EXPERIMENTAL STUDY OF THE BEHAVIOUR OF THE GLOBAL MPP OF PARTIALLY SHADED PV STRINGS

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ABSTRACT: Under uniform operating conditions, a photovoltaic (PV) array has only one maximum power point (MPP) and successful MPP tracking is simple to implement. However, under non-uniform operating conditions, such as partial shading, multiple MPPs can exist on the characteristic of the PV array and the global MPP can vary over a wide voltage range. When multiple MPPs exist, conventional MPP tracking algorithms can be trapped to operate at a local MPP instead of the global one, and consequently the energy yield of the array can be considerably reduced. It is essential to know the operational MPP voltage range of the installed PV array in order to adjust the voltage range of the inverter properly. In this article, the behaviour of the global MPP of partially shaded PV strings is studied experimentally based on measured current–voltage curves of two strings consisting of 17 and 6 series-connected PV modules. The results of this study show that the voltage of the global MPP varies over a wide voltage range and changes in the voltage and power of the global MPP can be very fast. The largest measured changes in the GMPP voltage and power during one second were 60% and 32%, respectively.
Keywords: Shading, Voltage Fluctuation, PV Array, Plant Control

1 INTRODUCTION

The operation of photovoltaic (PV) systems is highly affected by the operating conditions, mainly the irradiance incident on the PV cells of the system. Partial shading of a PV array refers to conditions under which the PV cells of the array receive different levels of irradiance due to non-uniform shading. Under uniform operating conditions, the non-linear electrical characteristics of PV arrays have exactly one maximum power point (MPP). However, under non-uniform operating conditions, such as partial shading, the cells of a PV array have divergent electrical characteristics, and as a result, the electrical characteristic of the whole array may have several MPPs. Only one of the MPPs represents true maximum power. This point is called global MPP (GMPP).

Under uniform operating conditions, effective tracking of GMPP is simple to implement. However, under partial shading conditions, conventional MPP tracking (MPPT) algorithms based upon hill climbing methods may get stuck to operate at a local MPP instead of the GMPP. For maximising the energy yield of the array, various more complex MPPT algorithms, like particle swarm optimisation [1] and artificial bee colony optimisation [2] have been proposed. The voltage of the GMPP may vary over a wide voltage range [3], [4]. Most PV inverters have specified allowed voltage ranges of proper operation and, accordingly, applied MPPT algorithms have defined operational voltage ranges to ensure that the GMPP is followed under changing operating conditions. Thus, it is essential to know the applicable operating GMPP voltage range of the installed PV array to select the inverter voltage range properly.

PV capacity is typically oversized with respect to the inverter such that the nominal DC power of the PV array is higher than the nominal power of the inverter [5]. An undersized inverter will operate in power limiting mode if the GMPP power of the PV array is higher than the inverter maximum power. In that case, the operating point of the inverter is moved to higher voltages than the GMPP voltage of the PV array to decrease the current and power of the inverter. Operating in power limiting mode results as losses of available energy production. Moreover, it affects the efficiency and operation of the inverter. The efficiency of some inverters decreases [6] and the inverter capacitor lifetime shortens with increasing DC side voltage [7].

The range of GMPP voltage of partially shaded PV systems has been studied earlier by simulations: in [8], [9] based on random irradiance values and in [10] based on irradiance measurements. However, only small PV systems up to 24 PV modules were considered in these studies. MPP characteristics of large-scale PV arrays have been studied by simulations in [3], [4], [11], [12]. However, static and unrealistic shading patterns were used in [12]. In this article, we have studied the behaviour of the global MPP of partially shaded PV strings. The study is based on measured current–voltage (*I*–*U*) curves of two PV strings located at Tampere, Finland. The PV strings consist of 17 and 6 series-connected PV modules. An equally exhaustive study on the GMPP behaviour of PV strings based on actual electrical measurements has not been presented earlier.

2 METHODS AND DATA

The experimental data used to obtain the results presented in this article was measured from two PV strings on four partly cloudy days at the PV research plant of Tampere University [13]. The *I*–*U* curves of strings of 17 and 6 series-connected PV modules were measured using an *I*–*U* curve tracer where IGBTs act as a variable load. The layout of the studied PV strings (Strings 1 and 4) is presented in Fig. 1. Details of the strings are compiled in in Table I and the measurement days are presented in Table II. Measurement period of each day was from 9:00 to 18:00 (UTC+2).

