Static and Dynamic MPP-Tracking Efficiency of PV-Inverter Using Recorded Irradiance

Witold Marańda, and Maciej Piotrowicz

***Abstract*—This paper investigates the energy losses introduced by Maximum Power Point Tracking operation of photovoltaic (PV) inverter. In contrast to other studies, this evaluation has been done with the recorded real-life solar irradiance data applied to the simulation of the PV-generator and tracking algorithm. The true MPP output of photovoltaic generator has been calculated with electro-thermal model and the simulation has been carried out with 1 s time resolution. The efficiency results have been presented for both static and dynamic MPP-tracking investigated with basic and simplified Perturb&Observe algorithm with several tracking speed rates. In addition to the simulation, the inverter efficiency measurements for field-installed inverter have been presented.**

***Keywords*—photovoltaics, MPP-tracking, PV-inverter, tracking efficiency.**

I. Introduction

ENERGY conversion in a grid-connected photovoltaic (PV) system is mainly a two-stage process: the photovoltaic effect inside PV-cells and the DC/AC transformation by a PV-inverter.

Since the solar energy flux is variable, the DC output parameters of the PV-generator change in a wide range, often with a high rate. The PV-inverter, apart from performing DC/AC conversion, must also follow the input changes by tracking the Maximum Power Point (MPP) of the photovoltaic generator. The efficiency of a PV-inverter is thus a twofold parameter combining both the MPP-tracking process and the essential DC/AC conversion.

Recently, a lot of effort has been put into the improvement of the MPP-tracking quality by proposing various tracking algorithms. Moreover, the tracking issue seems to be important especially for PV-systems operating in variable weather conditions with highly fluctuating irradiance, that are common in most of Europe. The study on MPP-tracking have so far concentrated on the theoretical analysis of tracking algorithms and measurements of inverter responses to input test-patterns in laboratories.

This paper investigates the efficiency of MPP-tracking of the PV-inverter using basic Perturb&Observe (P&O) algorithm with a constant step. In contrast to other studies, this evaluation is done by means of applying the recorded real-life irradiance data to the simulation of the PV-generator and tracking algorithm.

Witold Marańda and Maciej Piotrowicz are with the Department of Microelectronics and Computer Science, Faculty of Electrical, Electronic, Computer and Control Engineering, Lodz University of Technology, Wólczańska 221/223, 90-924 Łódź, Poland, e-mail: maranda@dmcs.p.lodz.pl

The high-quality irradiance data with 1 s time resolution, has been recored in solar laboratory at the Dept. of Microelectronics and Computer Science of Lodz University of Technology in Poland (N 51°44’46, E 19°27’20) [1].

II. Efficiency Measurement of PV-inverter

In a PV grid-connected system, the utility grid can accept any amount of energy with no restrictions, in contrast to chemical batteries. The operation of the inverter is not restricted and the efficiency parameter really reflects the construction quality.

In general, the only accurate record of the energy conversion efficiency η_E for any device, is the ratio of its energy output ($W_{\mathtt{AC}}$) to the input ($W_{\mathtt{DC}}$), over a specified operating period:

$$\eta_{\mathtt{En}} = \frac{W_{\mathtt{AC}}}{W_{\mathtt{DC}}} \qquad (1)$$

Energy efficiency is not very suitable for the inverter characterization, since the energy input is climate–dependent. Instead, the inverters are often rated by a power efficiency — a single-value parameter (usually peak efficiency) defined as ratio of inverter instant output $P_{\mathtt{AC}}$ to input power $P_{\mathtt{DC}}$:

$$\eta_{\mathtt{DC/AC}} = \frac{P_{\mathtt{AC}}}{P_{\mathtt{DC}}} \qquad (2)$$

According to the norm [2], the instantaneous power values must be averaged over 30 s to properly handle AC-signals, higher harmonics and DC-ripples:

$$P_{\mathtt{AC\ or\ DC}} = \frac{1}{T}\int_0^T i(t)v(t)dt = \frac{1}{T}\int_0^T p(t)dt \qquad (3)$$

Since the solar irradiance fluctuates, such a calculation cannot be representative for a longer period. A better solution, the industry standard known as European efficiency $\eta_{\mathtt{EU}}$, has been proposed in [3] to handle the inverter operation at various power levels:

$$\begin{aligned}\eta_{\mathtt{EU}} = \; & 0.03\eta_{5\%} + 0.06\eta_{10\%} + 0.13\eta_{20\%} + \\ & 0.10\eta_{30\%} + 0.48\eta_{50\%} + 0.20\eta_{100\%}\end{aligned} \qquad (4)$$

This expression can be relatively close to true energy efficiency [4], while still being a single-value parameter, suitable for devices comparison and it has been adopted by many manufactures.

