PV-WIREFREE VERSUS CONVENTIONAL PV-SYSTEMS: DETAILED ANALYSIS OF DIFFERENCE IN ENERGY YIELD BETWEEN SERIES AND PARALLEL CONNECTED PV-MODULES

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ABSTRACT: In the past several attempts have been made to measure the difference in energy yield between ac-modules, string systems and array systems. Unfortunately measuring and comparing the output is difficult since the compared systems use different inverters, different modules and are operating at different locations. A new pv-system concept, called PV-wirefree, is based on parallel-connected modules using aluminium current carrying mounting frames. The expectations are that parallel connected systems will produce more energy due to less influence of partial shading and a better matching of individual modules. To check whether these assumptions are indeed correct, a test rig has been set up where, by means of relays, the module interconnection can be changed from parallel to series instantly. An automatic measuring system continuously measured and logged the complete I-V curve of the system and a web cam was used to provide pictures of the actual shading conditions. Measurements are executed over a period of several months under different shading conditions varying from virtually unshaded to partially shaded. The results show a significant increase of output ranging from 2 to even 50 % for the parallel connection.
Keywords: Shading, Performance, Grid-Connected

1 INTRODUCTION

The mismatch effect is the phenomenon that pv-modules connected in parallel or in series can not operate in their individual maximum power point because their voltage (parallel) or current (series) is forced to be equal. The I-V curves of the various interconnected modules may differ from each other due to possible individual differences in the modules, due to differences in soiling, module temperature and irradiance. This phenomenon causes a loss of power of the array of modules with respect to the sum of their potential individual power values.

Since the current mismatch has a larger impact on the energy yield than the voltage mismatch, it is to be expected that systems consisting of pv-modules connected in parallel have a higher energy yield. This is one of the main assumptions behind the PV-wirefree concept, in which pv-laminates are connected in parallel using aluminium current carrying mounting frames.

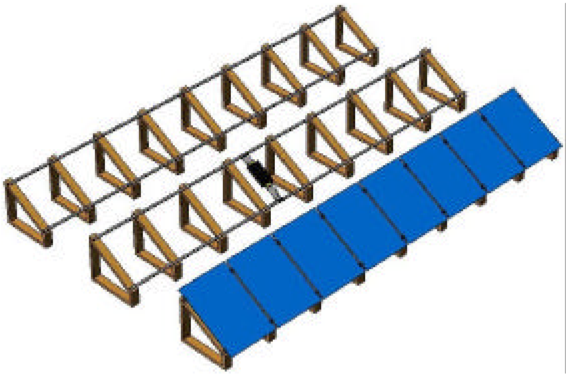

Fig 1: Impression of a PV-wirefree system. First the mounting buses are mounted on a support structure, then the inverter is mounted between the mounting buses, and finally the pv-laminates are clicked onto the mounting buses. All pv-laminates are connected in parallel using a current carrying mounting frame (= mounting bus).

2 PV-WIREFREE

PV-wirefree is based on the concept of combining the functions of support or integration with those of electrical connection and current conduction. Within one (sub)system all modules are connected in parallel, at a DC-voltage of less than 21 V. A PV-wirefree system consists *only* of pv-laminates, click-on-click-off dual-purpose clamps, aluminium extrusions and an inverter. No diodes, no cables, no connectors, no junction boxes, etc.

The main objective of PV-wirefree is to minimize costs of pv-systems and costs of electricity generated by pv-systems. The latter not only by the reduction of actual BOS costs, but also by an increase of annual energy yield especially in suboptimal conditions.

3 DEFINITIONS

Before describing the test setup and measurement results, it is essential to understand the difference between a pv-string and a pv-shunt.

A pv-string is defined as a series connection of pv-modules of which all cells are connected in series.

The duality of a pv-string is a pv-shunt: a parallel connection of pv-modules of which all cells are connected in parallel. However, connecting the cells of a pv-module in parallel is not practical due to high currents and associated losses. Therefore in this paper we define a pv-shunt as a parallel connection of pv-modules of which all cells are connected in series.

4 TEST SETUP

In order to validate the assumption that the annual yield of a pv-shunt (parallel connection) – like PV-wirefree - is higher than that of a pv-string (series connection), accurate comparative tests have been executed. To quantify the differences between the mismatch losses in the shunt and the string, experiments were conducted with nine modules alternately connected in parallel and connected in series. The measurements were conducted with the very same modules under virtually identical conditions excluding any other influences on the array power. The modules consist of 36 cells in series. A bypass diode is mounted across every 18 cells (2 diodes per module).

