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The Hot String and the Cool Module

Case study of fault detection in PV systems by means of IR photography

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Abstract

IR photography was used for the inspection of a PV system on the façade of a building. The IR photographs showed five PV modules having a temperature that was significantly higher than that of neighbouring modules. The open-circuit voltage and short-circuit current of the strings in the PV array were measured. It was concluded that a single module was connected in reverse in the string containing the hot modules. At the time the IR photograph was taken the PV inverter was not active and the PV array was effectively short-circuited. Thus the energy generated by the modules of the array was dissipated in the string with the module connected in reverse, which lead to the observed rise in the module temperature.

The resulting current-voltage curves of the PV array are calculated using models of the electrical characteristics of multicrystalline Silicon modules.

CONTENTS

1. INTRODUCTION

In June 2001 an infrared camera, the ThermaCAM PM695 of Flir Systems, was used to inspect the PV system on the façade of building 31. The IR image showed an interesting fact: in section 12, the second string from the top, five modules were quite hot, see figure 1. The second string consists of the modules in the third and fourth row.

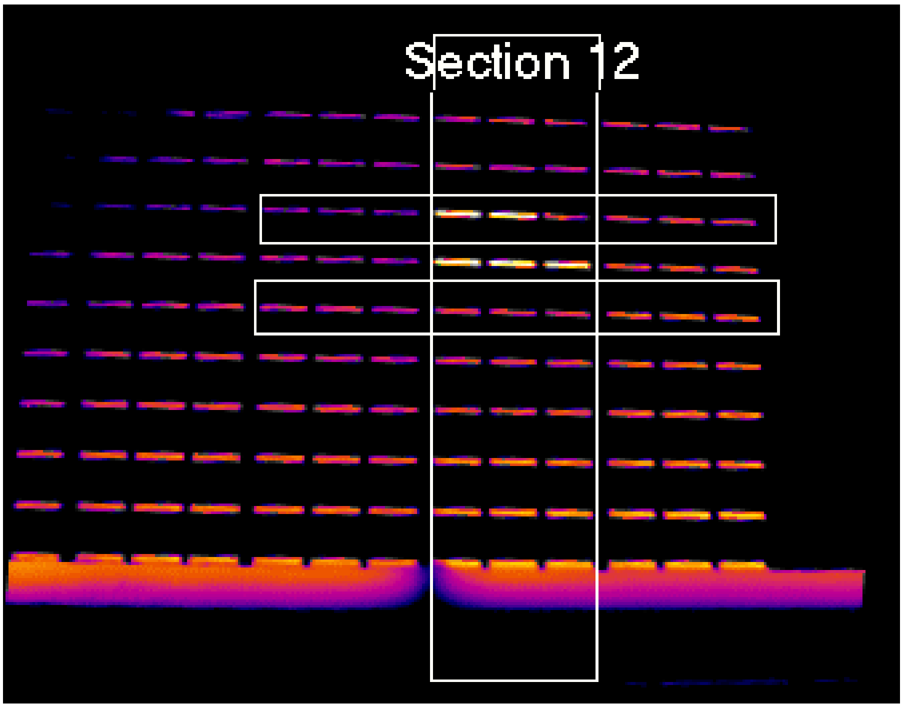


Figure 1 - IR image of eastern part of the PV system

The module temperatures in rows 3 and 5 from left to right are shown in table 1.

Row 3	45.5	45.7	45.4	54.2	54.0	47.4	48.2	48.3	48.1
Row 5	47.2	47.0	46.6	48.3	47.9	47.8	49.3	49.2	49.2

Table 1 - Module temperatures in ºC as determined by the IR camera in rows 3 and 5

The modules in section 13 have higher temperatures than those in section 11. Section 12 has five hot modules. Modules in section 11 are cooler than the normal modules in section 12. The table shows the temperatures as determined from the IR image without any correction for the view angle or emissivity.

It is known that PV modules that do not generate electricity have temperatures a few degrees higher than similar modules, which deliver power to the inverter. However, these five modules are not hot because they are sitting idle in the sun: one of the modules in the string remains cool and the temperature difference is rather large.

2. THE PV SYSTEM

On the façade there are 13 vertical sections, consisting of 9 strings of 6 modules in series. Figure 2 shows the building with the PV system on the southern face. Part of the strings is on the roof of the building. In the façade two rows of 3 modules form a string.

Each section was electrically connected to a Mastervolt 2500 inverter. However, it turned out that the inverters of sections 12 and 13 were switched off, because they did yet not have the recommended climatized enclosure. The PV array of section 12 was effectively open circuited at the time of the IR images.

