Detailed analysis of currents in PV-shunts

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Introduction

According to the current IEC-definition a string of PV modules is defined as one or more PV-modules connected in series. A PV-array is defined as two or more PV-strings in parallel. In this article the term PV-shunt will be used as the duality of the PV-string. A PV-shunt is defined as two or more PV modules connected in parallel. Note that according to the current IEC definition this is a special case of a PV-array. In this article it will be shown that the PV-shunt systems behave different compared to PV-string-systems with respect to fire hazards and therefore require different safety measures.

PV-strings

PV-cells operate at a typical voltage of approximately 0.5 V. The first application of PV-modules was battery charging. In order to charge a standard 12 V lead-acid battery usually 36 PV-cells were connected in series. Today's single and multi-crystalline 36 cell PV-modules have an open voltage of approximately 21-23 V and a maximum power point voltage (V_{mpp}) of approximately 15-17 Volts. As they were originally intended for charging 12 V batteries they are still called 12 V-modules. In order to obtain higher voltages, 12 V-modules are connected in series (strings); to obtain higher power, these strings are connected in parallel (arrays).

Connecting modules in series created a new problem. When a string of modules is illuminated and a few cells are shaded, the illuminated cells force the shaded cells to operate in reverse direction. In this case excessive power will be dissipated in the shaded cell. As the power is not distributed uniformly across the cell area this may lead to hot spots, which eventually may lead to a local short-circuit in the cell.

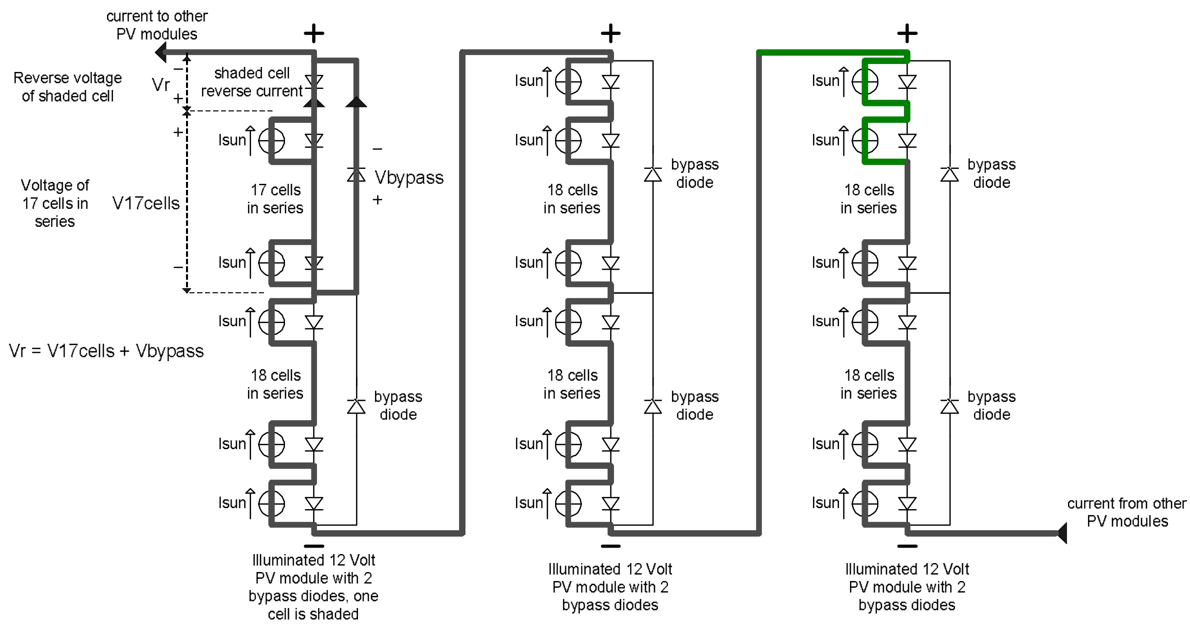

Figure 1: One shaded PV cell in a system of many illuminated PV modules connected in series