The inverter quality cannot be evaluated without studying the ability to maximize the PV output. The $\eta_{\mathtt{DC/AC}}$ (or $\eta_{\mathtt{EU}}$) describe the DC/AC conversion alone, but apart from the

DC/AC conversion, the inverter must maximize the output of the PV-generator by driving the operation point close to MPP.

Under variable irradiance, it requires a constant search for MPP and the adjustment is never perfect. This results in receiving lower power from PV than can be actually offered at MPP, thus lowering the overall performance.

The process of MPP tracking can be recognized as yet another chain in the energy conversion and the tracking efficiency can be defined as ratio of power at the inverter input $P_{\mathtt{DC}}$ to maximum power available $P_{\mathtt{MPP}}$:

$$\eta_{\mathtt{MPPT}} = \frac{P_{\mathtt{DC}}}{P_{\mathtt{MPP}}} \tag{5}$$

Since the tracking is not ideal, the offered power $P_{\mathtt{MPP}}$ is always greater than actual inverter input $P_{\mathtt{DC}}$ and $\eta_{\mathtt{MPPT}}$ may be not negligible.

For accurate inverter characterizations, the total efficiency ($\eta_{\mathtt{total}}$) parameter has been proposed [5], comprising the two stages of energy processing:

$$\eta_{\mathtt{total}} = \eta \cdot \eta_{\mathtt{MPPT}} = \frac{P_{\mathtt{AC}}}{P_{\mathtt{MPP}}} \tag{6}$$

Thus the inverter efficiency cannot be fully studied without taking into account MPP-tracking quality, involving the calculation of true location of MPP for a PV-generator.

III. Static and Dynamic MPP-tracking

In order to generalize the discussion and results, all the voltage and power values in the figures have been normalized to the nominal voltage and power of the PV-generator at MPP, $V_{\mathtt{MPP}}$ and $P_{\mathtt{MPP}}$, in Standard Test Conditions (STC: 25 °C, 1000 W/m^2, Air Mass 1.5).

In PV-devices the voltage depends logarithmically on irradiance, thus the voltage changes are relatively small (15% of nominal $V_{\mathtt{MPP}}$).

During stable sunny weather the evolution of I-V characteristics of PV-generator is slow, the location of MPP is fixed in short time intervals and the tracking is limited to oscillations around the MPP, as shown in Fig. 1. High solar irradiance G and cell temperature T will correspond to lower MPP voltage and low irradiance – to higher one, but the daily MPP transitions will be very slow and easy to follow for static tracking

The differences between the inverter instant input power $v_{\mathtt{DC}}(t) \cdot i_{\mathtt{DC}}(t)$ and the available constant power $P_{\mathtt{MPP}}$ over a period t_M define the static MPP-tracking efficiency, as follows:

$$\eta_{\mathtt{MPPT-Static}} = \frac{\int_0^{t_M} v_{\mathtt{DC}}(t) i_{\mathtt{DC}}(t) dt}{P_{\mathtt{MPP}} t_M} \tag{7}$$

On the other hand, during the rapid changes of irradiance, the transition of MPP can be treated as isothermal, since the PV-module time constant is in order of minutes [6]. The MPP transitions would be similar to those indicated with arrows in Fig. 2.

Since the location of MPP is no longer fixed, the calculation of dynamic MPP-tracking efficiency must take into account the true MPP power $p_{\mathtt{MPP}}(t)$ over the whole transition period, as follows:

$$\eta_{\mathtt{MPP-Dynamic}} = \frac{\int_0^{t_M} v_{\mathtt{DC}}(t) i_{\mathtt{DC}}(t) dt}{\int_0^{t_M} p_{\mathtt{MPP}}(t) dt} \tag{8}$$

The effect of rapid transitions on $\eta_{\mathtt{MPP-Dynamic}}$ is not symmetrical. The low-to-high operating-point transitions will cause higher power deviation from MPP and thus higher absolute energy losses as compared to high-to-low transitions. In both cases, the heating or cooling of PV-panel during the transition will reduce the time to reach true MPP.