An *I*–*U* curve was measured once a second during the measurement period of 9 hours. Thus, the dataset of each day consists of 32400 measured *I*–*U* curves. Each curve involves 4000 measurement points. Seven PV modules of String 1 and two PV modules of String 4 have been equipped with irradiance and temperature measurements. The irradiance incident on the PV modules was measured

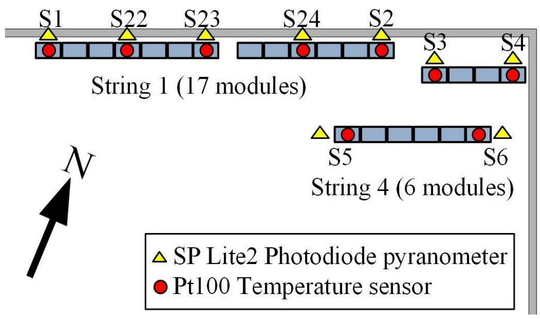

Figure 1: Partial layout scheme of the PV research plant of Tampere University.

Table I: Details of the studied PV strings.

	String 1	String 4
Number of modules	17	6
Nominal MPP power (W)	3230	1140
Nominal MPP voltage (V)	440	155

by photodiode-based SP Lite2 pyranometers (Kipp&Zonen), mounted with the same tilt angle of 45° than the PV modules. The back sheet temperature of the modules was captured by Pt100 temperature sensors. Irradiance and temperature were measured with a sampling frequency of 10 Hz.

The measured *I–U* curves were pre-processed by the following procedure. First, clearly abnormal measurement points were removed. A measurement point was removed if its power differed from the previous and next measurement point by more than 1.5 times the mean change of power between adjacent measurement points in its vicinity (previous and next 9 points). After the abnormal measurement points were removed, the measured current and voltage were separately smoothed using smooth.m function in MATLAB. Fig. 2 shows an example of measured *P–U* curves illustrating the pre-processing procedure.

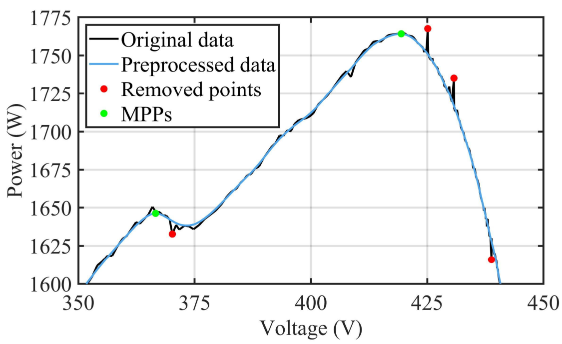

Figure 2: Example of an original and pre-processed measured *P–U* curve of String 1 near the GMPP.

Only the time when the studied PV string was under non-uniform operating conditions is of interest to this study. Partial shading events during which the difference between the measurement values of irradiance sensors located in the ends of the string (sensors S1 and S4 for String 1 and sensors S5 and S6 for String 4 (see Fig. 1)) was momentarily at least 200 W/m^2 were included in the study. A partial shading event started when the irradiance difference exceeded 100 W/m^2 and ended when the difference was not any more over 100 W/m^2.

The total number of identified partial shading events for String 1 was 256 and their total duration was 31 min and 47 s. For String 4, 80 partial shading events with a total duration of 6 min and 57 s were identified. The average duration of the identified partial shading events was 7.4 and 5.2 s for String 1 and 4, respectively. The lower number and shorter duration of the partial shading events for String 4 is expected since String 4 is shorter than String 1. The daily numbers and durations of the identified partial shading events are compiled in Table II.