The remedy for this problem is the bypass-diode. The ultimate solution is to connect a bypass diode across every cell. This is done in the Uni-solar amorphous –flexible PV module. For crystalline modules usually a bypass diode is used across every 18 cells, so two diodes per 12 V-module. Therefore the centre tap of a 12 V-module is wired to the junction box. The bypass diodes are usually mounted in the junction box. Figure 1 shows the situation of a PV-string with one shaded cell. When two bypass diodes are used, the maximum reverse voltage across a shaded cell is limited to approximately 11 Volts. The cell manufacturer has to make sure that at this voltage the power dissipation caused by the reverse current through the cell is so low that the cell cannot be damaged.

The use of bypass diodes however introduced another problem. The bypass diode is not a fail-safe component: when the bypass diode fails, for example by overheating or by induced voltages caused by lightning, the diode may become a short circuit.
For every short-circuited diode the PV-string open voltage will be reduced by approximately 11 Volt. When a string with one ore more short-circuited diodes is connected in parallel with other, normal operating strings, these strings will back-feed current in PV string with the defect bypass diode(s). This may lead to overheating of the modules and cause over-current in the wiring. This is considered as a fire hazard. The problem can be overcome by using a string (or blocking) diode. However, as a diode is not a fail-save component a fuse needs to be used as well.
The tendency is to rate the PV-modules and the string wiring for two times (plus additional safety margins) the short-circuit current of the PV-string. In that case up to three strings can be hard-wired to an array without the use of string-fuses (the worst case is that only two strings can back feed one string). For systems consisting of more than three strings each string needs to be fused separately.

Summary:

- Bypass diodes must be used in strings to protect the cells to be damaged in case of partial shading.
- A short-circuited bypass diode will result in current back-feeding in the string when more strings are connected in parallel.
- To prevent fire hazard the modules and the wiring in a string must be rated for twice the short-circuit current of the string and fuses must be used to limit the back-feed current.

PV-shunts

As mentioned before a PV-shunt is defined as two or more PV modules connected in parallel. As will be shown, PV-shunts have completely different characteristics compared to traditional configurations, affecting safety and therefore safety requirements. When a PV-shunt is treated in the same way as a PV-array this would implicate that each module must have bypass diodes and a series fuse. It will be shown that a safer situation is possible using PV-shunts without bypass diodes and series fuses.

In general it is believed that a shaded module can be damaged by the back-feeding current of the other, illuminated, modules in a PV-string. Figure 2 shows this situation for a 12 V PV-shunt. Each illuminated cell of the PV-modules is represented by a current source connected in parallel to a diode. The cells in the shaded module do not generate current and, therefore, are represented by diodes only. The voltage across the shaded module is maximal when the inverter current is zero. Note that although the back-feeding current in the shaded module is opposite to the normal module current, all cells are normally, forward, biased, i.e. the polarity of each cell in the shaded module is the same as the polarity of cells in the illuminated module. Therefore, the back-feeding power is equally distributed across each cell, and also the power in each cell is distributed uniformly across the cell area. Provided that the dissipation in the cell does not exceed the power of solar irradiation (1000 W/m^2) this can be seen as a normal PV module operation.

