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EXPERIMENTAL STUDY OF THE OPERATION OF PV STRINGS AT THE MPP CLOSEST TO THE NOMINAL MPP VOLTAGE INSTEAD OF THE GLOBAL MPP

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ABSTRACT: Under non-uniform operating conditions, photovoltaic (PV) generators can have multiple maximum power points (MPP) which may cause problems for MPP tracking. Since highly varying global MPP (GMPP) voltage causes large fluctuations in the inverter reference voltage, it would be beneficial to keep the operating point of the inverter all the time close to the nominal MPP voltage. In this way, operation of the PV system would be more predictable and straightforward. This paper presents an experimental study based on measured current–voltage curves of two PV strings of a scenario in which the MPP closest to the nominal MPP voltage is used all the time as the operating point instead of the GMPP. In total, 432000 *I–U* curves measured over 120 hours were analysed. The effects of inverter sizing on the selection of the operating point of the PV strings were also studied. The experimental results presented in this paper demonstrate that the wide operating voltage range when the GMPP is followed can be significantly reduced by operating at the MPP closest to the nominal MPP voltage at a cost of negligible energy losses.

Keywords: Voltage Fluctuation, Plant Control, Shading, PV System

1 INTRODUCTION

Photovoltaic (PV) power generators are constantly prone to variation in their operating conditions. Especially, fast irradiance fluctuations caused by overpassing cloud shadows can have negative effects on the operation of PV generators and electrical grids causing rapid fluctuations in the power fed into the grid. During uniform operating conditions, the electrical characteristic of a PV generator has only one peak, i.e., maximum power point (MPP). On the other hand, during non-uniform operating conditions, the electrical characteristics of the PV cells of the generator differ from each other, and as a result, the electrical characteristic of the entire generator may have several MPPs. The MPP where actual maximum power is achieved is called the global MPP (GMPP) while the MPPs with lower powers are called local MPPs (LMPP).

Existence of several MPPs makes MPP tracking (MPPT) more difficult and may lead to operation at an LMPP. Thus, several new algorithms for MPPT of partially shaded PV generators have been developed in the last few years [1], [2]. Moreover, the GMPP voltage can vary over a wide voltage range [3], [4]. Typically, inverters have defined allowed voltage ranges for proper operation and, accordingly, applied MPPT algorithms have defined operational voltage ranges to ensure that the GMPP is followed under varying operating conditions. Hence, the information about the applicable voltage range of the GMPP of the installed PV generator is of great value for successful choice of the inverter voltage range.

PV capacity is usually oversized with respect to the inverter meaning that the PV generator nominal DC power exceeds the inverter nominal AC power [5]. Oversizing of PV capacity restricts the output power of the PV generator to the inverter nominal power during high irradiance conditions. The inverter will operate in power limiting mode if the GMPP power of the generator rises above the inverter maximum power. In that case, the inverter operating point is forced to move to voltages higher than the GMPP voltage to reduce the power and current of the inverter. Hence, operating in power limiting mode leads to losses of available PV energy production. Moreover, it affects the operation and efficiency of the inverter: the inverter capacitor lifetime shortens [6] and the efficiency of some inverters decreases [7] with increasing DC side voltage.

In the last ten years, several studies have been presented related to the MPP characteristics of PV generators, based on simulations in [8], [9], [10], [11] and based on electrical measurements in [3], [4]. However, the effects of inverter sizing on the operating point were not considered in these studies. Moreover, fictitious irradiance values were used in [8], [11] and only the partially shaded time of the studied generators was considered in [3], [4].

Since the highly varying GMPP voltage causes large fluctuation of the inverter reference voltage, posing challenges for MPPT, it would be beneficial to keep the operating point of the inverter all the time at voltages close to the nominal MPP voltage. In this way, the operation of the PV system would be more straightforward, smoother and more predictable. This paper presents an experimental study of the scenario in which the MPP closest to the nominal MPP voltage (CMPP) is always the operating point instead of the GMPP. The study is based on measured current–voltage (*I–U*) curves of 2 PV strings located at Tampere, Finland. In total, 432000 *I–U* curves measured over 120 hours are analysed. Moreover, the effects of inverter sizing on the operating point behaviour of the PV strings are studied. An equally exhaustive study on the optimum operating point of PV strings founded on actual electrical measurements has not been presented before. The results presented in this paper are especially relevant for PV system and generator design as well as for improvement of MPPT algorithms while trying to achieve higher PV system efficiencies.

