OPERATION OF PV ARRAYS AT THE LARGEST MPP VOLTAGE INSTEAD OF THE GLOBAL MPP VOLTAGE DURING IRRADIANCE TRANSITIONS CAUSED BY CLOUDS

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ABSTRACT: Under non-uniform operating conditions, like partial shading, several maximum power points (MPPs) may exist on the electrical characteristic of a photovoltaic (PV) array and the global MPP may 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 PV array can be considerably reduced. The partial shading of well-designed large-scale PV power plants is mainly due to shadows of moving clouds. In this article, the operation of various PV arrays at the largest MPP voltage instead of the global MPP voltage has been studied during measured irradiance transitions caused by clouds. The voltage range of the MPP with the largest voltage was found to be clearly narrower than that of the global MPP and the energy losses resulting from the operation at the largest voltage MPP instead of the global one during cloud partial shading events were found to be slight. The results of this study justify the operation of PV arrays at the MPP with the largest voltage in lieu of the global one.
Keywords: PV system, Voltage Fluctuation, Shading, Performance

1 INTRODUCTION

The operation of photovoltaic (PV) systems is greatly affected by the operating conditions, mainly the irradiance incident on the PV cells of the systems. The partial shading of well-designed utility-scale PV power plants is mainly caused by shadows of moving clouds. Under uniform operating conditions, exactly one maximum power point (MPP) exists on the non-linear electrical characteristic of a PV module. Nevertheless, under non-uniform operating conditions, like partial shading, the PV cells of a PV array have distinct electrical characteristics. As a consequence, the array characteristic may have several MPPs and the global MPP, i.e., the MPP with the largest power, may vary over a wide voltage range. When multiple MPPs exist, conventional maximum power point tracking (MPPT) algorithms based upon hill climbing methods can easily get stuck to operate at a local MPP in lieu of the global one [1].

If a PV array is operating at a local MPP, the energy yield of the array can be considerably reduced. For the purpose of maximising the energy yield of the array, various more complex MPPT algorithms, like artificial bee colony optimisation [2], particle swarm optimisation [3] and cuckoo search [4], have been developed. MPPT algorithms have defined operational voltage ranges to secure that the operation point follows the global MPP under changing operating conditions. Some MPPT algorithms have to scan more than 80% of the whole array voltage range [5]. However, also MPPT algorithms with reduced voltage search ranges have been studied [6]–[8]. Most commercial PV inverters have specified allowed voltage ranges of proper operation. Thus, it is essential to know the applicable operating range of PV array MPP voltage to adjust the inverter voltage range properly.

The range of global MPP voltage under partial shading has been studied in [6]–[8] based on random irradiance values and in [9] based on irradiance measurements. The minimum global MPP voltages were found to be very low. However, only very small PV arrays up to 24 PV modules were considered in these studies. Greatly varying global MPP voltage of a PV array causes large fluctuation of the PV inverter reference voltage that is a challenge for MPPT and may cause bad power quality and operational problems. Thus, it would be beneficial to keep the operation point of the inverter all the time at large voltages close to the nominal MPP voltage. In this way, the operation of the PV system would be more predictable and straightforward. It might also decrease the need for a wide operational voltage range of inverters thus increasing the efficiencies of the inverters. In this paper, we have comprehensively studied the scenario of operating all the time at the largest MPP voltage instead of the global MPP voltage, for the first time, based on measured irradiance transitions. Wide range of physical and electrical PV array configurations were studied. The study was based on the characteristics of about 9000 measured irradiance transitions caused by clouds and was carried out by simulations using the well-known one-diode PV cell model.

2 METHODS AND DATA

2.1 Electrical simulation model

A PV submodule, i.e., a group of series-connected PV cells protected by a bypass diode, was used as a basic simulation unit in the simulations. Submodules were modelled by an experimentally verified MATLAB Simulink model, which is based on the widely used one-diode model of a PV cell that provides the following relationship between the current I and voltage U of the cell:

$$I = I_{\mathrm{ph}} - I_0\left(e^{\frac{U+R_\mathrm{s}I}{AU_\mathrm{T}}} - 1\right) - \frac{U + R_\mathrm{s}I}{R_{\mathrm{sh}}}, \qquad (1)$$

where A is the ideality factor, I_o the dark saturation current, I_{ph} the light-generated current, R_s the series resistance, R_{sh} the shunt resistance and U_T the thermal voltage of the PV cell. In order to obtain the simulation model for a PV submodule, the number of PV cells in the submodule N_s was used to scale the parameter values used in the model of a PV cell. The thermal voltage of the submodule can be expressed as $U_T = N_s kT/q$, where k is the Boltzmann constant, q the elementary charge and T the temperature of the cells. Bypass diodes were modelled using Eq. (1) by assuming that I_{ph} is zero and R_{sh} is infinite. The temperature of the bypass diodes was assumed to remain constant and the same as the submodule temperature.