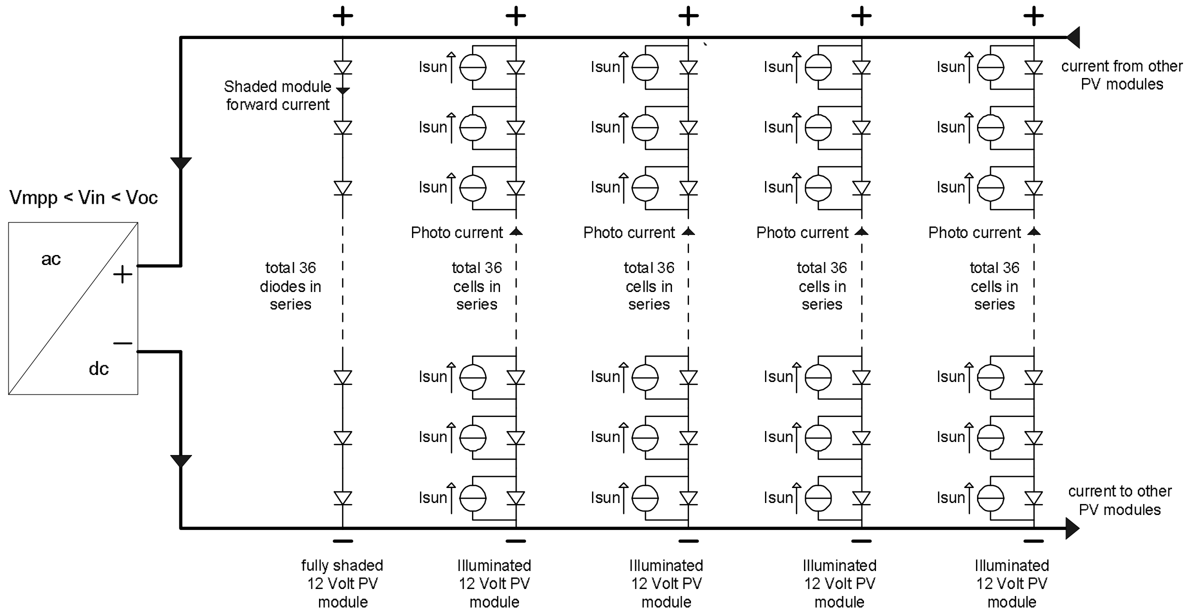

Figure 2: One shaded PV module is a system of many illuminated PV modules connected in parallel

In Figure 3 the blue-dotted line shows the I-V curve of a single PV-module illuminated with 1000 W/m^2 and 25^{o}C cell temperature, the normal blue line shows the I-V curve of the same module, cell temperature 25^{o}C, but shaded and back-feeded by an external voltage source. The lines cross at approximately 1.5 Ampere, which is 0.28 I_{sc}.

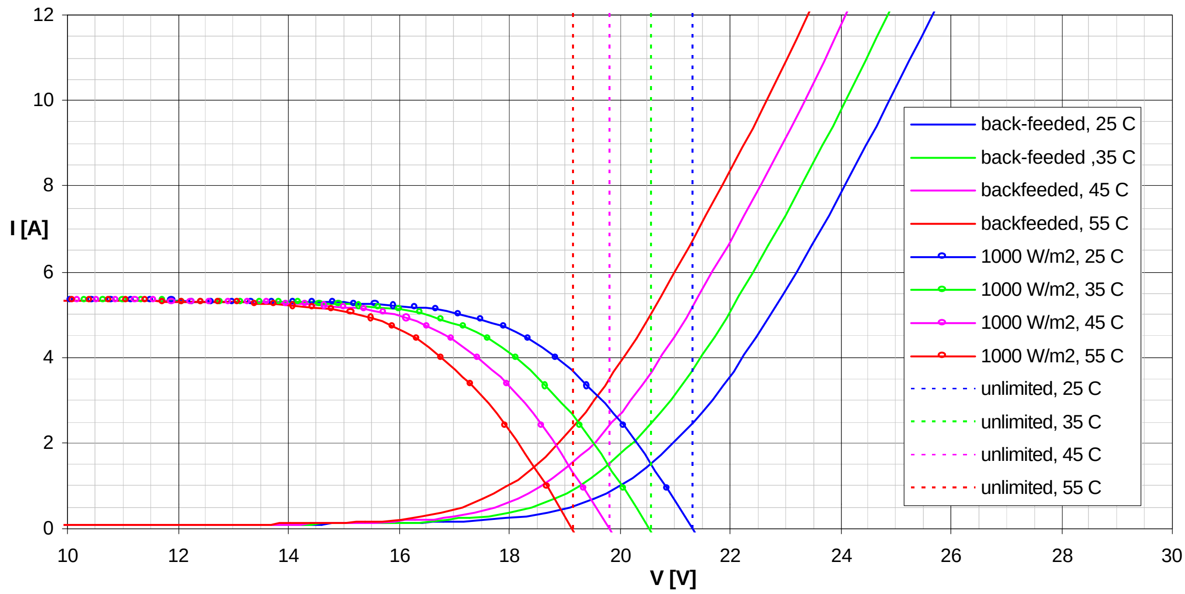

Figure 3: I-V curves at several PV-cell temperatures of a shaded PV-module, an illuminated PV-module and an unlimited number of illuminated PV-modules connected in parallel