2 EXPERIMENTAL DATA AND METHODS

The experimental data consists of over 400000 measured *I–U* curves of 2 PV strings of the PV research plant of Tampere University [12]. Six consecutive days of full-time measurements were analysed for both strings. Measurement period of each day was from 8:00 to 18:00 (UTC+2). The layout of the studied PV strings, consisting of 17 and 6 series-connected PV modules, is presented in Fig. 1 and the details of the strings are compiled in Table I. The analysed measurements of

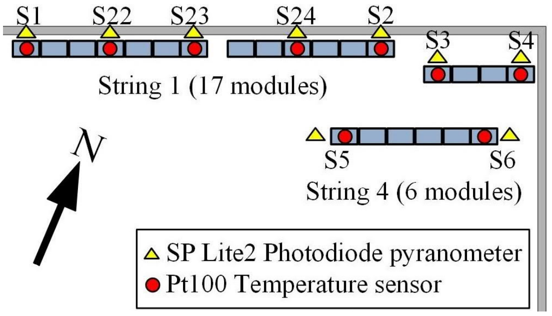

Figure 1: Layout scheme of Strings 1 and 4 of PV research plant of Tampere University.

Table I: Details of the studied PV strings.

	String 1	String 4
Number of PV modules	17	6
Nominal MPP voltage (V)	440	155
Nominal MPP power (W)	3230	1140
Length (m)	28.8	8.9

Strings 1 and 4 were performed on 14–19 and 7–12 August 2020, respectively. An *I–U* curve was measured once a second during the measurement period, using an *I–U* curve tracer where IGBTs act as a variable load. Thus, in total, 432000 measured *I–U* curves were analysed. Irradiance and temperature of seven PV modules of String 1 and two PV modules of String 4 were measured with a sampling frequency of 10 Hz. The irradiances incident on the PV modules were measured by photodiode-based SP Lite2 pyranometers, mounted at the same 45° tilt angle as the PV modules, while the PV module back-sheet temperatures were captured by Pt100 temperature sensors.

Each *I–U* curve involves 4000 measured *I–U* pairs. In order to reduce noise and other inaccuracies in the measured *I–U* curves, they were pre-processed by the following procedure. Firstly, the measurement points with identical voltage value were replaced with a single new point by averaging their current values. Thereafter, noticeably abnormal measurement points were removed. A measurement point was removed if its power differed from the power of the previous and next measurement point (to same direction) by more than 1.3 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 smoothed separately using smooth.m function in MATLAB. An example shown in Fig. 2 illustrates the pre-processing method. A similar pre-processing method was used in [4].

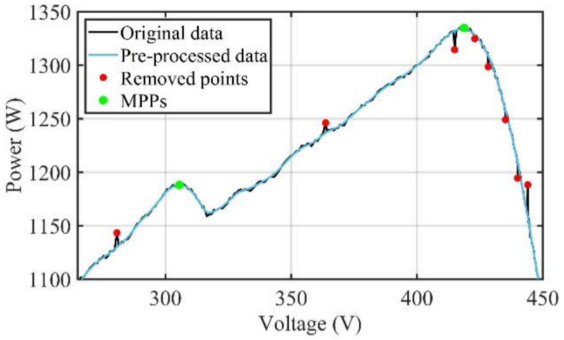

Figure 2: Example of an original and pre-processed measured *P–U* curve near the GMPP.

The effects of inverter sizing on the MPP behaviour of the PV strings were studied by altering the DC/AC ratio, i.e., the ratio of the nominal DC power of the PV string to the inverter nominal AC power. MPPT was assumed to work ideally, so that the string is operating at its GMPP (or CMPP) unless it is in power limiting mode. If the power at the GMPP (or the CMPP) exceeds the inverter nominal power, the string operates on the high voltage side of the GMPP (or the CMPP) at the lowest voltage where the inverter nominal power is not exceeded. The DC/AC ratio was altered from 0.8 to 2.0.

3 RESULTS AND DISCUSSION

The distributions of the measured voltages of the GMPP and the MPP closest to the nominal MPP voltage are presented in Fig. 3 for the studied PV strings. Both voltages were most of the time below the nominal value. This results from the typical operating conditions of the studied PV strings: during the studied periods, the irradiance was mostly lower and the cell temperature was higher than in standard test conditions, thus the MPP voltages were typically lower than the nominal MPP voltage. The GMPP voltage of String 4 was all the time below the nominal value and the GMPP voltage of String 1 was higher than the nominal value only 0.06% of time. The lowest and highest measured voltages of the two MPPs are compiled in Table II. The measured voltage ranges of the GMPP are largely in accord with the experimental results of [3] and [4] as well as with the simulation results of [9].

