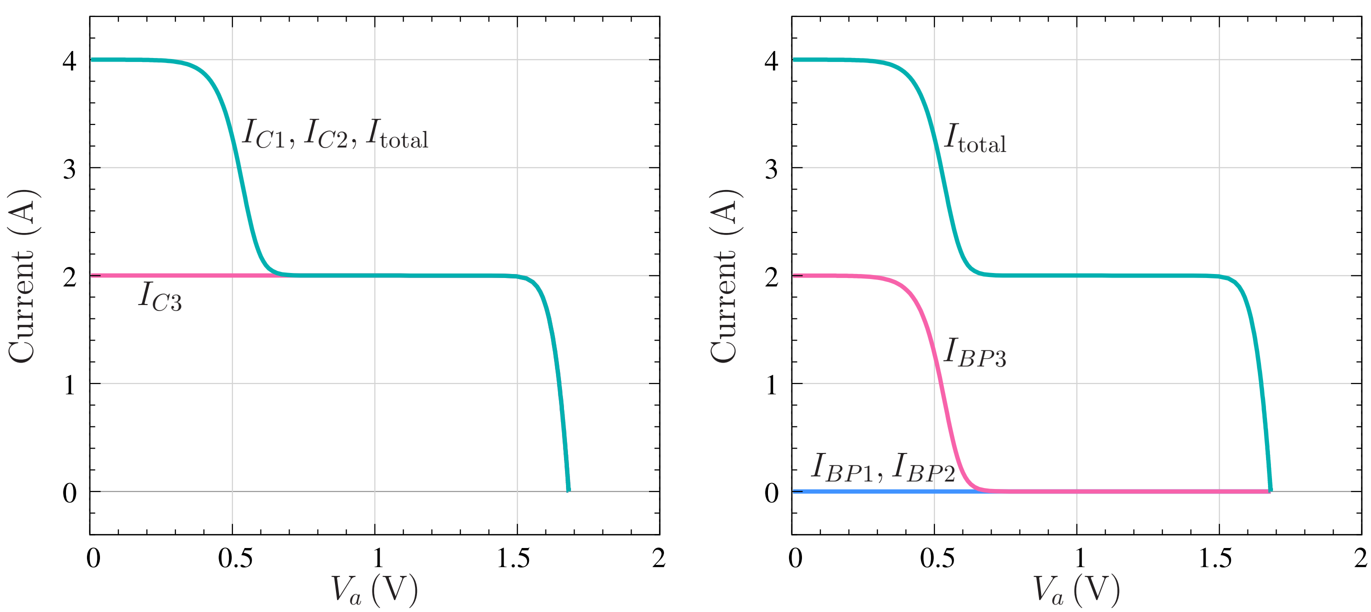
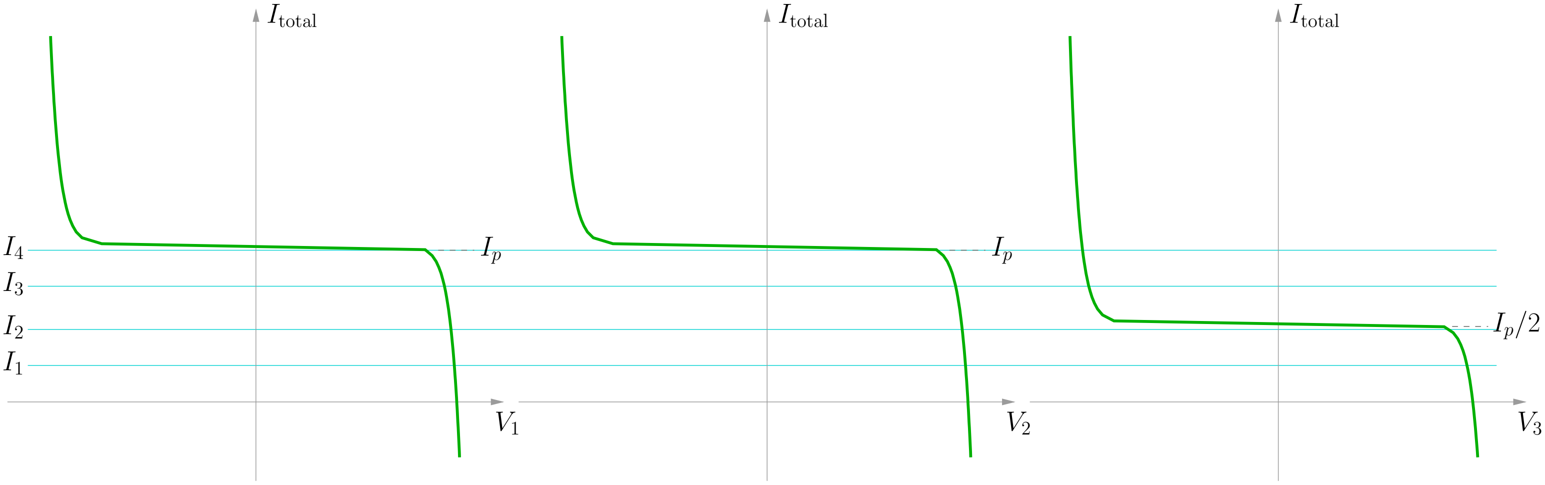