The vertical blue dashed line represents the I-V curve of an unlimited number of illuminated PV-modules in parallel. This line crosses the previous line at approximately 2.5 Ampere, which is 0.44 I_{sc}, well below I_{sc}. The dissipation in the module is approximately 20.4 V x 2.5 A = 51 Watts. The total cell area is approximately 0.56 m^2 (36 cells of 5"x5"), therefore, at an irradiation of 1000 W/m^2 the illuminated module will feel approximately 560 W. This difference in dissipation will result in a difference in temperature: the cells of the illuminated module will become much warmer than the cells of the shaded PV-module. In Figure 3 the red-dotted line shows the I-V curve of a module with a cell temperature of 55^{o}C and the dashed red line shows the I-V-curve of an unlimited number of PV-modules in parallel at a cell temperature of 55°C. At a temperature difference of 30°C the worst case back-feeding current will decrease to less than 0.5 Ampere (approximately 0.1 I_{sc}). Figure 4 shows the back-feeding current versus the number of illuminated modules at several differential cell temperatures. It can be concluded that in all circumstances the back-feeding current into the shaded module is well below I_{sc}, en will stabilize at approximately 0.1 I_{sc}.

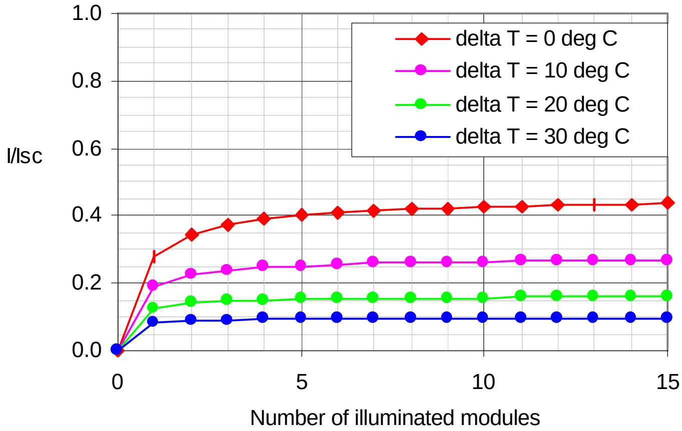

Figure 4: Normalized back-feeding current in one shaded module versus the number of parallel connected normally illuminated modules at several

Figure 5 shows the situation when only one cell of one module in a PV-shunt is shaded. Note that de modules do not have bypass-diodes. When the inverter is off the voltage across all modules is V_{oc}. The shaded cell feels the difference between V_{oc} of the modules and the V_{oc} of its 35 illuminated cells. Therefore the shaded cell remains forward biased. The current will be close to zero. The situation changes once the inverter starts operating. While the inverter is starting or when the inverter operates in an undersized system ($P_{inv} < W_p$) the voltage will always be higher than maximum power point voltage. The worst case for the shaded cell occurs when the inverter operates at the maximum power point voltage. In that case the reverse voltage across the shaded cell equals the difference between the voltage of the 35 illuminated cells in the module minus the maximum power point voltage.

