MAXIMUM POWER POINT TRACKING PERFORMANCE UNDER PARTIALLY SHADED PV ARRAY CONDITIONS

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ABSTRACT: Partial shading of PV arrays is one of the main causes for reduced energy yield of many PV systems. However, up to now very little attention has been drawn on assessing the performance of MPP trackers due to the complexity and extensive measurement equipment required for this purpose. Against this background, the presented work fills this gap by determining the actual impact of non-ideal, irregular conditions on MPPTs and develops solutions for improved performance. In total 13 MPPTs integrated in state-of-the-art PV inverters were tested with I/V curves measured at a real, shaded PV array. While all inverters have a very high MPPT accuracy under steady state, ideal conditions, shaded conditions led to difficulties as the MPPTs tend to keep a local maximum as long as it exists and are not able to recognise the evolution of another maximum on the I/V curve. This local maximum might not be the overall MPP. In total, this resulted in a reduction of energy yield during a whole simulated day of 1% to 2%. In addition, start-up tests with single partially shaded I/V curves showed very low MPP match which led to a power loss of up to 70%.

Keywords: Maximum Power Point Tracking, Performance, Inverters

1 INTRODUCTION

With new support mechanisms dedicated specifically to building integrated PV systems (BIPV), this market segment is becoming more and more important. While from the architectural viewpoint, this development is welcomed, in practise many BIPV systems suffer from reduced performance level and thus lower profitability of the investment compared to non-building integrated systems.

There are several reasons for this, such as e.g. less ideal mounting angles due to the orientation of the roof or façade, as well as higher array temperatures due to lower ventilation of the modules. All these factors lead to a reduced energy output of the modules and thus to a lower performance ratio.

In addition to the above mentioned factors, which can hardly be avoided, PV integrated into the built environment are frequently subject to partial shading resulting from the roof-landscape, other buildings located in the proximity of the array or also minor obstacles such as antennas or lightning protection masts. It is well known that partial shading of a string may considerably reduce its power output, which is practically determined by the weakest cell in the string. Although the impact of the shaded cells can be alleviated by inserting bypass diodes, partial shading still significantly impairs the energy yield of the whole system.

It is well known that partial shading is one of the main causes for reduced energy yield of many PV systems [1]. Accordingly research activities mainly focused on the influences of PV array configuration on the energy yield. In contrast very little attention has been drawn on the performance of the MPPT under shaded array conditions and so far hardly any information is available on the performance of MPPTs under such conditions, a fact which can be explained by the complexity and extensive measurement equipment required for this purpose

Against this background, the aim of the research work presented in this paper was to fill this gap by determining the actual impact of non-ideal, irregular conditions on MPPTs of state-of-the-art PV inverters and develop solutions for improved MPPT performance.

2 CHARACTERISTICS OF PARTIALLY SHADED PV ARRAYS

Shading of a single cell within a PV-module, which itself is part of a string of containing a number of modules connected in series, leads to a reverse bias operation of the cell which may result in hot-spots and potential breakdown of the shaded cell. In order to avoid this threat, bypass diodes are inserted into the modules, which take over the string current in case of a partially shaded module [1].

Looking at the electrical characteristics of a PV string, partial shading results in a deformation of the overall I-V curve (Figure 1). This effect can be explained by the mismatch between the individual modules' I-V curves. When connected in series, it is clear the resulting I-V curve may considerably differ in shape compared to a normal, unshaded curve.

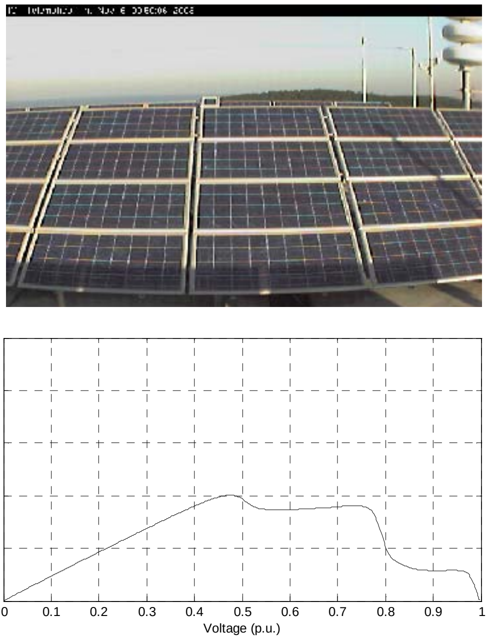

Figure 1: Measured P-V curve of a string of 9 in series connected modules showing local maxima due to shading and corresponding photo of the PV array [2].