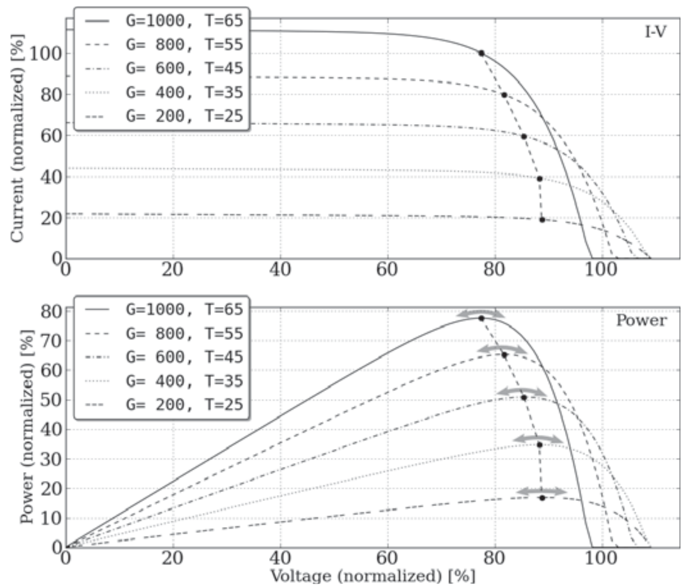

Figure 1. Daily evolution of I-V characteristics of PV-generator and static MPP-tracking under stable irradiance

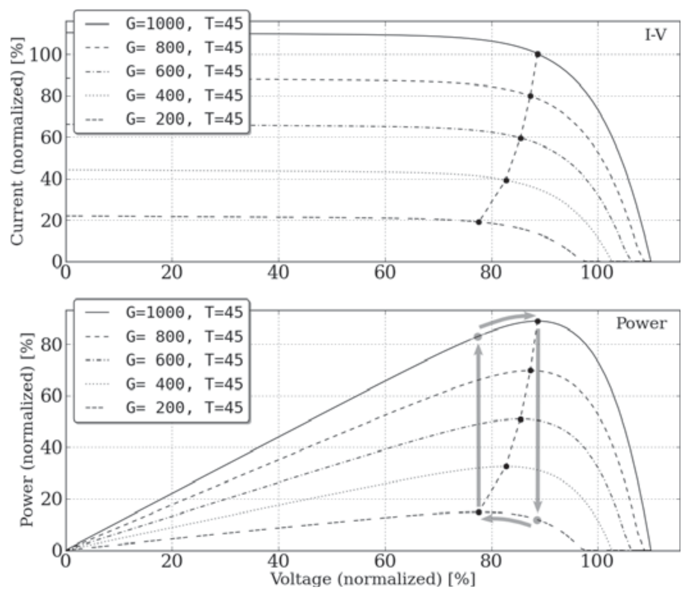

Figure 2. Instantaneous evolution of I-V characteristics of PV-generator and dynamic MPP-tracking under rapid irradiance changes

IV. Irradiance Data and Simulation Model

The irradiance data for the simulation have been recorded with 1 s time resolution in the Solar Laboratory at the Dept. of Microelectronics and Computer Science [1]. Only such a high time resolution allows studying the dynamic behaviour, but also makes the calculations very time consuming.

The calculations has been performed for one-day data, June 2^{nd} 2012, with highly variable irradiance, shown in Fig. 3, a very representative case for the season.

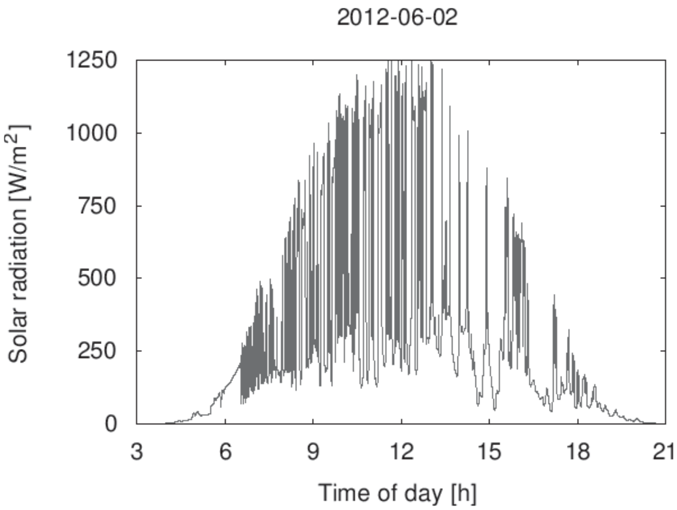

Figure 3. Solar irradiance pattern for variable weather day

The good accuracy of MPP calculation has required an electro-thermal simulation. The calculations have been performed for the 50 Wp PV-module Solar-Fabrik SF50A. The numerical modeling of PV-generator has been done according to [7], [8].