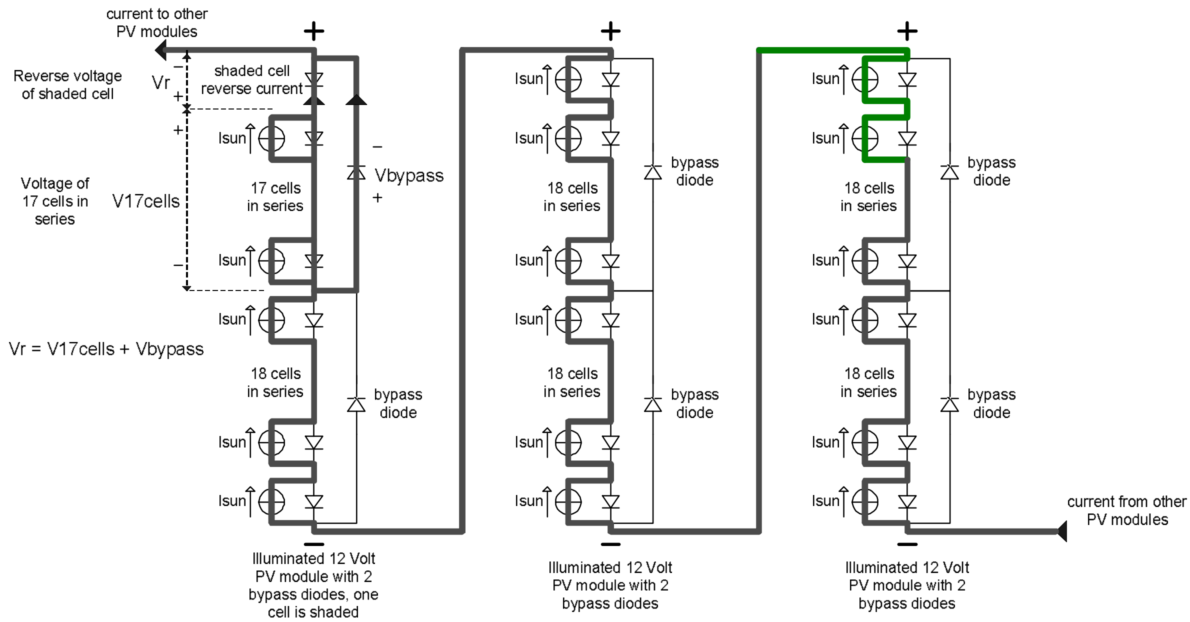

Figure 5: One PV-cell shaded in a system of many illuminated PV-modules connected in series

In figure 6 the situation of one shaded cell in a PV-string with bypass diodes across every 18 cells is compared with the situation of one shaded cell in a PV-shunt without bypass diodes. The green line represents an example of the reverse characteristics of one cell. The red line represents the I-V curve of 17 cells in series plus the voltage drop of the bypass diode. The maximum voltage available to damage the shaded cell is approximately 11 Volt. Figure 7 shows, based on the same data, the power versus the voltage. It can be seen that the dissipation in the shaded cell is approximately 20 Watts. The blue line shows the I-V curve of 35 cells in series minus the maximum power point voltage of the illuminated modules in a PV-shunt. The maximum voltage available to damage the cell is reduced to less than 4 Volts. The power (see figure 7) is remarkably reduced to as little as 0.2 Watt. At this power level hotspots cannot occur.

It must be noted that the reverse characteristics of a cell differs significantly between different cell types and even between equal cell types. However, as can be seen in Figure 6, the maximum available power to damage a shaded cell in a PV-string with bypass diodes is approximately 43 Watts. For the PV-shunt this is approximately 6 Watts. This implicates that cells of which the reverse current is too high or the ability of the cell to dissipate power is too low (thin film cells) to be used for PV-string systems may still be very suitable for modules for PV-shunt systems.