Every minute the full P-V (power-voltage) curve of the modules connected in shunt and connected in string were measured and a photograph of the pv-modules was taken. One P-V curve is based on 1000 samples and takes about 7 seconds. Therefore the time delay between the sweeps is approximately seven seconds.

Fig 2: Test setup at ECN in Petten (The Netherlands). Every minute the lower 9 pv-modules are connected in shunt and in string, and a photograph is taken. A 1000 points power versus voltage sweep takes 7 seconds

5 MEASUREMENT RESULTS

5.1 Introduction

In this section we present the results of the measurements. Before going into details we first take a closer look at figure 2. There is hardly any shade in this situation; the shadow of a pole is just in between two pv-modules. In figure 3 the corresponding measurements results are given.

On the left vertical axis the average power per module is shown. The horizontal axis gives the average

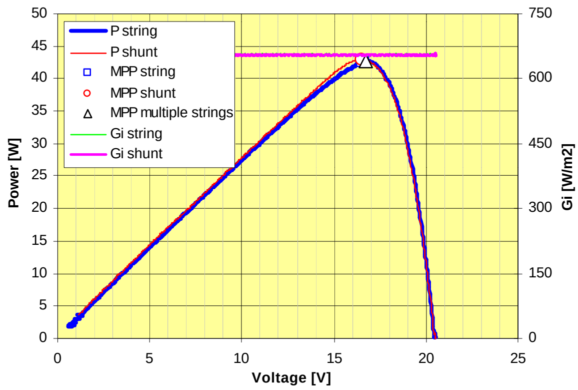

Fig 3: Measurements results of situation presented in figure 2: As expected there are hardly any differences in the P-V curves of the pv-modules in shunt and in string, resulting in ΔP shunt/string = 0.3% and ΔP shunt/string = 0.4% at V=81.5% of Voc.

module voltage of the string and the shunt. For the shunt the voltage of all modules are equal to the average voltage module. For the string usually the individual module voltages will be different. The right vertical axis shows the irradiation measured during the P-V sweep.

As expected the P-V (power-voltage) curve of the pv-modules in string (thick line) does not differ significantly from the P-V curve of the pv-modules in shunt (thin line). Furthermore the graph shows the maximum power point (MPP) of the string (□), the MPP of the shunt (O) and the MPP of the string when loaded at 81.5% of Voc (expected MPP, Δ). The purple line and the green line (in this example the latter is completely covered by the purple line) gives the irradiation during the 7 seconds I-V sweep for respectively the string and the shunt.

In this paper we distinguish three types of shading:

- Very lightly shaded: the shade covers roughly the area of one cell (par. 5.2);
- Lightly shaded: the shade covers several cells (par. 5.3);
- Moderately shaded: the shade covers parts of several modules (par. 5.4).

5.2 Very lightly shaded

Only three minutes after the photograph presented in Figure 2, the photograph shown in Figure 4 was taken. As can be seen the shadow of the pole is now covering – but just a bit – one pv-cell.

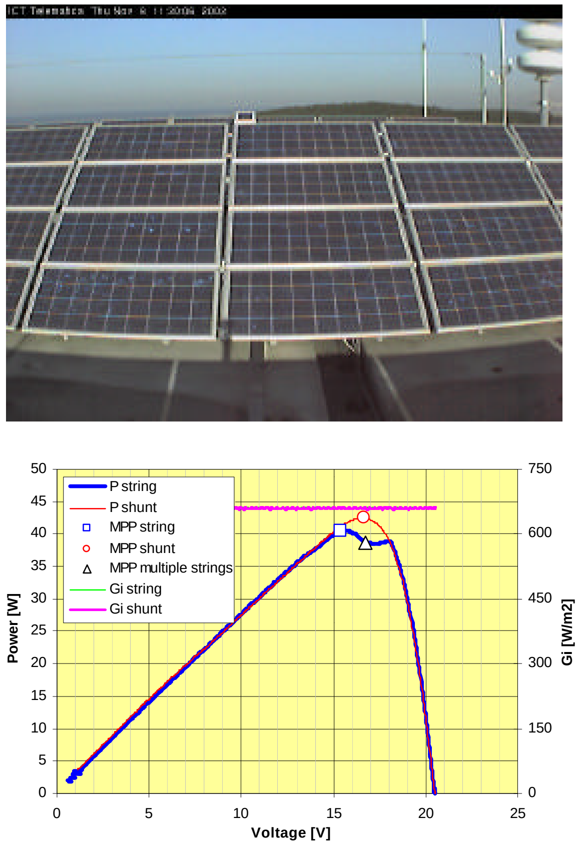

Fig 4: Photograph and measured P-V curves under ‘very lightly shading conditions’: the shadow of the pole is partly covering one pv-cell. The difference in energy yield is significant with ΔP shunt/string = 4.9% and ΔP shunt/string is 9.6% at V=81.5% of Voc.