The characteristics of the simulation model were fitted to the characteristics of the PV modules (NAPS NP190GKg) used in the PV power research plant of Tampere University. The parameter values of the electrical simulation model are compiled in Table I.

Table I: Parameter values of the electrical simulation model for the PV modules and bypass diodes.

Parameter	Value
A	1.30
A_{bypass}	1.50
R_s	329 mΩ
$R_{s,\ bypass}$	20.0 mΩ
R_{sh}	188 Ω
$I_{o,\ bypass}$	3.20 μA
$I_{SC,\ STC}$	8.02 A
$U_{MPP,\ STC}$	25.9 V
$U_{OC,\ STC}$	33.1 V

2.2 Irradiance transitions and the shading of PV arrays

Irradiance transitions on cloud shadow edges were modelled mathematically using the model given in [10]

$$G(t) = \frac{G_{us} - G_s}{1 + e^{(t-t_0)/b}} + G_s, \quad (2)$$

where G is the irradiance, t the time, G_{us} the irradiance of an unshaded situation and G_s the irradiance under full shading. Parameter b is related to the steepness of the transition and the sign of it defines whether the transition is a fall or a rise, i.e., irradiance decreases or increases. Parameter t_0 adjusts the transition time defining the midpoint of the transition. In [10], the operation of the mathematical model has been validated with nearly 40,000 irradiance transitions identified in measured data. The shading strength (SS), i.e., attenuation of irradiance due to shading, of an irradiance transition is defined as

$$SS = \frac{G_{us} - G_s}{G_{us}}. \quad (3)$$

By using the mathematical model of Eq. (2), irradiance transitions can be defined by using four variables: SS, parameter b and apparent speed and direction of movement, which have no correlation with each other [11]. A partial shading event of the studied PV arrays produced by an overpassing irradiance fall is symmetrical to an event produced by a similar rise. Thus, the absolute values of b were used for the irradiance transitions in the simulations.

In this study, the data measured in the PV power research plant of Tampere University was used. In total 9097 irradiance transitions (4438 falls and 4659 rises) were identified in five months (May–September 2013) of data, measured by three irradiance sensors by using the method presented in [10] and their apparent velocities were determined utilizing the method given in [11].

The edges of cloud shadows were assumed to be linear across a PV array, the cloud shadows were assumed to be wide enough to cover the whole PV array and the apparent velocities of the shadow edges were assumed to be constant during each simulation period, which are all justified approximations for the studied PV array sizes. A simulation period started when a linear shadow edge moved over the first PV submodule of the array and ended when the shadow edge had moved across the array. The used simulation time step was 0.1 s. To simplify the computation, the whole PV array was chosen to be at standard test conditions (STC) before each partial shading event and the PV submodule temperature was chosen to remain constant.

The studied PV arrays were composed of 5, 10, 15 and 20 parallel-connected strings of 25 series-connected PV modules. The increase in the number of the strings corresponds to the increase in nominal power in typical arrays of utility-scale PV power plants. The PV strings were located in straight lines without gaps between the modules having a distance of 2.0 m between the strings to form a rectangle. The studied electrical PV array configurations were series-parallel (SP), which is the most common one in existing PV power systems, and total-cross-tied (TCT), where groups of parallel-connected modules are connected in series. The TCT configuration is frequently suggested in literature, for example in [12], to improve PV system performance under partial shading conditions. However, it has been shown to have only negligible differences in output power variation [13] and mismatch losses [14] with respect to the SP configuration during cloud partial shadings.