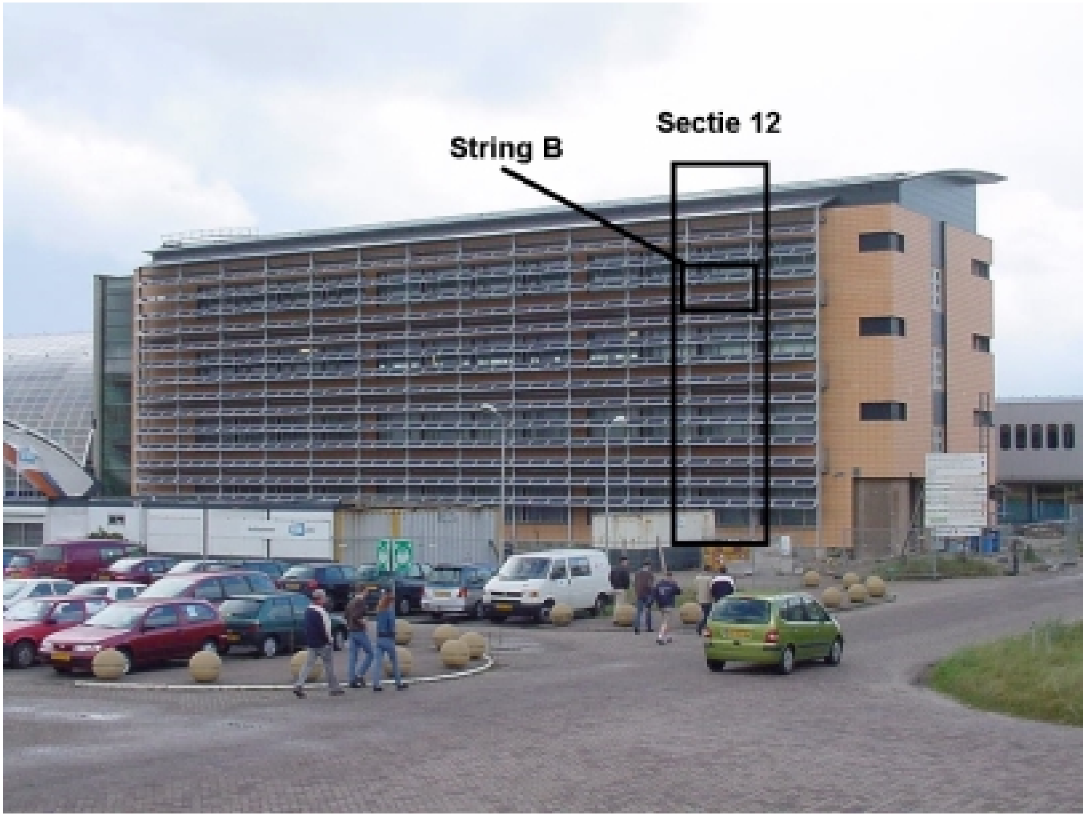


Figure 2 - PV system on the façade of building 31

3. THE ANALYSIS

The first step taken was measuring the short circuit currents of the 9 strings in section 12, to find out whether the current in one string was lower that in other strings. It was found that string B was connected to cable code E.

Inspection 25-th June 2001, 11.45 h, clear sky, inverter in operation, DC voltage about 88 V

Cable code	DC-current (A)	Remarks
A	2.22	
B	2.12	
C	2.11	
D	2.13	
E	(-) 2.22	Hindsight: the negative sign was not noticed, cable E was connected to string B
F	2.18	
G	2.14	
K	2.39	
L	2.39	

Table 2 - Measured currents in section 12

All strings seemed to behave as expected.

The next day it was decided to measure the open-circuit voltage of the strings. Inspection 26-th June, sky overcast, inverter not in operation, dc-voltage about 111 V (all strings parallel). One after the other the strings were disconnected and the voltage was measured. Per string there is a dc fuse of 6.3 A. All fuses were OK.

Cable code	Voc (V)
A	116
B	115
C	116
D	116
E	77
F	116
G	116
K	121
L	121

Table 3 - Measured open circuit voltages in section 12

The voltage of string B (cable code E) was about 40 V - i.e. double the Voc of the modules - lower that the others. This indicated that the voltage from the cool module was subtracted from the string voltage. It remained remarkable that all string currents of table 2 are of the same magnitude.

Additional measurements were made.

Inspection 28-th June, 10.00 h, clouded.