The effect on the P-V-curve of the pv-modules in string is clearly seen (thick line), and moreover the MPP of the string when loaded at 81.5% of Voc (expected MPP, indicated by Δ) is even less, resulting in ΔP shunt/string = 4.9% and ΔP shunt/string = 9.6% at V=81.5% of Voc. In other words, the energy yield of the pv-modules in shunt is at least 4.9% higher, and might even become 9.6% higher, than the pv-modules in string. Moreover, the P-V-curve of the shunt shows a local maximum at 18 Volt. As many inverters are approaching the MPP point from the right (they start at Voc) it is very likely that they may stick at this local maximum.

5.3 Lightly shaded

In Figure 5 a photograph is presented of what we defined as ‘lightly shaded’: more than one cell is (partly) shaded. In this case the shadow of a pole covers several cells of one pv-module and touches also one of the other pv-modules in the array.

The difference in energy yield is significant; in this situation the energy yield of the pv-modules in shunt is at least 10.6% higher than the pv-modules in string and the gain increases to 27% when the string is loaded at its expected MPP voltage (81.5% of Voc). Again the P-V curve of the string shows a local maximum at 18V.

5.4 Moderately shaded

In figure 6 a typical moderately shaded pv-array is shown, with more than one pv-module shaded. Also in this situation the minimum gain in energy yield is at least 12.2%, but, when the string is loaded at its expected maximum power point (81.5% of Voc) the expected gain has increased to a respectable 216%.

Note that the shunt shows a local maximum at around 6 Volt. At that voltage the bypass diodes across the lower 18 (shaded) cells of the lower three modules are conducting. Operation in this voltage area can easily be avoided by limiting the minimum input voltage of the inverter to approximately 12 Volt. This simplifies the inverter design and allows the removal of the bypass diodes for PV-wirefree systems.

Under these conditions it might be possible that a string performs better than a shunt: only one half of the lower three modules, is shaded and this part of each module is effectively bridged by a bypass diode. However, this has not been observed (see also the animations which are downloadable from www.pv-wirefree.com). Obviously the effect of the diffuse sunlight on the shaded cells in the shunt configuration (which prevents complete blocking of the unshaded cells) is more efficient than short circuiting these cells with a bypass diode in the string configuration.

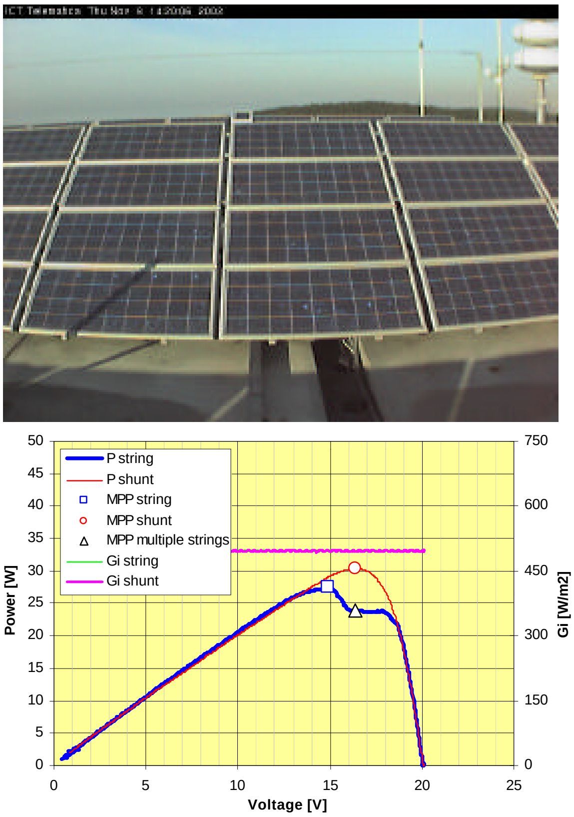

Fig 5: Photograph and measurements results under ‘lightly shaded conditions’: the shadow of a pole is covering several cells of one pv-module. The difference in energy yield is significant with ΔP shunt/string = 10.6% and ΔP shunt/string = 27% at V=81.5% of Voc.