3 RESULTS AND DISCUSSION

The distributions of the GMPP voltages are presented in Fig. 3 for the studied PV strings during the identified partial shading events. The peaks of the distributions are around 95% of the nominal value. The GMPP voltage was most of the time below the nominal value since the operating temperature of the modules was higher than the standard test conditions (STC) temperature of 25 °C. The average back sheet temperature of the PV modules at the ends of the string was around 35.7 and 34.4 °C during the partial shading events for String 1 and 4, respectively. The GMPP voltage ranges of Strings 1 and 4 were from 34.9% to 107.4% and from 84.1% to 105.9%, respectively. The GMPP voltage range of String 1 is largely in line with the simulation results presented in [3]. String 4 has narrower GMPP voltage range than String 1 since String 4 is shorter, i.e., the operating condition differences between the modules are smaller. This is in

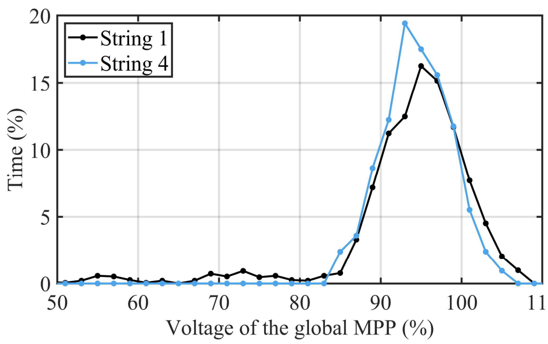

Figure 3: Distributions of the measured GMPP voltages of the studied PV strings during the partial shading events. The values are with respect to the nominal MPP values of the strings.

Table II: Details of the experimental data.

Day	String	Measurement period (h)	Number of identified partial shading events	Duration of partial shading events
August 7, 2018	1	9	135	18 min 14 s
May 12, 2020	1	9	121	13 min 33 s
May 29, 2020	4	9	52	5 min 32 s
May 30, 2020	4	9	28	1 min 25 s

line with [3] showing that the length of the strings has a notable effect on the lower limit of the GMPP voltage range of a PV array, whereas the number of parallel-connected strings and the electrical PV array configuration have only minor effects on the voltage range of the GMPP.

Fig. 4 shows the distributions of the GMPP powers for the studied PV strings during the partial shading events. The GMPP power of String 1 varied between 11.5% and 110.6% and the GMPP power of String 4 between 19.3% and 117.7% of the nominal power. The weight of the distribution is at larger values for String 4 than for String 1, which is an expected result as String 4 is shorter than String 1. The GMPP power of both the strings was almost all the time smaller than the nominal power. This is reasonable, as the irradiance received by the PV modules naturally varies during the day and the highest clear sky irradiance during a year in the Tampere region is just over 900 W/m^2 for an optimally installed fixed PV system. Further, the increased PV module temperature decreases also the power. However, GMPP powers larger than the nominal value were measured for both of the strings. The reason for these values is cloud enhancement phenomenon: irradiance under partly cloudy conditions can be larger than under clear sky due to scattering of photons off clouds near the direct path of sunbeams [14].

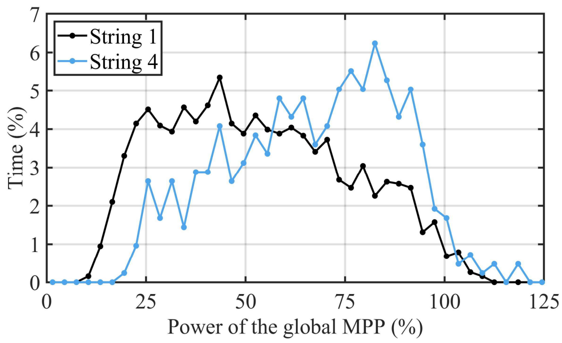

Figure 4: Distributions of the measured GMPP powers of the studied PV strings during the partial shading events. The values are with respect to the nominal MPP values of the strings.

The cumulative frequencies of the rate of change of the GMPP voltage are presented in Fig. 5 for the studied PV strings during the partial shading events. The figure shows a large difference between the strings. The largest change in the GMPP voltage during one second was

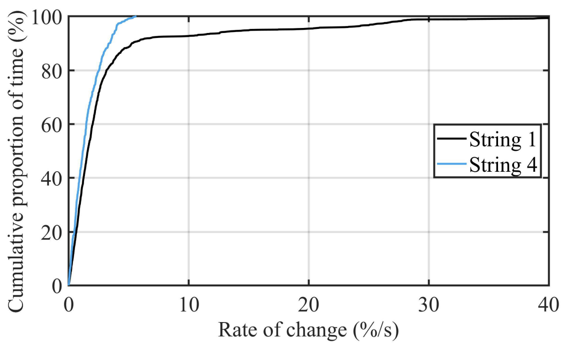

Figure 5: Relative cumulative frequencies of the rate of change of the GMPP voltage for the studied PV strings during the partial shading events. The values are with respect to the nominal MPP values of the strings.