Cable code	String current, with inverter ON Udc total 91.1 V, [A]	String current, with inverter OFF Udc total 117.5 V, [A]
A	0.70	0.53
B	0.85	0.76
C	0.73	0.33
D	0.62	0.31
E	-0.80 !	-3.70 !
F	1.05	0.30
G	0.62	0.28
K	0.86	0.83
L	0.80	0.82

Table 4 - Measured currents in section 12 with inverter ON and OFF

It is seen that the current with inverter ON in cable E is of the same magnitude, but has opposite sign. During the first measurements as reported in table 2 the sign of the current was overseen. With the inverter OFF the difference between the currents becomes large: here the joint strings in section 12 are heating string B.
Again the current in string B has the same magnitude as the other currents.

During a clear sky - similar to table 20 - the currents were measured.

Inspection 28-th June, 13.00 h, clear sky

Cable code	Inverter ON Udc total 92.1 V	Inverter OFF Udc total 117.3 V
A	2.58	0.63
B	2.42	0.43
C	2.32	0.38
D	2.32	0.32
E	- 2.32 !	- 4.45 !
F	2.40	0.33
G	2.36	0.26
K	2.68	1.07
L	2.79	1.06

Table 5 - Measured currents in section 12 with inverter ON and OFF

For some reason the string current in string B has for different irradiances the same magnitude as other strings, but opposite sign.

So as a hypothesis it was formulated that the simplest of errors had occurred, namely interchange of plus and minus terminals in the junction box of the cool module. The connection of the terminals in the cool module in string B could be verified by on-the-spot inspection. It was decided to check the connection inside the junction box. The module could be reached, it was lifted out of the support, the junction box was opened and it was observed that indeed plus and minus were wrongly connected. This defect was repaired.

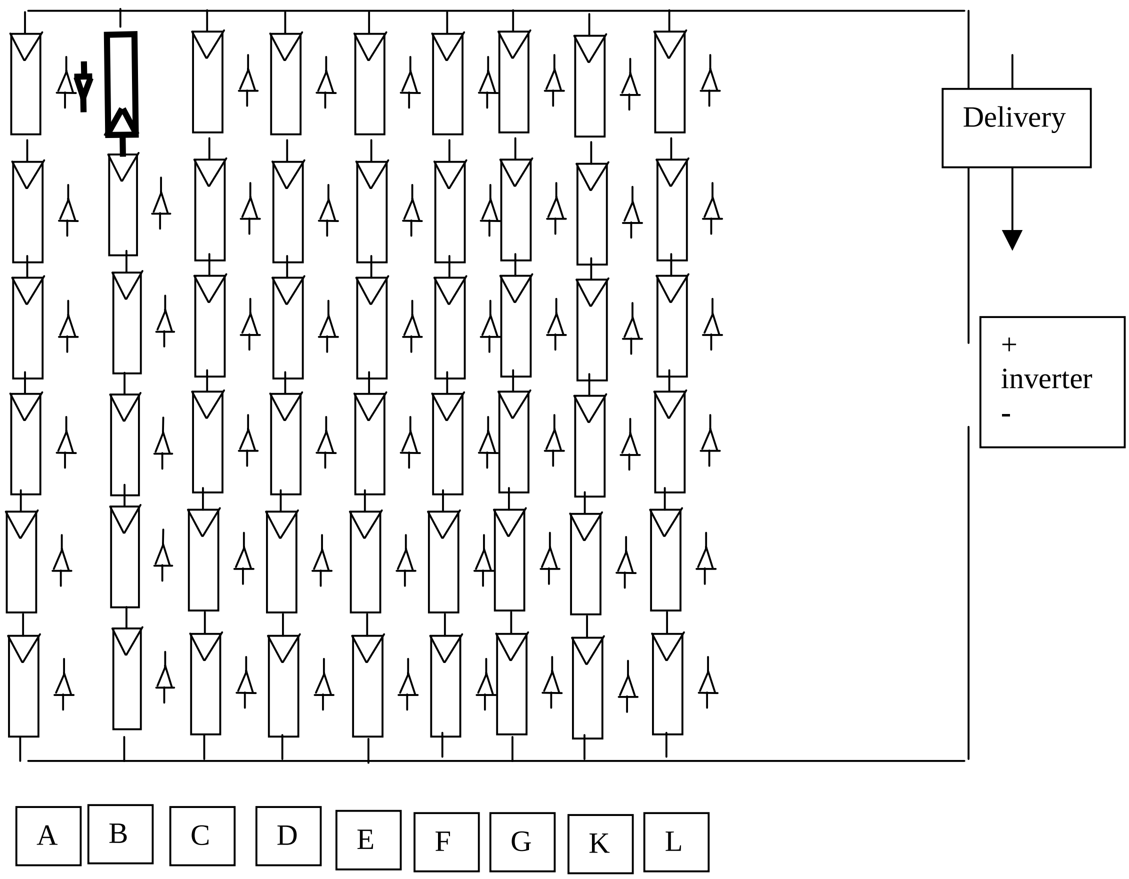
So finally after the repair the results of additional measurements on section 12 were as shown in table 6.