A single section RC-thermal model has been used to find the relation between the temperatures of PV-cells T_C and the ambient T_A. The thermal capacitance C_{th} and thermal R_{th} have been found experimentally [6]. The T_A has been recorded together with irradiance G. The evolution of T_C in time has been found by solving the following equation:

$$C_{th}\frac{dT(t)}{dt} + \frac{T(t)}{R_{th}} = G(t) \quad (9)$$

where $T = T_C - T_A$ is the temperature excess over the ambient.

Fig. 4 shows a close-up of PV-cell temperature evolution with 1 s simulation step. It is worth noticing, that under highly variable irradiance the T_C cannot reach steady-state due to the long time-constant of PV-modules.

V. Tracking Operation

The measurements of MPP-tracking quality for market-available PV-inverters have already been performed with PV-generator simulators using artificial irradiance test-patterns. The results revealed that handling dynamic operation by some inverters is not acceptable [9].

In contrast to those efforts, in this paper the real irradiance pattern is applied to the simulated PV-generator and widely used P&O tracking algorithm [10].

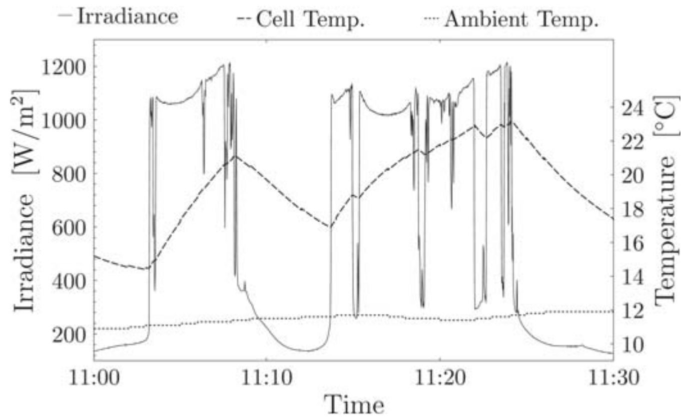

Figure 4. Close-up of PV-module temperature response to fast irradiance fluctuations and ambient temperature

P&O introduces small changes to the inverter input voltage ΔV and analyses the resulting power deviations to establish the correct direction of voltage change.

The simplified criterion for detecting the MPP-location has been assumed that true instantaneous $V_{\mathtt{MPP}}$ is known during the tracking operation. This allows to study the MPP-tracking without the phenomena of voltage drift in reverse direction — a well-known drawback of basic P&O algorithm.

The value of ΔV cannot be too high to avoid wide oscillations around MPP, but too small would result in a slow search. Several improvements to P&O exist, but in this study only the basic algorithm with $\Delta V = \mathtt{const}$ has been assumed.

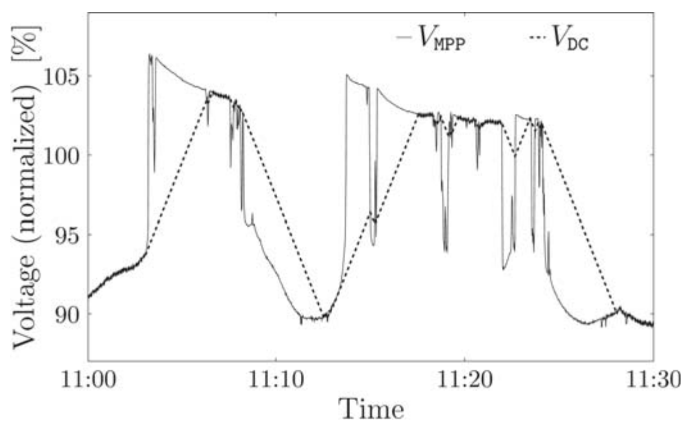

Figure 5. Close-up of dynamic tracking voltage (with small tracking step)

Fig. 5 demonstrates the tracking operation in case of dynamic transitions (as in Fig. 4) with small ΔV that is causing troubles to dynamic tracking, while the static tracking is almost perfect.