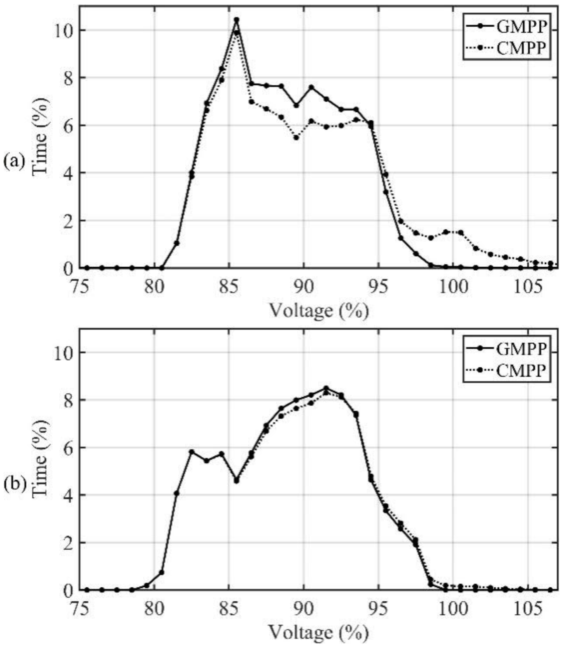

Figure 3: Distributions of the measured voltages of the GMPP and CMPP for Strings 1 (a) and 4 (b). The voltages are with respect to the nominal MPP voltages.

The differences in voltage distributions between the two MPPs are much larger for the physically longer String 1 (Fig. 3 (a)) than for the shorter String 4 (Fig. 3 (b)). The GMPP voltage range of String 1 was very wide from 38% to 104%. The voltage range can be significantly reduced by operating at the CMPP with a voltage range from 81% to 116%. This is an important finding, demonstrating that it would be beneficial for PV systems

Table II: Measured voltage ranges of the GMPP and CMPP for the studied PV strings. The voltage values are with respect to the nominal MPP voltages.

	Minimum voltage (%)	Maximum voltage (%)
String 1, GMPP	38.2	104.4
String 4, GMPP	79.2	99.6
String 1, CMPP	81.0	115.5
String 4, CMPP	79.2	108.7

to operate at the MPP closest to the nominal MPP voltage instead of the GMPP. However, for very short PV strings (String 4) corresponding advantage is not achieved. For String 4, both MPPs have the same quite high lower bound of voltage range, while the maximum CMPP voltage is higher than the maximum GMPP voltage.

The distributions of the measured powers of the GMPP and the MPP closest to the nominal MPP voltage are presented in Fig. 4 for the studied PV strings. By comparing Figs. 3 and 4, it can be seen that the differences in power between the two MPPs are smaller than in voltage. Small differences in power mean that operation at the CMPP instead of the GMPP does not cause significant energy losses. MPP powers higher than the nominal power were measured for both strings. These situations are caused by the cloud enhancement phenomenon [13]. Power values higher than the nominal value are more common for String 4 as it is physically shorter than String 1 and thus exposed to higher enhanced irradiances. One should also note in here that the clear sky irradiance in Tampere region never reaches the standard test condition irradiance of 1 kW/m^2, which causes the nominal MPP power.

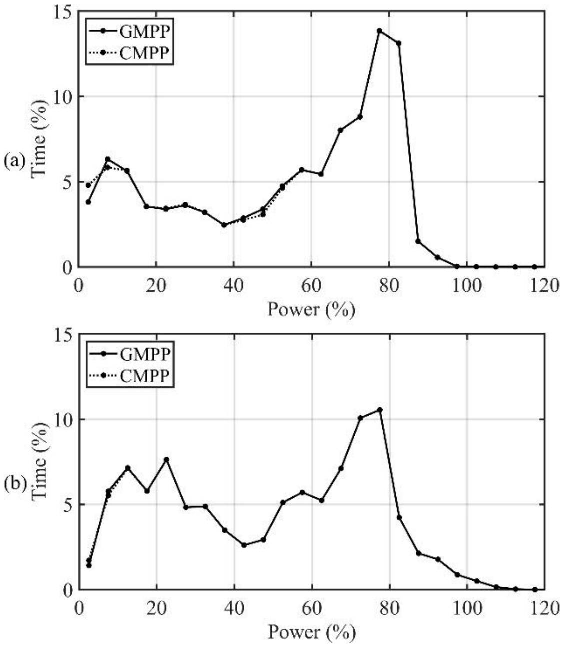

Figure 4: Distributions of the measured powers of the GMPP and CMPP for Strings 1 (a) and 4 (b). The powers are with respect to the nominal MPP powers.