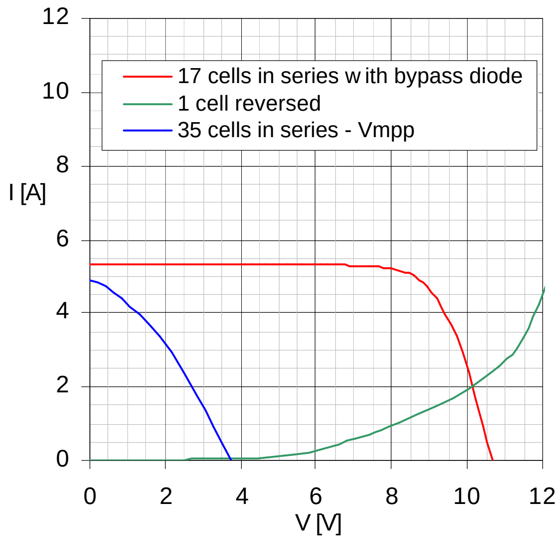

Figure 6: I-V curves of 17 PV-cells (at STC) in series with bypass diode, one shaded (reverse biased) cell and the voltage difference between 35 cells (at STC) in series and the MPP-voltage of a PV-normal module at STC.

Note that one or more short circuited cells in a module will reduce the voltage across the shaded cell with approximately 0.6 V per cell. So short-circuited cells will not start an avalanche effect, but will reduce the chance for other cells to become short-circuited.

Suppose the PV-shunt uses bypass diodes. In that case the diode will never conduct and therefore is not of any use. However, when this diode is short-circuited (or reverse mounted) excessive currents may flow through the diode and the cells. Therefore bypass diodes should never be used in PV shunts as they create a fire hazard.

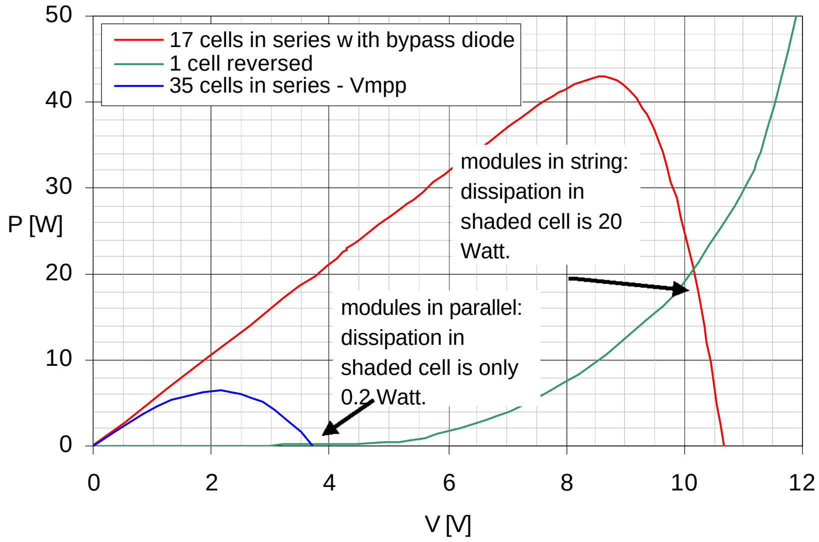

Figure 7: Power dissipation of one shaded PV-cell in a PV-module in a normal string configuration and in a PV-module connected in parallel configuration.

Even though it is shown clearly that hot-spots in PV-shunts cannot occur, and therefore the chance on cell defects is dramatically reduced, still the situation needs to be considered in which one or more of the cells in a module of a completely shaded module of a PV-shunt is short circuited. In that case the back-feeding current will increase. The worst case situation is shown in figure 7. The solid lines represent the I-V curves of a module respectively without defects (blue), with two short circuited cells (green), with four short circuited cells (purple) and with six short circuited cells (red). The worst case module back-feeding current is respectively 2.5 A (no defects), 4.7 A (two short circuits), 7.7 A (four short circuits) and 11.9 A (six short circuits). In the case of six short circuits in one module the power dissipation due to back-feeding is approximately 260 Watt. As mentioned before this power is distributed equally across the whole surface of the not short circuited cells. This power is much lower than the power from the sun (approximately 560 W, see above). Therefore, even in this extreme case the cell temperature of the back-feeded module will stabilize at a lower temperature than the illuminated modules. Due to this temperature difference the back feeding current will be reduced to approximately 10 A, close to I_{sc}.