When tracking step ΔV becomes too big, the static oscillations around MPP dominate the tracking operation, as shown in Fig. 6. The dynamic transitions, on the other hand, are handled much better.

Since the value ΔV has the opposite influence on static and dynamic tracking, one can expect an optimal value of tracking step, yielding the best overall efficiency.

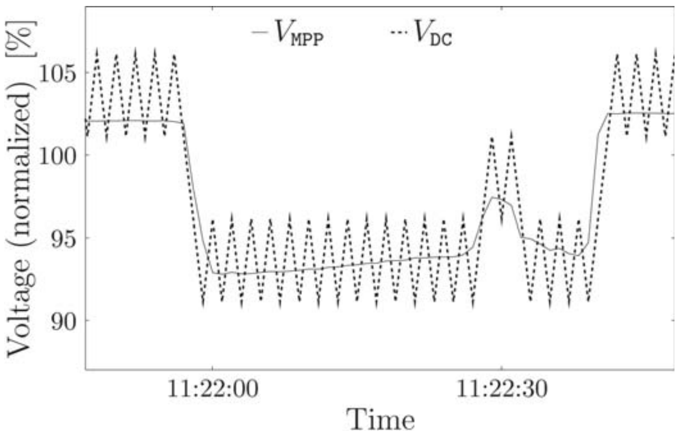

Figure 6. Close-up of static tracking voltage (with big tracking step)

VI. Efficiency Results

The results have been found for one day with highly variable irradiance, June 2^{nd} 2012, shown in Fig. 3. The efficiency results for static and dynamic tracking have been calculated separately. The criterion is the crossing the V_{MPP} in one simulation step, which allows for distinguishing between oscillations around MPP (static) and unidirectional voltage drift towards the MPP (dynamic).

The example of differences between those two categories have been presented in Fig. 7 and Fig. 8, showing the close-ups of MPP and DC-power and tracking efficiency for the corresponding voltage changes in Fig. 5 and 6.

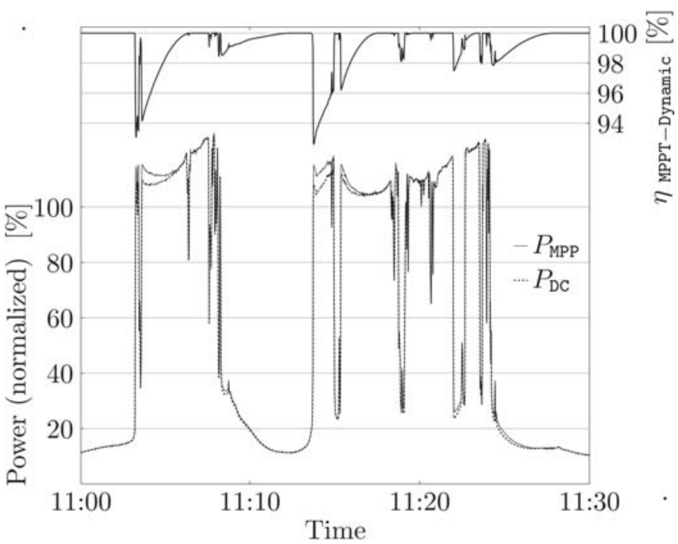

Figure 7. Close-up of dynamic tracking: instant powers and efficiency

During the dynamic MPP transitions (Fig. 7), the tracking performance can decrease (up to 6% only during low-to-high transitions), but only for a short time, so the overall result is much better. Increasing the ΔV value would shorten the duration of dynamic operation but not efficiency drop values.

On the other hand, the non-ideal static tracking affects mainly the operation under steady irradiance, as shown in Fig. 8, while rapid fluctuations are handled correctly. The instantaneous efficiency decrease is well below 1%.