59.9% for String 1 while it was only 5.6% for String 4. The average rates of change were 3.4 and 1.5 %/s for String 1 and 4, respectively.

Fig. 6 shows the cumulative frequencies of the rate of change of the GMPP power for the studied PV strings during the partial shading events. Changes in GMMP power are faster for String 4 than for String 1 as expected since String 4 is shorter than String 1, i.e., changes in its average irradiance are typically faster. The largest change in the GMPP power during one second was 23.0% for String 1 and 32.5% for String 4. The average rates of change were 5.3 and 8.6 %/s for String 1 and 4, respectively.

The following example illustrates the behaviour of the *P*–*U* curve of a PV string during fast changes in irradiance. Fig. 7 (a) presents five consecutive *P*–*U* curves of String 1 measured during a partial shading event during which an extremely large rate of change of

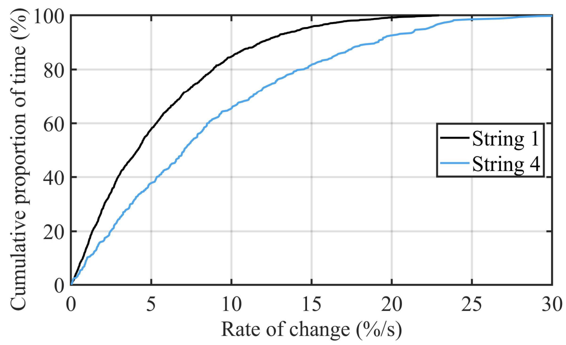

Figure 6: Relative cumulative frequencies of the rate of change of the GMPP power for the studied PV strings during the partial shading events. The values are with respect to the nominal MPP values of the strings.

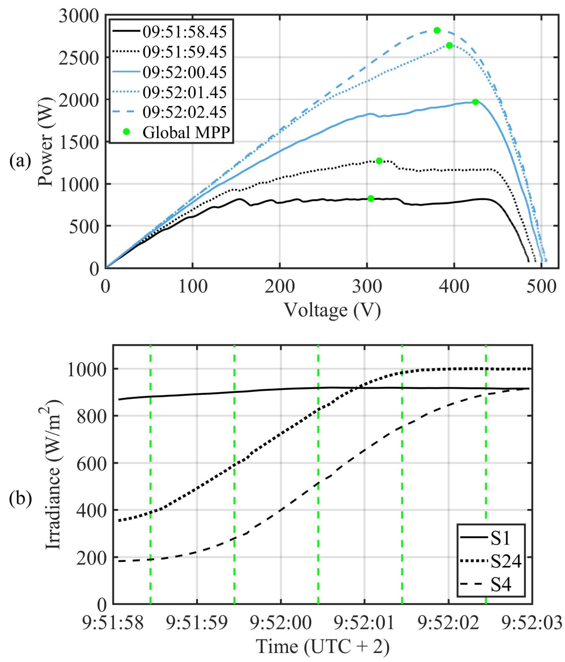

Figure 7: (a) Five consecutive power–voltage curves of String 1 measured during an identified partial shading event on August 7, 2018. (b) The irradiances measured by three irradiance sensors during the period in (a). The moments when the curves of (a) were measured are indicated with vertical green lines in (b). Consult Fig. 1 for sensor numbers.

the GMPP power was measured. On August 7, 2018, the largest change in the GMPP power of String 1 within one second was 21.6% with respect to the nominal MPP power and occurred between the second and third lowest curve of Fig. 7 (a). The GMPP changed from 314 V to 424 V and the increase in power was 698 W. During the next second the power increased 669 W. Thus, the change in power in two seconds was 1367 W, or 42.4% of the nominal MPP power. The irradiances measured by three irradiance sensors during the partial shading event are presented in Fig. 7 (b). During the period presented in Fig. 7, irradiance of the PV modules on the right hand side of the studied string (see Fig. 1) increased as the edge of a dark cloud shadow moved over the modules while the irradiance of the modules on the left hand side was almost constant during the period, i.e., the shadow had already moved away from the modules.