3 RESULTS AND DISCUSSION

Fig. 1 illustrates the behavior of the MPP voltages and the number of MPPs of a PV array during a partial

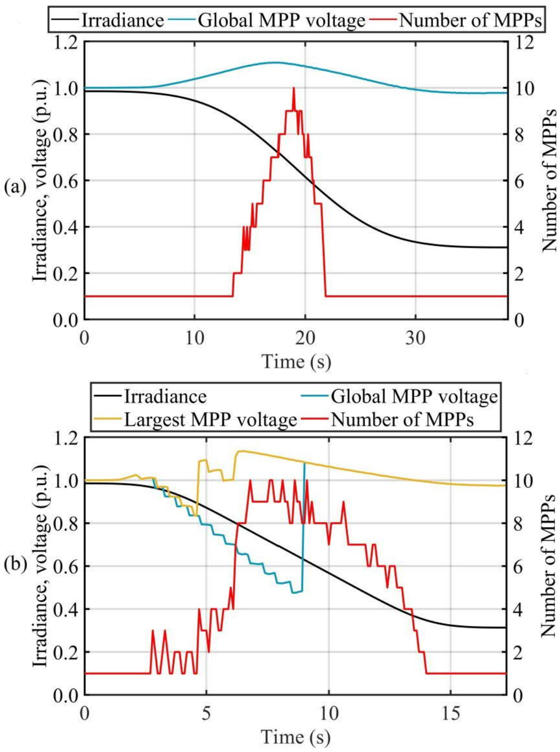

Figure 1: Average irradiance, global MPP voltage, largest MPP voltage and number of MPPs for the 10 × 25 SP array during two identified irradiance transitions.

shading event caused by a cloud shadow by two examples where identified shadow edges move over the 10 × 25 SP array. When the shadow edge moves over the first submodules of the array in the beginning of the transition in Fig. 1 (a), there is only one MPP and the global MPP voltage is nearly constant near the nominal MPP voltage $U_{MPP,\ STC}$. When more PV submodules become shaded, several MPPs appear on the power–voltage (*P*–*U*) curve of the array up to 10 in the halfway of the partial shading period. However, the MPP with the largest voltage is the global one all the time just increasing about 10% during the transition.

The second example of transitions in Fig. 1 (b) begins similarly. However, when the number of shaded PV submodules increases, several MPPs appear on the *P*–*U* curve of the array over a wide voltage region and the global MPP alternates between the MPPs leading to fluctuation in the global MPP voltage. During this stage, the global MPP voltage decreases with increasing system shading down to below 50% of the nominal MPP voltage until the local MPP with the highest voltage becomes the global MPP. At this point, the global MPP voltage leaps above the nominal MPP voltage of the array. After that, as the average irradiance decreases, the global MPP voltage decreases slowly just below to the nominal MPP voltage of the PV array, when the array is entirely shaded.

The proportions of time during all the identified irradiance transitions when the studied PV arrays had more than one MPP and when the largest voltage MPP was not the global one are presented in Table II. The studied PV arrays had more than one MPP from 5% to 10% of the time, depending on the array type. The proportion of time when the largest voltage MPP was not the global one was from 2% to 3%. Both the proportions decreased as the number of the PV strings in the array increased. The TCT arrays had more than one MPP more often than the corresponding SP arrays.

Table II: Proportions of time (%) during the identified irradiance transitions when the studied PV arrays had more than one MPP and when the largest voltage MPP was not the global one.

Array	More than one MPP	The largest voltage MPP was not the global one
SP, 5 × 25	8.31	3.02
SP, 10 × 25	6.76	2.70
SP, 15 × 25	5.58	2.30
SP, 20 × 25	4.67	2.05
TCT, 5 × 25	10.21	3.30
TCT, 10 × 25	9.25	2.71
TCT, 15 × 25	8.24	2.09
TCT, 20 × 25	6.84	1.59

The ranges of the global and the largest MPP voltage for the studied PV arrays during the identified irradiance transitions are presented in Table III. For all the studied PV arrays, the largest observed global MPP voltage was around 112% of the nominal MPP voltage of the array (about 88% of the nominal open-circuit voltage). The smallest observed global MPP voltage was 25.5% for the 5 × 25 SP array and increased with the increasing number of parallel-connected strings. The electrical PV array configuration had slight effects on the global MPP voltage range: the smallest observed voltages were only slightly larger for the TCT arrays. The minimum value of the largest MPP voltage was much higher and the maximum value slightly higher than the corresponding global MPP values for all the studied PV arrays. The effect of the electrical PV array configuration was much larger on the voltage range of the largest voltage MPP than on the voltage range of the global MPP.