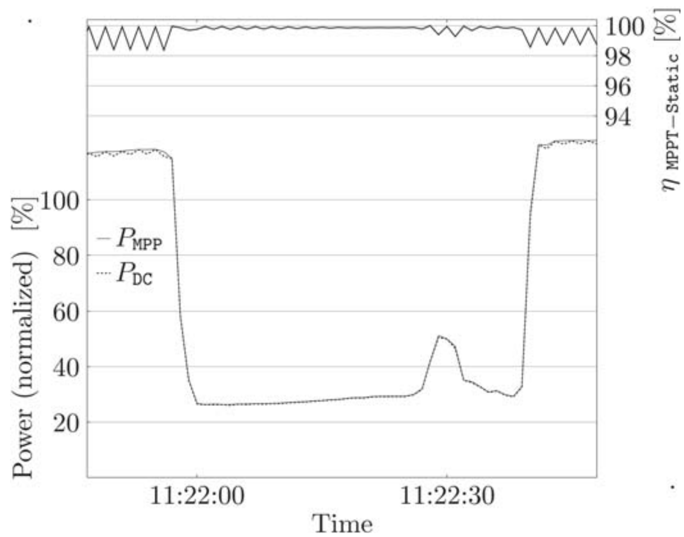

Figure 8. Close-up of static tracking: instant powers and efficiency

During the whole day, the PV-inverter is capturing the energy with either static or dynamic tracking. Both amounts of energy are collected daily with various proportions depending on tracking step ΔV, as shown in Fig. 9. For small ΔV almost all the daily energy comes with static tracking, but for big ΔV – with dynamic. The equal energy shares are with ΔV between 0.1% and 0.2% for the analyzed single-day data.

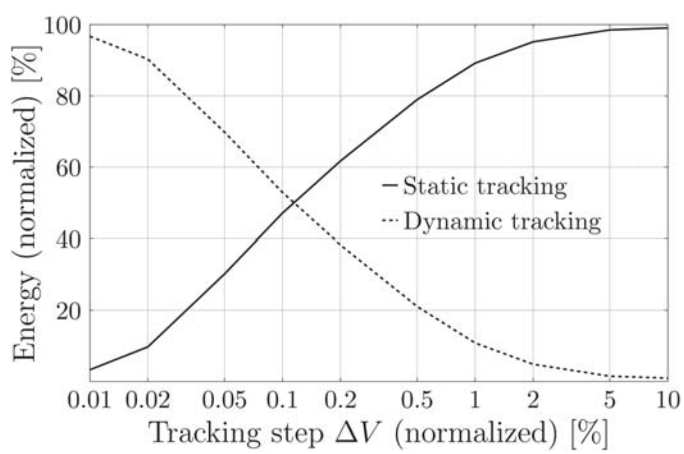

Figure 9. Daily energy amount handled by static and dynamic tracking

The total tracking efficiency during the day is a composition of static and dynamic efficiency, corrected for the their energy share, depending on the tracking speed ΔV. Fig. 10 shows all the three efficiency curves.

Fig. 10 reveals the flat optimum of the total efficiency curve, for tracking speed between 0.5% and 2%. Exceeding the value of 5% has the most negative effect on efficiency, since almost all energy is tracked statically with low efficiency. In contrast, for very slow tracking (small ΔV), the dynamic and total tracking losses are below 1%.

According to Fig. 9, the best total tracking efficiency corresponds to mostly static operation (80%-90% of energy contribution) even for a very variable irradiance conditions.

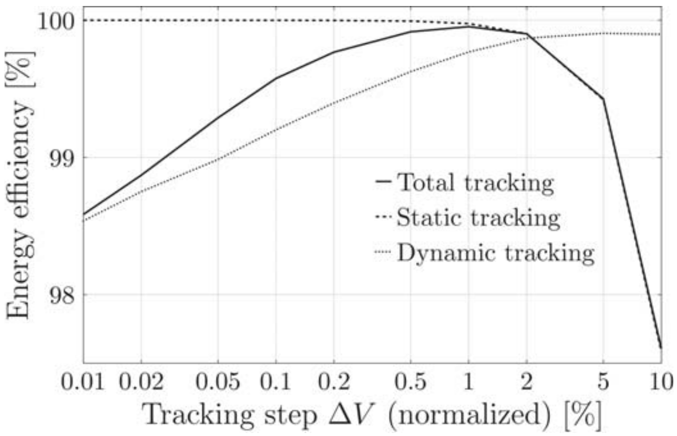

Figure 10. Final daily efficiency for total, static and dynamic tracking

VII. Report on Efficiency of Field-installed PV-inverter with Focus on Radiation Variability

In order to demonstrate real energy conversion losses, including static and dynamic MPP-tracking, the authors have calculated the efficiency of the Top Class Spark TCS1500 grid-connected inverter operating in 1kWp photovoltaic installation at the Dept. of Microelectronics and Computer Science [1]. Maximum value of the efficiency of this inverter, declared by the manufacturer (Advanced Solar Product AG) is 94%.