Cable code	Voc [V]	Idc, Inverter ON, [A]	Idc, Inverter OFF, [A]
A	120.0	2.05	0.08
B	119.5	1.93	-0.12
C	119.1	1.82	-0.15
D	118.7	1.84	-0.22
E	120.1	1.97	-0.05
F	118.8	1.93	-0.02
G	118.8	1.87	-0.26
K	124.0	2.56	0.60
L	123.9	2.57	0.60

Table 6 - Measured currents after repair in section 12 with inverter ON and OFF

Herewith everything seemed to be working well. Figure 3 shows the electrical connections of section 12, every module has a bypass diode.

Figure 3 - the electrical connections in section 12



4. THE MODEL

The power delivered or dissipated by PV modules is determined by the external load, in general the inverter. The inverter is supposed to keep the modules in the Maximum Power Point MPP. The inverter thus maximises the output power of the entire array of modules.
It may happen that the inverter's choice of current and voltage at its terminals leads to non-optimal current and voltage for individual strings or modules. In that case there is a mismatch between the strings/modules.

As a PV module is a totally non-linear device in terms of voltage and current, it is not always easy to have correct intuition of the consequences of mismatch in a PV array. In order to model IV curves for any arrangement of modules, bypass-diodes and blocking diodes the software tool MM has been developed. It is based on a very simple methodology of calculating the effect of connecting PV components. The starting point is an IV curve for the device, either a PV cell or any kind of diode. When two devices are in series, the algorithm determines the IV curve of the combination, by adding for all possible currents the sum of the voltages of the two devices in question. For devices in parallel the individual currents for any given voltage are added. The resultant IV curve can be the basis for the next combination of any other device. Calculations are done on basis of linear interpolation. IV curves are given by arrays of V and I values, they can be stored as ASCII data and manipulated at will. The programme incorporates a section where IV curves of crystalline Si cells of any area can be generated for any given irradiance and temperature. The model uses typical data for mc-Si cells.

Figure 4 shows the IV curve of a single PV module (T=45 ºC), consisting of 36 Si cells in series, with a bypass diode, which conducts when the voltage over the module is negative. It also shows the IV curves of strings of 5 (T=55 ºC) and 6 (T=45 ºC) of these PV modules. When a module is connected in a string in reverse way its IV curve is reversed, also shown in the figure.

Figure 5 shows what happens if a string with 5 modules forward is connected in series with a single reverse module, for comparison the string with 6 modules forward is shown too.
It is clear from this figure that a string with 6 modules in series, where one is reverse connected, will have a open-circuit voltage which is about 40 V lower than that of a string where everything is properly connected. Logically for negative currents the bypass diode in the reverse module stops conducting and a plateau in current shows up.

When 9 strings with 6 modules in series are put parallel the effect of the reverse module in one of the strings is shown in figure 6. The array with 8 parallel strings is put in parallel with a single string with the reverse module. The hot string has a temperature of T=55 ºC, the cool module (and the other strings) are assumed to have a uniform temperature of T=45 ºC. The maximum power of the array with the reverse module is 1511 W, without the reverse module it would have been 1949 W. This means a single reverse module among 54 modules reduces the maximum output power by 23%.

Figure 6 also shows that for system voltages between 90 V and 110 V the currents in the normal strings and that in the string with the reverse module have the same magnitude, but opposite sign.

Figure 7 shows the IV curves of the array with the reverse module at module temperatures of 25 ºC and 45 ºC , the hot string in both cases has a temperature 10 ºC higher. Also shown in figure 7 is the power as function of the system voltage. At 45 ºC the maximum power is at Vmpp=78V, whereas at 25 ºC it is at 102 V. The inhomogeneous temperature distribution in the real array is not incorporated in this model.