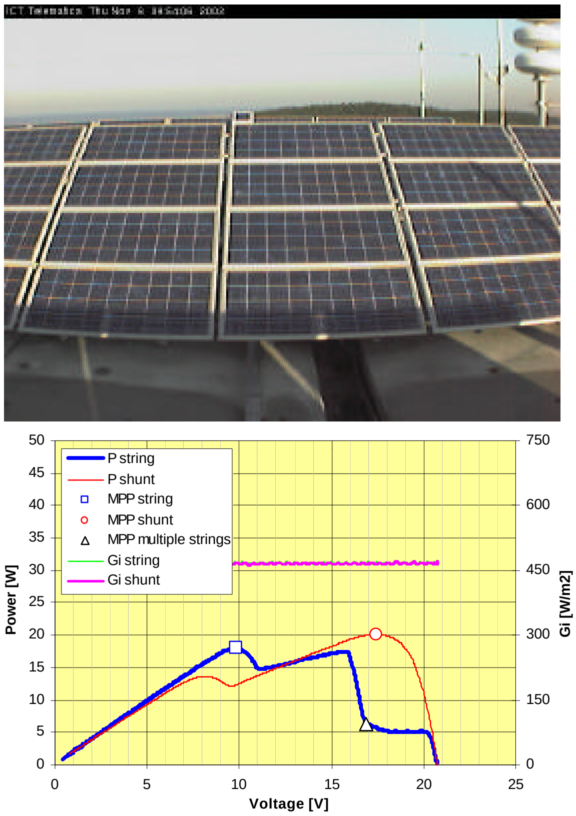

Fig 6: Photograph and measurements results of situation ‘moderately shaded’: shadow is covering parts of more than one pv-module. The difference in energy yield is astonishing with ΔP shunt/string = 12.2% and ΔP shunt/string = 216% at V=81.5% of Voc.

6 CONCLUSIONS

From the measurements – from which we have shown only some examples – it is clear that in shaded pv-systems in which pv-modules are connected in shunt (in parallel) always have a higher energy yield than pv-modules connected in string (in series).

The increase of energy yield depends on the situation, as the presented figures show. In table 1 we present an overview of expected increase of energy yield.

Table 1: Summary measurement results

Shading conditions	Very lightly shaded	Lightly shaded	Moder-ately shaded
MPP range shunt [% of Voc]	80 – 82	80 – 83	82 – 84
MPP range string [% of Voc]	75 - 87	67 – 85	46 – 76
Shunt power gain minimum [%]	2 - 5	10 - 20	0 – 50
Shunt power gain practical [%]	5 - 25	10 - 40	30 – 400

The shape of the P-V curve of a pv-wirefree system (shunt) is always the same, and shows a clear maximum, at an almost constant voltage. The maximum power point of the string fluctuates strongly, even under very light shading conditions. Moreover the strings usually have multiple local maxima. Therefore proper maximum power point tracking is hard to implement for a string, and easy for a shunt. Even under very light shading conditions the minimum gain of a shunt system is in the range of 2% to 5%, however due to the practical limitations of MPP-trackers, or when more strings are connected in parallel the practical gain of the shunt will be in the order of 5% to 25%. With increasing shade the yield of a pv-wirefree system (shunt) can easily be 100% to 400% higher than the string!

In other words, pv-modules connected in parallel always perform better in shaded conditions and also offer additional advantages. Since the MPP voltage is nearly constant, simple and efficient MPP tracking is possible. And therefore:

- Inverters can have significantly narrower input voltage windows, which will reduce costs and/or increase efficiency of inverters.
- MPP tracking efficiency of these inverters will always be significantly better.

7 REFERENCES, PARTNERS, INFORMATION AND ACKNOWLEDGEMENTS

7.1 References

[1] Roche, D.M.; Economic comparison of central versus module inverters in residential rooftop photovoltaic systems, 2002

[2] Oldenkamp, H, Detailed analysis of currents in PV-shunts, 18 February 2002

[3] Oldenkamp, H.; PV-wirefree: redesigning and innovating grid-connected PV-systems, October 2002.

[4] Oldenkamp, H.; PV-wirefree: bringing pv systems back to their essentials, May 2003.

7.2 Partners of the PV-wirefree project

In the PV-wirefree project partners from different background participate: Bear Architects, Energy research Center of the Netherlands, OJA-Services, OKE-Services, Oskomera Solar Power Solutions BV and TNO Bouw. Multi-Contact is developing the connector for PV-wirefree.

7.3 Information

For more information visit www.pv-wirefree.com, with nice animations of shading effects on the P-V curves of shunt and string systems.

7.4 Acknowledgements

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