Based on Table III it is evident that the voltage range of the MPP with the largest voltage is clearly narrower than that of the global MPP. Next, it was found out how often the voltages of the two MPPs were in the vicinity of the nominal MPP voltage. The proportions of time when the global and the largest MPP voltage of the studied PV arrays were within 5% from the nominal voltage are presented in Table IV. The voltages of the two MPPs were within 5% from the nominal voltage from 87% to 93% of the total duration of the irradiance transitions. The proportions increased with the increasing system size (number of parallel strings) and were a bit higher for the SP than the TCT configuration. The differences between the global and the largest voltage MPP were marginal. For the SP arrays, the largest voltage MPP was within 5% from the nominal voltage more often than the global one, whereas the situation was opposite for the TCT arrays.

The average rates of change of the global and the largest MPP voltage during the identified irradiance transitions are presented in Table V for all the studied PV arrays. The average rates of change of the global MPP voltage were from 0.7 to 1.2 %/s being the highest for the smallest 5 × 25 PV arrays. There were only minor differences between the SP and TCT electrical configurations indicating that the TCT configuration does not provide extra value in response to the more complex array structure. The average rates of change of the largest MPP voltage were from 0.5 to 1.0 %/s.

As shown in Fig. 1 (b), an irradiance transition caused by a cloud shadow may cause a large step on the

Table III: Ranges of the global and the largest MPP voltage for the studied PV arrays with respect to $U_{MPP,\ STC}$ (%) during the identified irradiance transitions.

Array	Minimum of the global MPP voltage	Maximum of the global MPP voltage	Minimum of the largest MPP voltage	Maximum of the largest MPP voltage
SP, 5 × 25	25.5	112.0	52.7	116.7
SP, 10 × 25	25.7	112.0	49.0	116.7
SP, 15 × 25	30.2	111.9	45.6	116.6
SP, 20 × 25	30.1	111.9	51.0	116.1
TCT, 5 × 25	26.0	112.1	54.9	116.9
TCT, 10 × 25	26.0	112.0	56.5	116.9
TCT, 15 × 25	30.2	111.9	59.2	116.8
TCT, 20 × 25	30.2	111.9	63.7	116.7

Table IV: Proportions of time (%) when the global and the largest MPP voltage of the studied PV arrays were within 5% from $U_{MPP, STC}$ during the identified irradiance transitions.

Array	Global MPP voltage	Largest MPP voltage
SP, 5 × 25	87.0	87.0
SP, 10 × 25	89.4	89.6
SP, 15 × 25	91.5	91.7
SP, 20 × 25	93.2	93.3
TCT, 5 × 25	86.6	85.9
TCT, 10 × 25	87.6	86.8
TCT, 15 × 25	88.5	87.8
TCT, 20 × 25	89.8	89.3

global MPP voltage if a local MPP close to the nominal MPP voltage, resulting from the fully shaded PV modules, becomes the global one after a global MPP at low voltages. In general, the largest steps on the global MPP voltage take place when a local MPP at another voltage region than the global MPP becomes the global MPP. The maximum changes of the global and the largest MPP voltage over a simulation time step of 0.1 s are presented in Table V. The maximum changes in the global MPP voltage were over 75% for the 5 × 25 and 10 × 25 SP arrays. Large steps of the global MPP voltage can lead to failures in MPPT and to disturbances to the operation of PV inverters. The maximum changes in the largest MPP voltage (about 55%) were much smaller than in the global MPP voltage.

The average rates of change of the powers of the global and the largest voltage MPP and their maximum changes during a simulation time step are presented in Table VI for the studied PV arrays during the identified irradiance transitions. The average rates of change were from 2.3 to 2.8 %/s and almost the same for the global and the largest voltage MPP. The maximum changes in the global MPP power during a simulation time step were around 7% for the smallest 5 × 25 PV arrays and about 5% for all the other studied PV arrays. For the largest voltage MPP, the maximum changes during a time step were from 29% to 52% decreasing with the increasing system size and being smaller for the TCT configuration than for the SP. In general, the largest changes in the power of the largest voltage MPP occur when the largest voltage MPP disappears or a new MPP appears at the voltages larger than the existing ones. The negligible difference in the average rate of change of the power and the lower variation of the voltage justify the operation of PV arrays at the MPP with the largest voltage in lieu of the global one.