The inverter found the maximum power point at Tmod=45 ºC in a similar range. This particular type of inverter however does not search for a local/absolute maximum in the power. It measures the open circuit voltage Voc and determines the MPP voltage as a fixed percentage (80%) of the measured Voc. In this case the model calculates Voc=114.8V, 0.8x114.8V=91.8 V, which corresponds well with the value Udc=92V in table 5.
The shape of the IV curves of the array with the reverse module and the Vmpp set by the inverter explain the rather surprising fact that the currents in the strings are at different irradiances of similar magnitude when the inverter operates.

When the inverter is not operating the open-circuit voltage of the array is seen in figure 6 to be 114.8 V. In this situation the current through every normal string is positive 0.78 A, see figure 6. At this voltage the current through the string with the reverse module is -6.3 A. This means that in the string with the reverse module 723 W is dissipated. The eight other strings generate this power.
The MPP voltage of the entire array is calculated to be 77.7 V. At this voltage the string with the reverse module does not generate any power at all, the other module are working far below their MPP voltage, which is at 94.6 V.

This amount of energy dissipated in the hot string of figure 1 explains - at last - the temperature increase as observed by the IR camera. Normally a module at the simulated irradiance of 850 W/m^2 and Tmod=45 ºC generates 36 W. When the module is disconnected electrically for some reason, this amount of irradiated power is dissipated too inside the module and its temperature increases a few degrees above that of similar electrically active modules. Here a hot module has to dissipate an additional 145 W and its temperature increases substantially more than a few degrees.

Table 7 shows the loss factor for the array with the single reversed module for several irradiances and module temperatures. The loss factor is defined as the MPP power with reversed module in the array divided by the MPP power with all strings correctly wired.

Irradiance W/m^2	Module temperature ºC	Loss factor
50	10	0.81
100	10	0.77
250	10	0.76
250	25	0.76
500	25	0.77
850	25	0.77
850	45	0.78
1000	50	0.78

Table 7 - Loss factor for PV array as function of irradiance and module temperature

5. CONCLUSIONS

The IR camera has observed the effects of the simplest mistake during module installation: wrong connection on the module electrical terminals. During the commissioning of the PV system this mistake has somehow been overlooked.

Its consequences are rather great: when the inverter is operating a fraction of about 23% of the power is lost at irradiances of 850 W/m^2 and Tmod=45 ºC. This fraction is more or less the same for other irradiances and module temperatures.

When the inverter is not operating the correctly wired strings start heating up the string with the reverse module; they almost blew the string fuse. When the fuse would have been blown it could remain unnoticed for some time, resulting in loss of power.

For detection of this kind of mistake with an IR camera it can be advised to shut the inverter down in order to obtain more pronounced temperature differences.

The mismatch programme MM can give a good indication of the size of the electrical effects.