Figure 5: (a) I_{C1}, I_{C2}, I_{C3}, and I_{total} versus V_a, (b) I_{BP1}, I_{BP2}, I_{BP3}, and I_{total} versus V_a for the series connection of solar cells shown in Fig. 1.

* $I_{\text{total}} = I_4 \approx I_p$: As seen in Fig. 6, the cell C_1 (or C_2) can conduct this current over a relatively wide range of V_1 (or V_2) since there is a flat region at $I_{\text{total}} = I_p$ in the I-V



(a) I-V curve for S_1 (b) I-V curve for S_2 (c) I-V curve for S_3

Figure 6: Schematic diagram showing I_{total} versus V for the three sub-circuits S_1, S_2, S_3 of Fig. 1. The photocurrents for cells C_1 and C_2 are identical, i.e., $I_{p1} = I_{p2} = I_p$. The photocurrent for cell C_3 is $I_{p3} = I_p/2$. The lines marked I_1, I_2, I_3, I_4 indicate different values of I_{total}.

relationship. This "plateau" in voltage gets reflected in the overall I-V curve as well (Fig. 3 (a)). In this region, V_3 is clamped by the bypass diode D_{BP3}, and the change in V_a is shared between V_1 and V_2, as seen in Fig. 4.

In the region $0\,\text{V} < V_a < 0.7\,\text{V}$, D_{BP3} is conducting. The cell current I_{C3} is constant $(= I_p/2)$, and the difference $(I_{\text{total}} - I_{C3})$ is conducted by D_{BP3}. The bypass diodes D_{BP1} and D_{BP2} do not turn on, and $I_{C1} = I_{C2} = I_{\text{total}}$, as seen in Figs. 5 (a) and 5 (b).

Exercise Set

1. Compare plots of the various quantities of interest (cell currents, cell voltages, bypass diode currents) versus V_a for the case of Cell 3 under shade and the normal case of $I_{p1} = I_{p2} = I_{p3} = I_p$. Explain the salient features observed from each comparison.

2. If the shaded cell is C_2 and not C_3, what changes do you expect to see in the overall I-V curve? Verify with simulation.

3. Draw approximately the I-V curve for $I_{p1} = I_{p2} = I_p$, and $I_{p3} = I_p/4$. In addition, plot the cell currents, bypass diode currents, and cell voltages as a function of V_a. Verify

with simulation.

4. Repeat for $I_{p1} = I_{p2} = I_p$, and $I_{p3} = 3I_p/4$.

References

1. L. Castaner and S. Silvestre, *Modelling Photovoltaic Systems with PSpice,* John Wiley and Sons, 2002.

2. C. S. Solanki, *Solar Photovoltaics: Fundamentals, Technologies, and Applications,* Prentice-Hall India, 2011.