The range and average rate of change of the largest MPP voltage have been found to be smaller than those of the global MPP voltage during the shading transitions. Another question that remains to be answered is whether there is a bigger difference in the operation of the PV arrays at the largest MPP voltage and at the global one when the arrays have more than one MPP caused by clouds shading events (see Table II).

The average differences in voltage, current and power between the global and the largest voltage MPP for the studied PV arrays are presented in Table VII. The average differences in voltage and current were notable and of the same magnitude from 4% to 10%. The current of the largest voltage MPP is always smaller than or equal to the current of the global MPP, while the voltage

Table V: Variation of the global and the largest MPP voltage for the studied PV arrays with respect to $U_{MPP, STC}$ during the identified irradiance transitions.

Array	Average rate of change (%/s) of the global MPP voltage	Average rate of change (%/s) of the largest MPP voltage	Maximum change of the global MPP voltage during a time step (%)	Maximum change of the largest MPP voltage during a time step (%)
SP, 5 × 25	1.23	0.96	77.0	53.0
SP, 10 × 25	0.98	0.81	75.6	54.7
SP, 15 × 25	0.81	0.70	72.0	54.9
SP, 20 × 25	0.69	0.61	72.1	44.7
TCT, 5 × 25	1.16	0.80	74.6	47.5
TCT, 10 × 25	0.97	0.69	74.1	44.2
TCT, 15 × 25	0.82	0.60	72.0	41.1
TCT, 20 × 25	0.70	0.52	72.1	39.8

Table VI: Variation of the powers of the global and the largest voltage MPP for the studied PV arrays with respect to $P_{MPP, STC}$ during the identified irradiance transitions.

Array	Average rate of change (%/s) of the global MPP power	Average rate of change (%/s) of the power of the largest voltage MPP	Maximum change of the global MPP power during a time step (%)	Maximum change of the power of the largest voltage MPP during a time step (%)
SP, 5 × 25	2.80	2.82	6.8	52.0
SP, 10 × 25	2.60	2.61	5.2	42.9
SP, 15 × 25	2.42	2.43	5.2	43.2
SP, 20 × 25	2.27	2.27	5.2	42.5
TCT, 5 × 25	2.80	2.82	7.1	43.8
TCT, 10 × 25	2.60	2.61	5.2	41.6
TCT, 15 × 25	2.42	2.43	5.2	36.3
TCT, 20 × 25	2.27	2.27	5.2	28.8

of the largest voltage MPP is, naturally, always larger than or equal to the global MPP voltage. Consequently, the differences in the power were clearly smaller, from 0.8% to 2.2%, than in the voltage or current. All the differences decreased with the increasing system size and were a bit smaller for the TCT than for the SP configuration.

Table VII: Average differences in *U*, *I* and *P* between the global and the largest voltage MPP for the studied PV arrays with respect to the nominal array values (%) during the time when there were more than one MPP.

Array	Voltage	Current	Power
SP, 5 × 25	9.50	9.09	2.23
SP, 10 × 25	7.56	6.53	1.40
SP, 15 × 25	6.50	5.35	1.08
SP, 20 × 25	5.96	4.80	0.94
TCT, 5 × 25	8.35	7.82	2.10
TCT, 10 × 25	6.42	5.46	1.31
TCT, 15 × 25	5.19	4.22	0.97
TCT, 20 × 25	4.74	3.78	0.84

Table VIII presents the largest differences in voltage, current and power between the global and the largest voltage MPP for the studied PV arrays. The largest differences in the voltage were a bit larger than in the current and the differences in the power were clearly smaller than in the voltage or current. The largest differences between the SP and TCT configuration existed in the power. Although momentary power differences between the two MPPs can be large, the small average differences indicate that there is no considerable difference in the energy production between the MPPs.

Table VIII: Maximum differences in *U*, *I* and *P* between the global and the largest voltage MPP for the studied PV arrays with respect to the nominal array values (%) during the time when there were more than one MPP.