The practical impact of partial shading on the I-V curves of a PV system with series and parallel connected PV modules in the framework of the PV-WIREFREE project [2]. For this purpose, a test system was set up which allowed a continuous tracing of the I-V curves of a PV array in both, shunt and series connection mode. In addition, for every measurement an automatic web cam provided a picture of the actual shading. Figure 1 exemplary shows a picture of the test system illustrating the picture of the shade together with the resulting I-V curve for the series connection.

The investigations [2] have furthermore shown that with steadily increasing system voltages of modern, transformerless PV inverters and the high number of modules connected in series the impact of partial shading gains significance.

3 ANALYSIS OF MPP TRACKING TECHNIQUES UNDER NON-IDEAL I-V CONDITIONS

For the MPP Tracking (MPPT) algorithm, which aims at maximising the power output of the array, it is obvious that non-ideal conditions resulting from partial shading can create considerable difficulties: I-V curves often exhibit multiple local maxima at different locations, which may also resulting in quite odd ratios between global MPP voltage and open-circuit voltage. These two factors can present a considerable hindrance to the accurate operation of a MPPT.

Among the large number of MPPT techniques described in literature [3], most work on the principle of driving either dP/dI or dP/dV to zero. Accordingly the MPPT will exhibit a “local maximum tracking behaviour”. That means once the MPPT has found a local maximum, it will track this maximum, irrespective of other maxima which might eventually be present at other positions of the I-V curve. In particular, this applies to the generic implementation of the most common methods Perturb and Observe (P&O), Incremental Conductance and Ripple Correlation Control. It is clear that considerable yield loss may occur if such a local maximum is tracked over time instead of the global MPP.

4 LABORATORY TEST

4.1 Test Objectives and Approach

Usually, MPPT accuracy is assessed in the laboratory by using ideal, modelled I-V curves, or outdoor with different methods using a normal PV array [4]. The potential effects of I-V curves with irregular shape due to partial shadowing are not considered, since the actual deformation of the I-V curves depends on a variety of factors, such as the grade and shape of the shading, and the array interconnection.

In this context, the aim of the work presented here is to develop a test method which allows the determination of the fundamental behaviour and performance of the MPPT for a PV array which is partially shaded. For this purpose, the I-V curves recorded at the partially shaded PV test installation presented above[1] was used as an input for the dynamic PV array simulator available at the arsenal research Solar Laboratory.

The MPPT test procedure itself includes two individual tests, covering different situations the MPPT has to cope with in reality. For the first test the whole day of I-V curves recordings at the test installation were used 1:1 to assess the MPPT energy yield and behaviour under non-ideal conditions for a whole day from sunrise to sunset.

The second test aims at assessing the performance of the MPPT during start-up at individual, I/V curves during the day. This situation may happen when the inverter stops during operation e.g. due to a network disturbance and restarts again after a moment.

For both tests the measured I-V curves are scaled in terms of voltage and current to properly fit the input range of the MPPT.

4.2 Test Environment

The tests were performed at arsenal research’s test stand for PV inverters, which provides a flexible environment for PV array as well as grid simulation. The used PV array simulator is based on a linear current source, controlled by a digital PC coupled I-V curve generator. For the automated assessment of the dynamic response of MPPTs, I-V curves can be programmed at a resolution of one second, which allows simulating even very fast fluctuations in irradiation. Furthermore, the simulator also includes a highly accurate measurement and data logging system for the determination of MPPT accuracies.

4.3 Devices under Test

From the experience with inverter testing, it was well known that MPPT implementation differs considerably among inverter manufacturers. Accordingly in order to get representative results, it was necessary to test a broad range of MPPTs integrated in PV inverters.

Finally a set of devices from 13 different manufacturers was selected representing 10 years of inverter history for typical residential small scale systems. Table I summarises the range of technical specifications of the tested devices.

Inverter data	Range
Input power range	1.1 kW – 5.0 kW
MPPT input voltage range	70 V – 700 V
Market introduction	1996 – 2006

Table I: Overview of technical data of the tested inverters

4.4 Whole Day Test

During the course of a day, a broad range of continuously changing shading conditions with resulting I-V curves occur. Particularly interesting in this context is the evolution of the I-V curves, the development and disappearance of local maxima.

The aim of this test is to measure the performance of the MPPT under these conditions in order to determine if and how the MPPT influences the daily energy harvest of the test object. Based on the measurements, the instant MPPT accuracy as well as the MPPT energy accuracy during the course of the whole day was evaluated.

The measurement results for the “Whole Day” test show, that there are fundamental differences between the MPPTs. This becomes obvious during situations, where a

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[1] I-V curves were recorded in November 2003 at ECN, Petten, in the framework of the PV-WIREFREE project.

new maximum evolves beside the MPPT operation point in that moment creating an I-V curve with two or more local maxima.