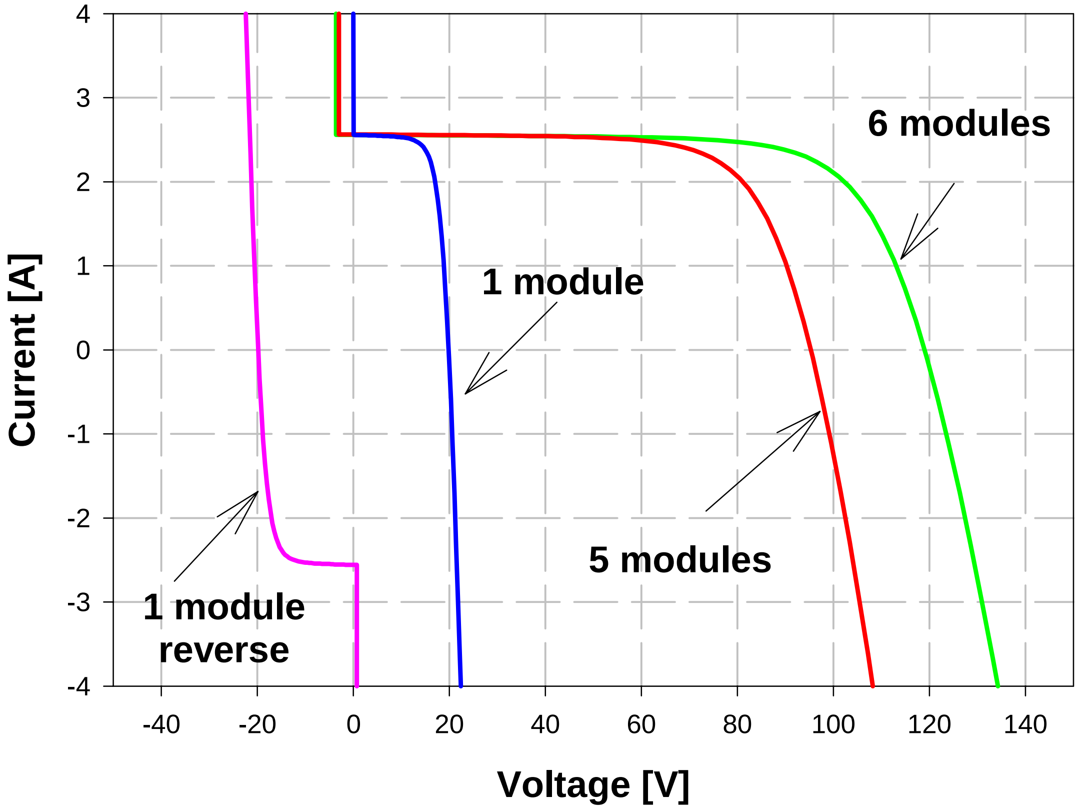


Figure 4 - IV curves of various strings

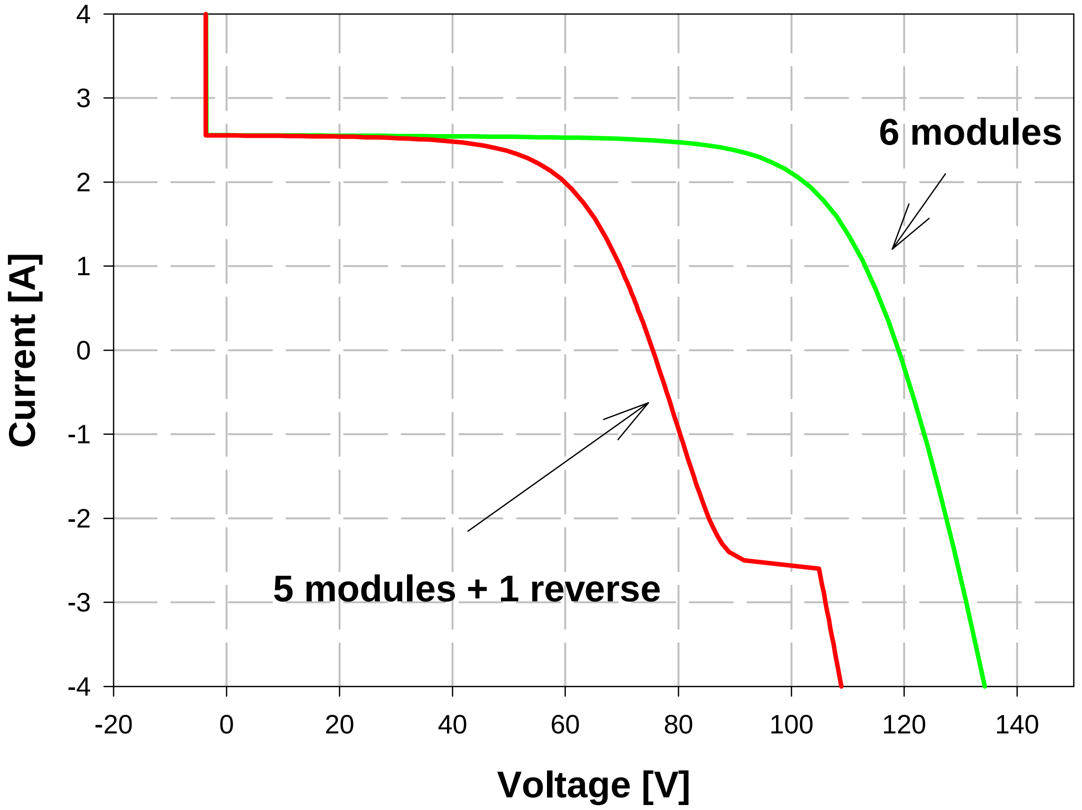


Figure 5 - IV curves of strings with 6 modules, a string with 5 modules forward and one reverse connected module