Difference in length explains the differences between the studied strings in Figs. 3 and 4. String 1 is physically over three times longer than String 4 (see Table I). Thus, there are typically larger irradiance and temperature differences between the modules of String 1 than between the modules of String 4. As a result, multiple MPPs exist more often for String 1 than for String 4. Indeed, String 1 had more than one MPP 15.8% of the time while String 4 had multiple MPPs only 2.5% of the time.

In Fig. 5, the shares of time when the studied PV strings operated in power limiting mode are presented as a function of DC/AC ratio. Naturally, the shares of time when the PV strings operated in power limiting mode increased with the increasing DC/AC ratio, since the irradiance level needed to produce PV power exceeding the nominal inverter power decreases as the DC/AC ratio increases. There is a clear difference between the studied strings. With DC/AC ratios below 1.2, String 4 spends more time in power limiting mode than String 1. That is logical since with low DC/AC ratios relatively high irradiance level is needed to produce PV power exceeding the nominal inverter power. String 4 has smaller area than String 1, and thus its modules receive high enough irradiance more often. However, as the DC/AC ratios increase, the proportion of time in the power limiting mode increases sharply, and String 4 spends less time in power limiting mode than String 1. The differences between the GMPP and CMPP were very small with virtually overlapping curves but the shares were a bit larger for the GMPP.

Fig. 6 presents the highest, median and lowest operating voltages as a function of DC/AC ratio while operating at the GMPP or at the CMPP for the studied strings. The voltages increased with the increasing DC/AC ratio since the strings were operating on the high voltage side of the GMPP (or the CMPP) in power limiting mode. The maximum GMPP voltage approached the maximum CMPP voltage as the DC/AC ratio increased. Thus, the difference in voltage ranges between the MPPs increased as the DC/AC ratio increased. The maximum GMPP voltage of String 4 reached the maximum CMPP voltage already with a DC/AC ratio of 1.2 but not completely for the longer String 1.

Fig. 7 presents the relative energy losses due to operation at the CMPP instead of the GMPP and due to power curtailment. The relative energy losses due to operation at the CMPP increased with increasing DC/AC ratio for String 1 and were much larger than for String 4, which remained quite constant. However, only negligible amount of energy would be lost if the PV strings operated all the time at the CMPP instead of the GMPP. This demonstrates that the wide operating voltage range when the GMPP is followed can be significantly reduced by operating at the MPP closest to the nominal MPP voltage at a cost of negligible energy losses. The relative energy

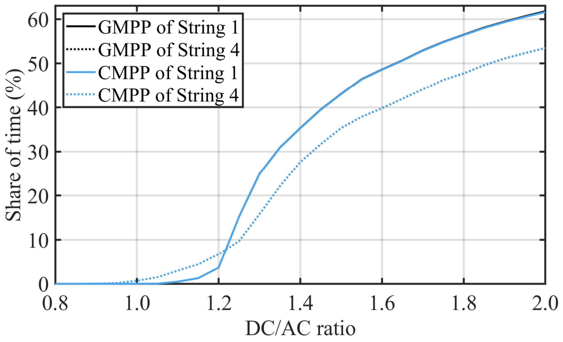

Figure 5: Shares of time when the studied PV strings were in power limiting mode when operating at the GMPP or at the CMPP as a function of DC/AC ratio.