During the simulated day, such conditions occur twice at periods when considerable power is provided by the PV array. Figure 2 below shows exemplarily the results of the measurements for two inverters with different behaviour. The upper graph shows irradiation, ideal MPP and actual power obtained by the MPPT while the lower figure shows the resulting MPPT match. The three critical periods mentioned above are indicated by $T_{A,}$ T_B, and T_C.

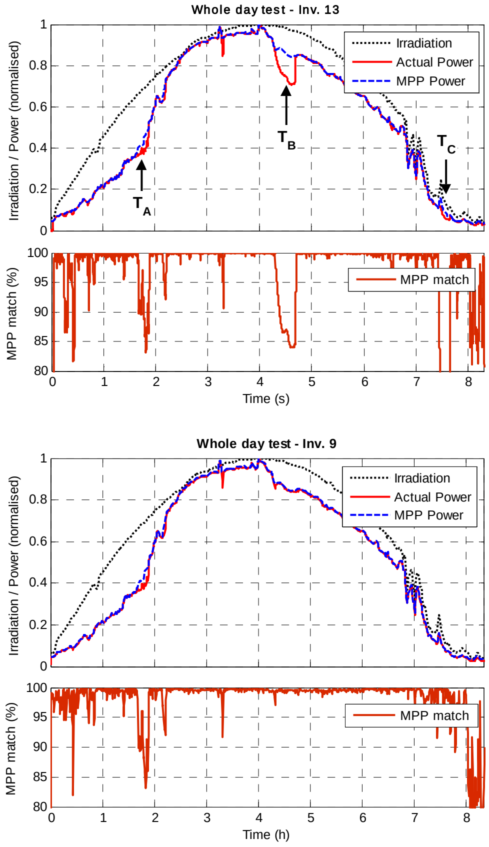

Figure 2: Comparison of MPP, actual power and irradiation as well as MPP-match during the Whole Day test for 2 inverters with different MPP tracking behaviour. Top: Inverter 13, bottom: Inverter 9.

Most of the inverters, particularly those with a fast and very accurate MPPT (represented by Inverter 13 in Figure 2) showed the expected “local maximum tracking” characteristic. In contrast, some other inverters (represented by Inverter 9 in Figure 2) did not follow the previous MPP.

However, this behaviour could not be explained by “intelligent” MPPT techniques able to continuously track the global MPP. It rather seems that the more optimal behaviour of these inverters is due to lower measurement accuracy, higher voltage steps and a generally higher input voltage fluctuations level (e.g. resulting from less accurate current control or feed through of current pulses on the AC side). In these cases strong voltage fluctuations on the DC side caused to temporarily move the MPPT to a point left of the local minimum between the local power maxima. There the gradient *dP/dU* already is negative, which caused the MPPT algorithm to reduce its voltage setting.

On the other hand, inverters with a low level of fluctuations on the input and very accurate tracking do not reach the above mentioned local minimum point. Accordingly, they keep tracking the local maximum as long as it disappears. Figure 3 illustrates this behaviour and shows the evolution of the I-V curve as well as the traces of the MPPT (red) and the global MPP (green) during the period T_A.

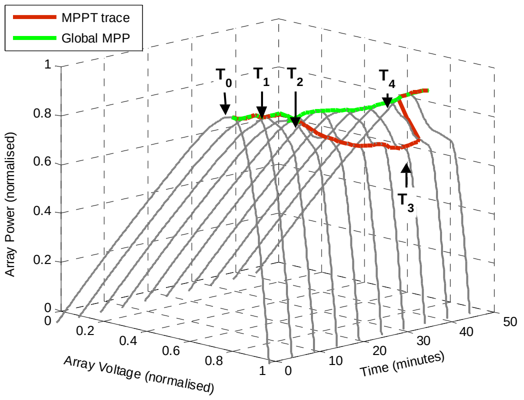

Figure 3: Visualisation of exemplary MPPT behaviour during the evolution of a new local maximum.

At time T_0 the I-V curve has only one maximum. The MPPT operates as expected. At T_1 a second, local maximum evolves at another position due to increased shading of the array. The power of the local maximum tracked by the MPPT starts to decrease (T_2) while the MPP voltage steadily increases and the 2nd local maximum at lower voltage becomes the global maximum. In the following minutes, the MPPT continues tracking the previous maximum until the gradient *dP*/*dU* left of the MPPT operation point becomes negative and the local maximum disappears at time T_3. At this moment the MPPT recognises this and reduces its voltage setting until the global MPP is hit again at T_4.

Although the measured reduction of MPP match during these periods was considerable (up to 15%), this loss is not reflected as dramatically by the figures of the resulting MPPT energy yield during the whole day, shown in Figure 4.

In total, the critical periods accounted for a measured MPP energy loss of only 1% to 2%. Nevertheless it has to be noted that with proper MPPT techniques, e.g. a two stage approach described in [5] this loss could be easily avoided.