Summary:

- The worst-case back-feeding current in a 12 V PV-shunt system is limited by the system and will stabilize to approximately 0.1 I_{sc}.
- Even when 6 cells are short circuited the back-feeding current in a 12 V PV-shunt system will stabilize to approximately I_{sc}.
- In a 12 V PV-shunt system bypass diodes should not be used as they create a fire hazard.
- Hot spots problems in shaded cells will not occur in PV-shunt systems.

Safety

The basic functions of the guidelines for most PV installations are written in order to limit all possible hazards to acceptable risk levels. With respect to the modules and the DC-wiring the main concerns are fire hazard and touch safety.

Most regulations for PV installations are based on the fact that a single fault in the electrical installation may not result in any hazard. In the previous section it is clearly shown that without any additional protection, and provided that bypass diodes are omitted, even six independent faults in one PV-module cannot cause a hazardous situation. The use of fuses and diodes does not affect issues related to touch safety. Additionally, any PV system below 30 V is inherently touch-safe.

In practice this means that the DC side of a 12 Volts PV-shunt system can consist only of 12 V PV modules (without bypass diodes), wiring and connectors. Additional fuses and diodes are not needed. Of course the wiring and the connectors must be capable to carry the full short-circuit current, multiplied by the normal safety factors, of the all the modules in the PV-shunt system.

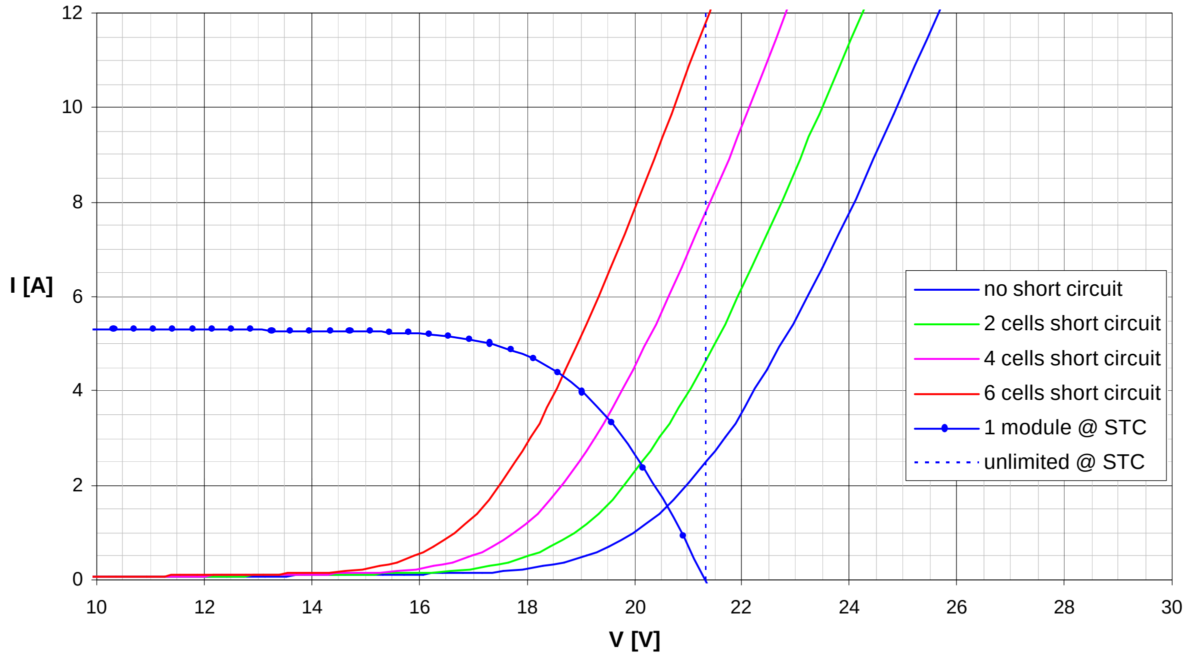

Figure 8: I-V curves of a shaded module, shaded modules with 2, 4 and 6 short-circuited cells, a normal illuminated module and an unlimited number of illuminated modules in parallel.