All the calculations have been based on the measurements taken during normal operation of photovoltaic system covering the whole year 2012. The data collected from photovoltaic system include both DC and AC power values together with solar irradiance sampled every 5 seconds. Thus it allows to calculate both types energy and power efficiency of the inverter, as defined by equations and respectively.

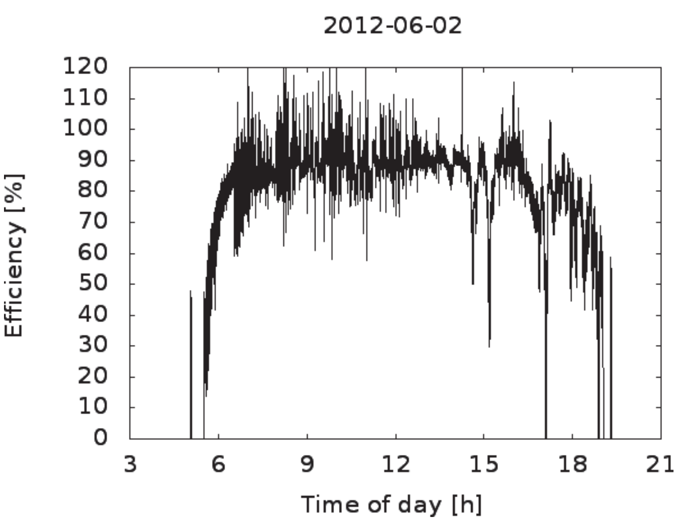

Figure 11. Inverter efficiency for variable irradiance day (see Fig. 3)

The data with irradiance value lower than 50 W/m^2 have been omitted. The minimum input power limit for inverter operation is located close below this value, so calculation of the efficiency for this samples is pointless. Calculated instantaneous (power) efficiency values have been presented in form of daily profiles, similarly to the irradiance data. As an example, the daily profile of power efficiency for June 2nd 2012 (see Fig. 3) is shown in Fig. 11.

Continuous operation of MPP-tracking algorithm may suggest that the inverter is able to manage with less favorable irradiance conditions. However, analysis of the efficiency of the device for rather cloudy day leads to different conclusion. The example is presented in Fig. 12. Rapid irradiance rises have an effect of efficiency drop implying that the tracking algorithm works too slow to keep up with irradiance variations.

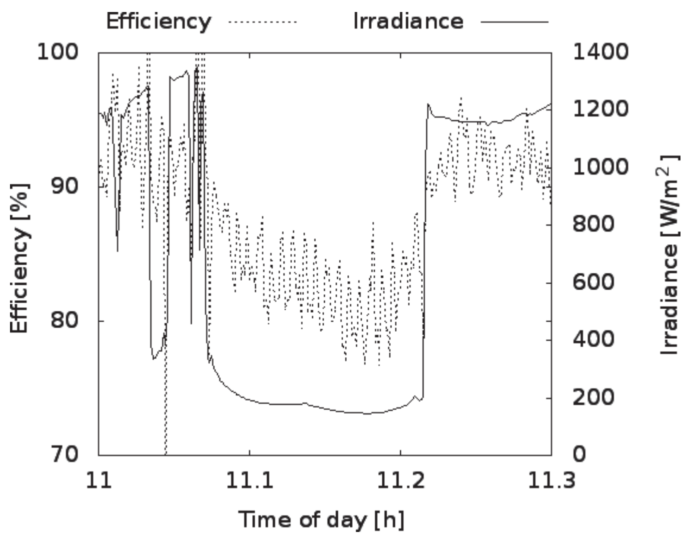

Figure 12. Closeup of inverter efficiency under variable irradiance (11^{00}–11^{30} of Fig. 11 and Fig. 3)

Another interesting phenomenon can be observed when the irradiance rapidly drops. In these cases the instantaneous efficiency rises for a short time, reaching even the values above 100% (which means, that the output AC power from the inverter temporarily exceeds the input DC power value). These results can be explained basing on the inverter structure. The device contains electrical inductors and the set of buffering capacitors, that both act as the energy storage. In case of rapid drop of input power, the inverter uses the energy stored to sustain the output power for a short time.

Apart from the instantaneous (power) values, also the long-term calculations of the inverter (energy) efficiency have been performed, as they provide more general information about the device operation. Energy differences have been calculated for each data sample by numerical integration of the power values using trapezoidal rule. Also, the solar irradiance gradient has been calculated. The energy values obtained have been summed up for the whole year and divide for different gradient ranges (5 W/m^2/s wide each), to calculate averaged efficiency for each gradient range (Fig. 13).