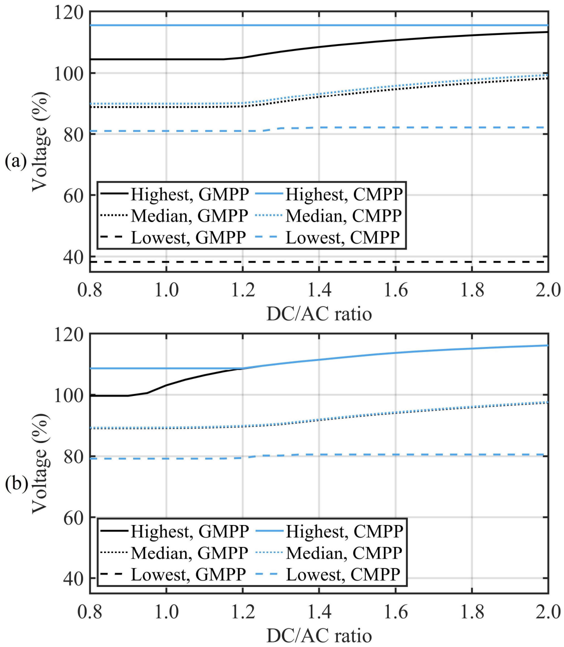

Figure 6: Highest, median and lowest operating voltages as a function of DC/AC ratio while operating at the GMPP or at the CMPP for Strings 1 (a) and 4 (b). The voltages are with respect to the nominal MPP voltages.

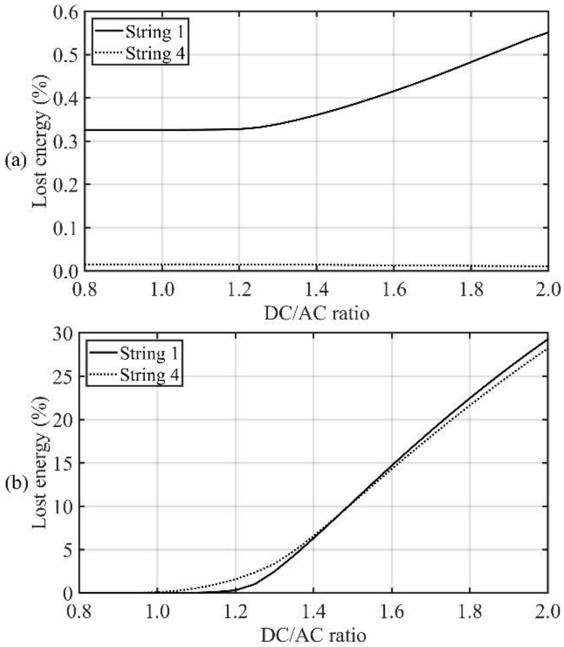

Figure 7: Relative energy losses of the studied PV strings due to operation at the CMPP instead of the GMPP (a) and due to power curtailment (b) as a function of DC/AC ratio. The relative energy losses due operation at the CMPP instead of the GMPP were calculated with respect to energy produced at the GMPP (taking power curtailment into account). The relative energy losses due to power curtailment were calculated with respect to energy produced at the GMPP without power curtailment.

losses due to power curtailment were much larger than the relative energy losses due to operation at the CMPP. They increased strongly with increasing DC/AC ratio being around 30% with a DC/AC ratio of 2.0. With small DC/AC ratios below 1.1, the strings were in power limiting mode only during cloud enhancement. As explained earlier, the share of time spent in power limiting mode increases with the increasing DC/AC ratio since the irradiance level needed to produce PV power exceeding the nominal inverter power decreases.

4 CONCLUSIONS

This paper presented an experimental study of the GMPP characteristics of PV strings and a scenario in which the MPP closest to the nominal MPP voltage is always the operating point instead of the GMPP. The effects of inverter sizing on the operating point behaviour of the PV strings were also studied. The study was based on 432000 *I–U* curves of 2 PV strings measured over 120 hours.

The experimental results demonstrate that it would be beneficial for PV systems to operate at the CMPP instead of the GMPP. For a string of 17 PV modules, a wide GMPP voltage range from 38% to 104%, with respect to the nominal MPP voltage, can be significantly reduced by operating at the CMPP with a voltage range from 81% to 116%. Moreover, the results show that only negligible amount of energy would be lost if the PV strings operated all the time at the CMPP instead of the GMPP. Thus, the wide voltage range of the GMPP can be significantly reduced by operating at the CMPP at a cost of negligible energy losses compared to operation at the GMPP. However, for very short PV strings corresponding voltage range reduction is not achieved while the energy losses due to operating in the CMPP remain small.

Energy losses due to power curtailment were found to be much larger than energy losses due to operation at the CMPP instead of the GMPP. For example, with a typical DC/AC ratio of 1.5, over 10% of available energy in both strings would be lost due to power curtailment. These losses increased strongly with increasing DC/AC ratio being close to 30% with a DC/AC ratio of 2.0. The experimental results presented in this paper confirm the findings of earlier simulation studies.

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