Array	Voltage	Current	Power
SP, 5 × 25	77.5	74.3	51.8
SP, 10 × 25	75.7	73.5	42.9
SP, 15 × 25	74.8	72.1	43.2
SP, 20 × 25	74.9	67.6	42.5
TCT, 5 × 25	76.9	74.5	48.9
TCT, 10 × 25	75.6	72.5	41.8
TCT, 15 × 25	74.7	67.4	38.1
TCT, 20 × 25	74.5	67.6	37.9

The differences in the produced energy between the global and the largest voltage MPP for the studied PV arrays are presented in Table IX. The energy differences were small, from 1.4% to 4.0%, during the time when there were more than one MPP. These energy differences were negligible with respect to the energy produced during all the identified irradiance transitions: from 0.1% to 0.3%. The relative differences between the energies produced at the global and the largest voltage MPP decreased with the increasing system size. The differences in the energies produced during the time when there were at least two MPPs were a bit smaller for the TCT than for the SP configuration. However, the energy differences with respect to the energy produced during all the identified irradiance transition were smaller for the SP configuration. The reason for this is that the TCT configuration had more than one MPP more often than the SP (see Table II).

Table IX: Differences in the produced energy between the global and the largest voltage MPP for the studied PV arrays with respect to the energy produced when operating at the global MPP (%) during the time when there were more than one MPP and during the total duration of the identified irradiance transitions.

Array	More than one MPP	Total duration of transitions
SP, 5 × 25	3.96	0.27
SP, 10 × 25	2.48	0.14
SP, 15 × 25	1.92	0.09
SP, 20 × 25	1.69	0.06
TCT, 5 × 25	3.50	0.32
TCT, 10 × 25	2.17	0.18
TCT, 15 × 25	1.60	0.12
TCT, 20 × 25	1.41	0.08

There were only minor differences between the SP and TCT electrical configurations in most of the studied electrical quantities. The TCT arrays had more than one MPP more often than the corresponding SP arrays. The TCT arrays produced only marginally more energy than the corresponding SP arrays during all the identified irradiance transitions: from 0.08% to 0.56% (with respect to the energy production of the SP configuration) when operating at the global MPP and from 0.03% to 0.54% when operating at the largest voltage MPP. The relative difference in energy production increased with the increasing size of the PV array. The results indicate that the TCT configuration does not provide extra value in response to the more complex array structure compared to the simple SP configuration.

In conclusion, the energy losses due to the operation at the largest voltage MPP in lieu of the global one were found to be slight during cloud partial shading events. The average total duration of all the identified partial shading events was from 21 to 25 minutes per day, depending on the PV array, and, accordingly, multiple MPPs appeared less than 3 minutes per day. On the other hand, only a part of all the partial shading events resulting from moving clouds was considered in this study. Moreover, sharp shadings due to nearby objects can cause larger differences between the operation at the largest voltage MPP and the global MPP. Further, inverters used in PV plants have certain operating voltage ranges and the efficiencies of the inverters are not constant for the whole voltage ranges but higher at high voltages. For these reasons, the energy losses due to the operation at the largest voltage MPP in lieu of the global one may be somewhat larger than presented in this paper. However, the energy losses are so small in any case that there is no reason to ably complicated MPPT algorithms in practice because of cloud shading events.

4 CONCLUSIONS

This paper provided a comprehensive study of the scenario of operating PV arrays all the time at the largest MPP voltage instead of the global MPP voltage during partial shading events resulting from moving clouds. The study was based, for the first time, on the characteristics of around 9000 irradiance transitions caused by moving clouds identified in measured irradiance data and was conducted using the one-diode PV cell model. Various physical and electrical array configurations of 125 to 500 PV modules were studied.

It was shown in this paper that the voltage range of the largest voltage MPP is clearly smaller than that of the global MPP. Moreover, the changes in the largest MPP voltage were found to be slower than in the global MPP voltage. In addition, the differences in the average rate of change in power between these two operation points were found to be negligible. However, large power differences between the two MPPs can take place momentarily.

The energy losses resulting from the operation at the largest voltage MPP in lieu of the global one during cloud partial shading events were found to be slight. These results give reason to operate PV arrays at the largest voltage MPP in lieu of the global one. That is a valuable finding for PV inverter design. In the end, it is evident that operating at the largest voltage MPP in lieu of the global one has only minor effect on the total energy production of well-designed utility-scale PV systems for which partial shading is mainly due to shadows of moving clouds.

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