The voltage and power values of the GMPP of String 1 corresponding to the *P–U* curves of Fig. 7 (a) are compiled in Table III. During the partial shading event, the GMPP voltage varied between 304 and 424 V while the GMPP power increased from 821 to 2816 W. This example demonstrates why the power distributions in Fig. 4 are flatter than the voltage distributions in Fig. 3.

Table III: GMPP voltage and power of String 1 at the five moments presented in Fig. 7 (a).

Time (UTC + 2)	GMPP voltage (V)	GMPP Power (W)
09:51:58.45	304	821
09:51:59.45	314	1272
09:52:00.45	424	1970
09:52:01.45	394	2639
09:52:02.45	380	2816

At the end of the partial shading event (the uppermost curve in Fig. 7 (a)), the PV string was unshaded and the *P–U* curve of the string had smooth shape with only one MPP. On the other hand, the bottom curve of Fig. 7 (a) shows a typical example of the shape of the *P–U* curve of a partially shaded PV system. The power is almost constant over a large voltage range from 150 to 450 V with power between 739 and 821 W. Under that kind of conditions, large and fast changes in GMPP voltage may occur.

Fig. 8 (a) presents four consecutive *P–U* curves during a partial shading event during which the largest rate of change of the GMPP power for String 4 was measured. The largest change in the GMPP power within one second occurred between the second and third lowest curve when the GMPP power decreased 370 W, or 42.4% of the nominal MPP power. During the partial shading event, the GMPP power decreased from 1132 to 375 W while the variation in GMPP voltage was small between 143 and 156 V. Fig. 8 (b) shows the irradiances measured by the irradiance sensors at the ends of the string during the partial shading event. A dark cloud shadow covered the studied string starting from the PV modules on the left side of the string.

Fig. 8 illustrates how the irradiance differences between the PV modules of short PV strings remain relatively small during even fast irradiance transitions caused by moving clouds. The reason for this is that typical cloud shadows produce gentle irradiance transitions, causing only minor irradiance differences

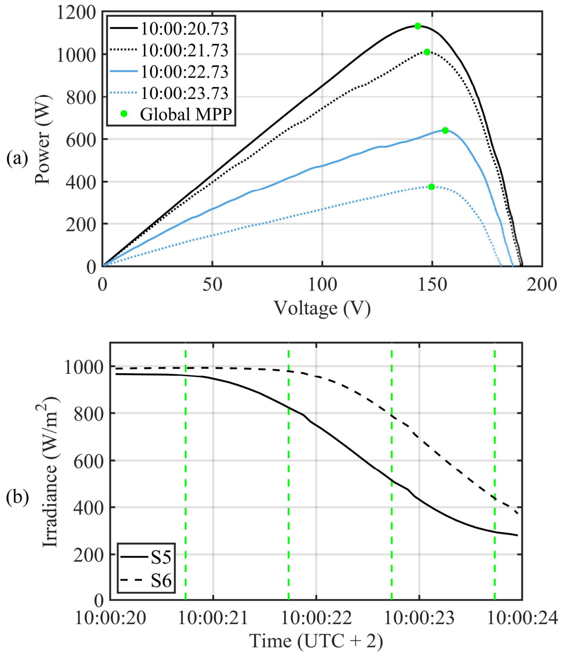

Figure 8: (a) Four consecutive power–voltage curves of String 4 measured during an identified partial shading event on May 29, 2020. (b) The irradiances measured by two irradiance sensors during the period in (a). The moments when the curves of (a) were measured are indicated with vertical green lines in (b). Consult Fig. 1 for sensor numbers.

between adjacent PV modules. The average length of irradiance transitions on the edges of cloud shadows was found to be around 150 m [15]. Since String 4 consists of only six PV modules, the nearly constant voltage range under partial shading cannot be as wide as it is for String 1 (see Fig. 7). For this reason, the fastest changes in GMPP voltage are slower for String 4 than for String 1 as presented in Fig. 5.