It must be noticed, that the dependency between the efficiency and the gradient of irradiance has the form of monotonic decreasing function, i.e. the efficiency value drops with the rise of gradient value. Specifically, for negative gradient values (corresponding to irradiance drops), the efficiency values are greater than for positive. This observation confirms the conclusions from the present chapter, that the inverter uses

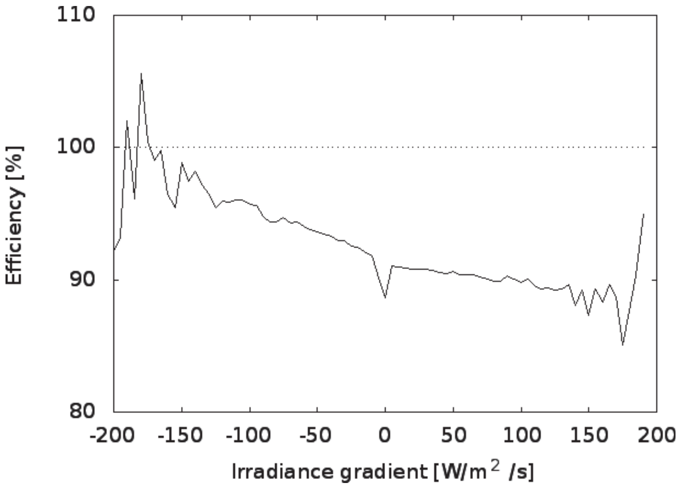

Figure 13. Inverter efficiency for different irradiance gradient values

the energy stored in inductor and capacitors for maintaining the output energy at stable level. It also demonstrates that the dynamic MPP-tracking operates too slow to react properly to fast changes of the irradiance and thus of the input DC power.

Another interesting result is the drop of efficiency for low (close to zero) gradient values. This phenomenon reflects the low efficiency of static MPP-tracking algorithm operation, which continuously tries to find MPP during stable irradiance conditions. This efficiency drop has a magnitude of 2-3%.

In this paper only a single the PV-inverter with one MPP-tracking algorithm has been studied. However, it demonstrates, that tracking operation is the compromise between keeping up with irradiance variability and maintaining the output power level continuous. Moreover, the controller of the inverter does not receive any direct information about the solar irradiance, as this option was not provided by the firmware. Such solution could provide some additional data for the algorithm, thus optimizing the inverter MPP-tracking operation.

VIII. Conclusions

The efficiency of modern PV-inverters for grid-connected systems is advertised as approaching 99%. While this may be true according to some measurements standards, the true energy efficiency over a longer period is always below the expectations.

The MPP-tracking is one of the reasons that lower the total operation efficiency of the PV-inverter, without affecting its DC/AC conversion. It is now obvious, that the inverter quality cannot be evaluated without studying the tracking behavior.

The simulation in this paper has been aimed at studying the static and dynamic MPP-tracking efficiency for basic P&O algorithm. However, the use of real-life irradiance patterns makes the calculations of practical importance for similar type of climatic conditions. Due to assumed simplifications of the P&O algorithm, the results presented herein should be treated as the upper theoretical limit for tracking efficiency of field operating inverters.

In response to dynamic conditions the instantaneous efficiency may drop to 94%, while during the static operation it is usually above 99%. The best results are expected for tracking step values between 0.5% and 2.0% of system nominal MPP voltage, which favors the static operation (over 80% of delivered energy) over the dynamic one (with less than 20%). The results have been obtained for single day with a very variable weather.

The performance of field-installed inverters may still be worse as there is evidence that handling this phenomenon is not satisfactory and the problem deserves more attention.

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Witold Marańda received the M.Sc. degree in electronics from Technical University of Lodz, Poland, and Ph.D degree in electrical engineering from University of Ghent, Belgium, in 1993 and 1998 respectively. His main field of study is photovoltaic systems technology: electrical and thermal modeling and conversion efficiency under highly variable irradiance. His research interests also include microprocessor systems, data acquisition and visualization.

Maciej Piotrowicz received the M.Sc. and Ph.D. degrees in electronics from the Technical University of Lodz, Poland, in 2001 and 2006 respectively. His main areas of interests are microprocessor systems, industrial electronics and photovoltaic systems. He also deals with embedded systems hardware/software co-design and is involved in research on embedded systems modeling in terms of coloured Petri nets.