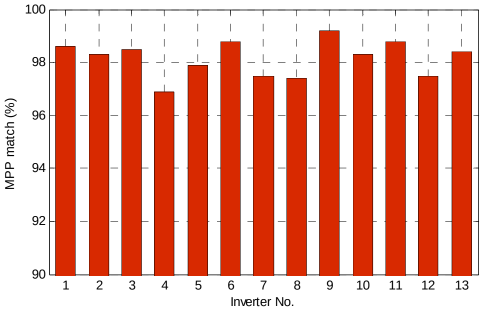

Figure 4: Whole Day test – comparison of the resulting energy yield for different MPPTs integrated in the tested inverters.

2.1 Single Curve Test

The aim of the single curve test is to measure the MPPT's behaviour on static P-V curves during the reconnection after a temporary fault condition, which is e.g. frequently caused by a grid disturbance.

For test, 6 P-V curves were selected out of the whole set of curves, characterised by differences regarding number and location of local maxima. As during the first test the curves are programmed into the PV array simulator and the MPPT behaviour after restart is observed.

Figure 5 and Figure 6 show the steady state operating points of the tested MPPTs for two P-V curves. Particularly at the first P-V curve with 3 local maxima (Figure 5), MPPTs exhibited considerable difficulties and none could find the global maximum at a normalised voltage of 0.45. Most of the MPPTs identified the second maximum, with a MPP match of 90%. However, 3 devices stopped at the first local maximum coming from open-circuit, resulting in a power loss of more than 70%.

For the second P-V curve presented, the loss was less dramatic. Nevertheless, even in this case only half of the tested MPPTs were able to find the global maximum at a normalised voltage of 0.72.

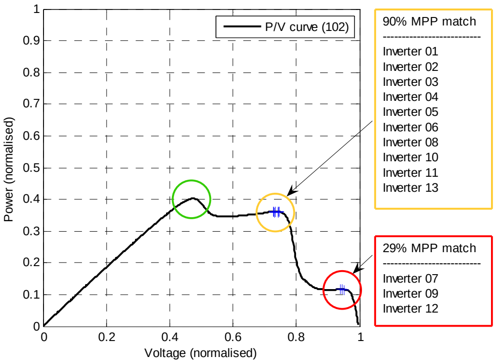

Figure 5: Single curve test (curve No. 102) – Steady state operating points reached by the tested inverters.

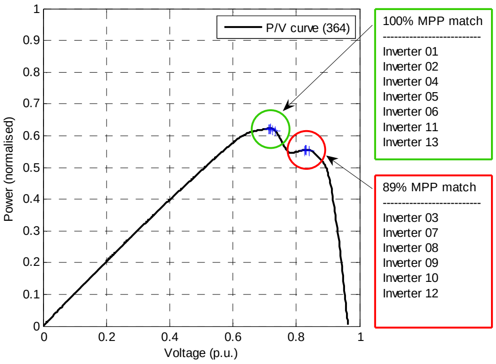

Figure 6: Single curve test (curve No. 364) – Steady state operating points reached by the tested inverters.

7 CONCLUSIONS

In total 13 MPPTs integrated in state-of-the-art PV inverters were tested. While all inverters have a very high MPPT accuracy under stationary, ideal conditions, irregular, partially shaded PV array conditions led to considerable difficulties and a reduced MPP match.

The tests showed that the MPPTs usually have "local maximum tracking" behaviour and are not able to recognise the evolution of another maximum on the I-V curve. In total, this resulted in a 1 % to 2 % reduction of energy yield for the tested P-V curves during a simulated whole day.

During the tests with single P-V curves, this behaviour was even more evident: The MPPTs approach the MPP from the open-circuit point and several tested MPPTs stopped already at the first local maximum instead of scanning the I-V curve for other maxima. For these devices, the MPPT loss was up to 70 % for certain P-V curves. Other, more optimised MPPT algorithms did not stick to the first maximum, but directly started tracking at a voltage where the MPP would be expected under normal, non-shaded conditions. The tests confirmed that with this technique most of the unwanted local maxima are bypassed and considerably higher MPPT accuracies can be achieved. Even more sophisticated MPPT techniques, as e.g. developed in [5] are also useful and enable to guarantee the operation at the global MPP.

In summary, the work showed that a number of the tested state-of-the-art PV inverters achieves an optimal MPPT performance only under ideal, non-shaded array conditions. Irregularities in the P-V curve resulting from partial shading of the curves led to increased MPP loss and a reduction of the overall energy yield.

During the development of future, standardised PV performance assessment procedures such as [6], it is recommended to include the proposed tests into the sequence in order to provide the user with information on the performance of MPPTs even under shaded array conditions. These data could be particularly useful when it comes to the choice of inverters for BIPV systems.

8 REFERENCES

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