4 CONCLUSIONS

This article presented a study on the behaviour of the global MPP of partially shaded PV strings based on measured *I–U* curves of two PV strings located at Tampere, Finland. The PV strings consist of 17 and 6 series-connected PV modules. The *I–U* curves of the strings were measured once a second using an *I–U* curve tracer on four partly cloudy days. Irradiance and temperature of nine PV modules of the studied strings were measured with 10 Hz sampling frequency.

It was shown in this article that the GMPPs of partially shaded PV strings vary over a wide voltage range: the GMPP of the longer string varied from 34.9% to 107.4% and the GMPP of the shorter string varied from 84.1% to 105.9% with respect to the nominal MPP voltage. Correspondingly, the GMPP power of the longer string varied from 11% to 111% and the GMPP power of the shorter string varied from 19% to 118% of the nominal MPP power.

It was found that changes in the voltage and power of the GMPP can be very fast. The largest measured changes in the GMPP voltage and power during one second were 60% and 32%, respectively. Changes in the GMMP power were faster for the shorter string since its average irradiance changes typically faster than that of the longer string. However, changes in the GMPP voltage were faster for the longer string. Fast changes in GMPP voltage may cause failures in MPP tracking.

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REFERENCES

[1] K. Ishaque, Z. Salam, IEEE Trans. Industrial Electronics 60 (2013) 3195. https://doi.org/10.1109/TIE.2012.2200223.
[2] D. Karaboga, C. Ozturk, Applied Soft Computing 11 (2011) 652. https://doi.org/10.1016/j.asoc.2009.12.025.
[3] K. Lappalainen, S. Valkealahti, IET Renewable Power Generation 13 (2019) 2864. https://doi.org/10.1049/iet-rpg.2019.0085.
[4] K. Lappalainen, S. Valkealahti, Proceedings of 36th European Photovoltaic Solar Energy Conference, Vol. I (2019) 1579. https://doi.org/10.4229/EUPVSEC20192019-5CV.4.8.
[5] H.X. Wang, M.A. Munoz-García, G.P. Moreda, M.C. Alonso-García, Renewable Energy 118 (2018) 709. https://doi.org/10.1016/j.renene.2017.11.063.
[6] G.A. Rampinelli, A. Krenzinger, F. Chenlo Romero, Renewable and Sustainable Energy Reviews 34 (2014) 578. https://doi.org/10.1016/j.rser.2014.03.047.
[7] J.M.S. Callegari, A.F. Cupertino, V.N. Ferreira, E.M.S. Brito, V.F. Mendes, H.A. Pereira, Microelectronics Reliability 100–101 (2019) 113439. https://doi.org/10.1016/j.microrel.2019.113439
[8] A.M.S. Furtado, F. Bradaschia, M.E. Cavalcanti, L.R. Limongi, IEEE Trans. Industrial Electronics 65 (2018) 3252. https://doi.org/10.1109/TIE.2017.2750623.
[9] M. Boztepe, F. Guinjoan, G. Velasco-Quesada, S. Silvestre, A. Chouder, E. Karatepe, IEEE Trans. Industrial Electronics 61 (2014) 3302. https://doi.org/10.1109/TIE.2013.2281163.
[10] A. Mäki, S. Valkealahti, Proceedings of 28th European Photovoltaic Solar Energy Conference, Vol. I (2013) 4063. https://doi.org/10.4229/28thEUPVSEC2013-5BV.7.3.
[11] K. Lappalainen, S. Valkealahti, Renewable Energy 152 (2020) 812. https://doi.org/10.1016/j.renene.2020.01.119.
[12] H. Patel, V. Agarwal, IEEE Trans. Energy Conversion 23 (2008) 302. https://doi.org/10.1109/TEC.2007.914308.
[13] D. Torres Lobera, A. Mäki, J. Huusari, K. Lappalainen, T. Suntio, S. Valkealahti, International Journal of Photoenergy 2013 (2013) 837310. https://doi.org/10.1155/2013/837310.
[14] K. Lappalainen, J. Kleissl, Journal of Renewable and Sustainable Energy 12 (2020) 043502. https://doi.org/10.1063/5.0007550.
[15] K. Lappalainen, S. Valkealahti, Solar Energy, 138 (2016) 47. https://doi.org/10.1016/j.solener.2016.09.008.