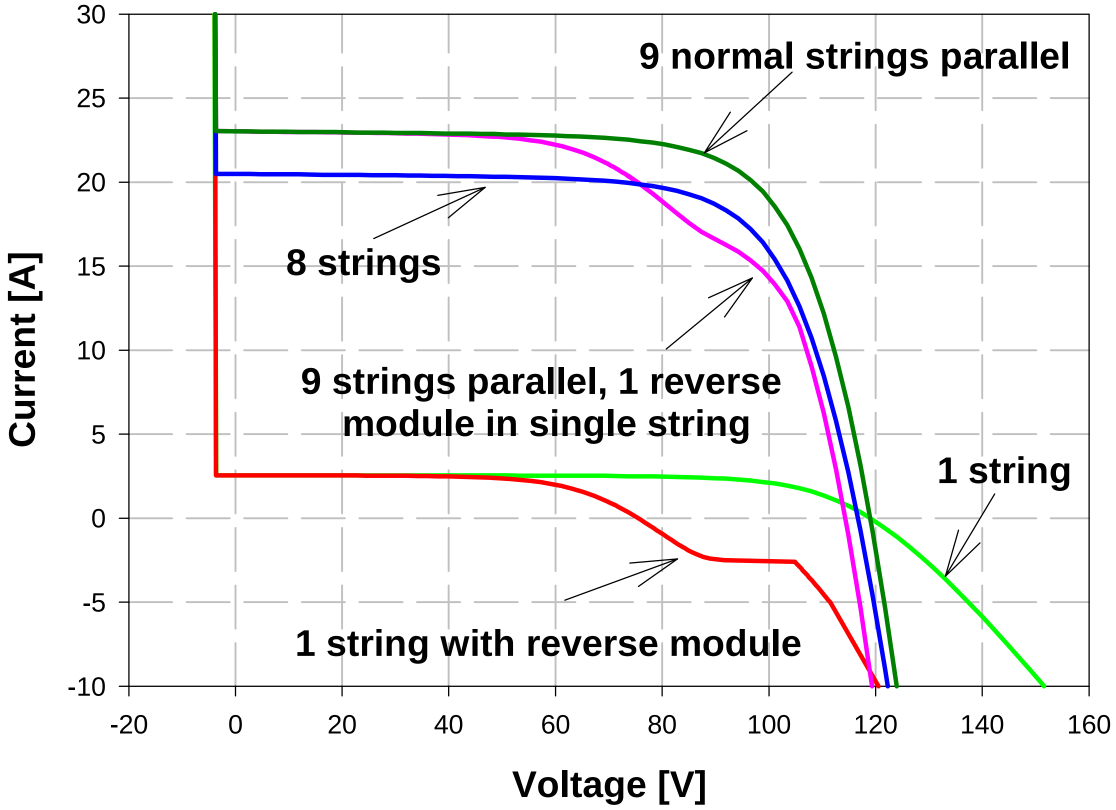


Figure 6 - IV curves of strings and arrays consisting of parallel strings

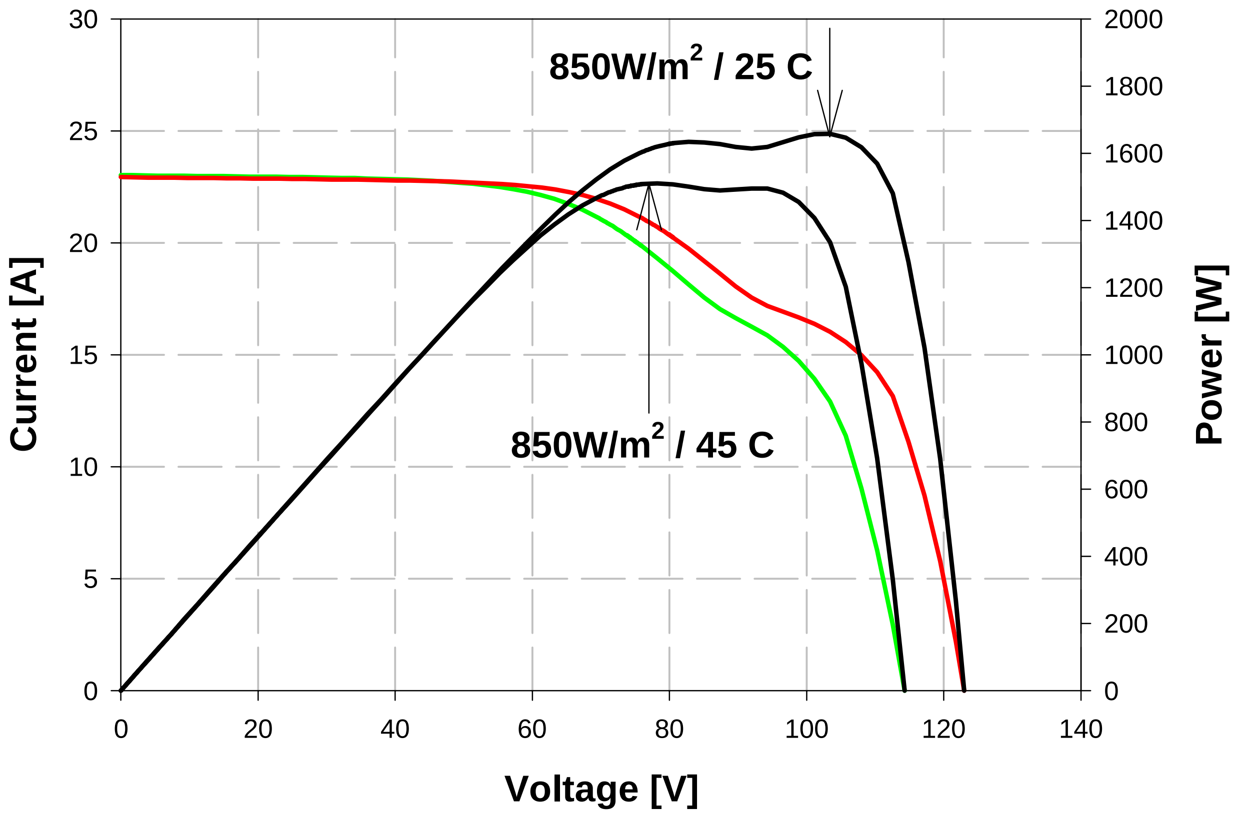


Figure 7 - IV and power curves for the array with the reversed module at irradiance of 850 W/m^2 and module temperatures of 10 and 50 º.

6. APPENDIX - THE PROGRAM MM

In this appendix all instructions will be described to generate the IV curves used in this report. MM is a programme developed for internal use at ECN and is written in the ASYST language.

The MM program (version 7.0) contains three menus:

1. Mismatch calculations - F1 function key
2. IV curves - F4 function key
3. Distributed cell properties - F3 function key

In the methodology of the programme the PV cell is called a **unit**. The IV curve of a Si cell can be generated with the F4 menu and can be stored in ASCII file (give the name of the unit and write to file) or copied to UNIT1 of UNIT2. In the F4 menu the cell area (default 10×10 cm^2), the irradiance and cell temperature can be given.

The F1 menu can generate **strings** from **units** stored in ASCII file (give their name) or from UNIT1 of UNIT2. A number of units can be put parallel or in series and their resulting IV curve is shown. The IV curves of string1 or string2 are generated, they too can be stored in ASCII file by the storing menu item in menu F4 (give the name of the unit and write to file).

When string1 and string2 are generated, they can be put parallel or in series to form string 3 (actually an array) and the resulting IV curve of string 3 is shown. It can be stored in ASCII file.
The effect on MPP points of connecting S1 and S2 to S3 is shown in the menu.
For any stored IV curve the current for a given voltage, or: the voltage for a given current, can be determined and the resulting power is calculated.

So the steps for generating the IV curves are:

1. Generate and store the IV curve of a module with 36 cells in series, store is as file **M36**. This can be done by copying a single cell in unit1 (F4) and making string1 with 36 units (F1). The effect of the bypass diode in every module is incorporated by changing in the ASCII file the value of the current for negative voltages in two lines, e.g.

Voltage	Current
-0.7	1000 (or any high value)
-0.6	2.51
0.0	2.50

   …….

2. Take these arrays of currents and voltages of M36 and reverse their sign, to model a reverse module, store it as file **M36R**
3. Generate and the IV curve of a module with 216 cells in series, store it as file **M216**. This represents the IV curve of a string with 6 modules in series. This can be done by copying a single cell in unit1 (F4) and making a string with 216 units (F1, store with F4).
4. Generate and the IV curve of a module with 180 cells in series, store is as file **M180**. This represents the IV curve of a string with 5 modules in series.
5. Generate the IV curve of the string with 5 modules normal and one reverse module. This can be done taking **M180** as string1 and string2 as **M36R**, put them in series and store the IV curve of the resulting string3 as an ASCII file in file **M216R**.

6. Now the array of 8 normal strings in parallel can be formed by taking for string1 the file **M216** and putting 8 strings parallel, store the string1 as **M216P8**.
7. The overall IV curve of the entire system can be generated by taking **M216P8** and put it parallel to **M216R**. The resulting IV curve is stored as ASCII file **M216P9**.

All these steps executed manually in the MM programme on the PC take about 10 minutes. The entire procedure can also be run in batch mode in a few seconds. The programme MM can also be used to determine the effects of homogeneity of irradiance or cell properties on the electrical performance of PV modules and arrays.