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TOTAL EFFICIENCY η_{TOT} – A NEW QUANTITY FOR BETTER CHARACTERISATION OF GRID-CONNECTED PV INVERTERS

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ABSTRACT: For accurate characterisation of PV inverters, not only DC-AC-conversion efficiency, but also MPP-tracking behaviour must be considered. The goal of this contribution is at first to demonstrate again the voltage dependency of DC-AC conversion efficiency $\eta = P_{AC}/P_{DC}$ and encourage manufacturers to supply sufficient data about it. Then MPP-tracking efficiency $\eta_{MPPT} = P_{DC}/P_{MPP}$ will be defined and illustrated by some measurements. If η and η_{MPPT} are known, total efficiency $\eta_{tot} = \eta \cdot \eta_{MPPT} = P_{AC}/P_{MPP}$ can be introduced. Then examples for measured curves of η_{tot} at several different DC voltage levels for two inverters will be shown.

If measured values of total efficiency η_{tot} are available for an inverter at different DC voltage levels, a plant designer can create an optimal match between PV array and PV inverter not only considering array power, but also as far as DC voltage is concerned. It would also make sense to include measured values of η_{tot} at different voltage levels in PV simulation programs. Together with improved data about energy rating of PV modules this will increase the accuracy of calculation of energy yield of grid-connected PV-plants.

KEYWORDS: Inverter, Efficiency, Maximum Power Point Tracking, Grid-Connected.

1. Introduction

Many inverters for grid-connected PV plants have relatively poor specifications from the manufacturer. Today they often have a relatively wide DC input voltage range, but many manufacturers only indicate a peak (DC-AC-conversion-) efficiency η and the European efficiency η_{EU}. Often a rated DC input voltage is indicated, and the efficiency figures given can then be attributed to this nominal DC voltage. Sometimes also a diagram showing efficiency vs. power is indicated, but in most cases such a diagram is very small.

For optimal design of grid-connected PV systems these data are often not sufficient. It is obvious that DC-AC conversion efficiency depends on the DC- (and probably a little less also on the AC-) voltage used [1, 3, 4]. Usually there are no indications about voltage dependency of conversion efficiency. Only a few manufacturers give values for European efficiency or even measured efficiency curves for two or more voltages. Examples of measured voltage dependent efficiencies are given in [3, 5], but also in many other publications of HTI's PV laboratory.

The I-V-curve and the maximum available power P_{MPP} at the maximum power point (MPP) of a PV array depends on actual in-plane irradiance and module temperature. Depending on actual in-plane irradiance and module temperature, a PV array operates on a certain I-V-curve and a correlated P-V-curve. At a certain point (maximum power point, MPP), the available power from the array reaches its maximum value P_{MPP} at the voltage V_{MPP}. For optimum performance, a grid-connected inverter is equipped with a MPP-tracker that tries to keep the operating point of the inverter always at the MPP despite irradiance- and/or module temperature-changes that also influence P_{MPP} and V_{MPP} (MPP-Tracking, MPPT).

As measurements of actual MPPT-performance of a PV-inverter are quite difficult and require sophisticated measuring equipment [5], it is usually assumed by manufacturers, plant designers and simulation programs, that a grid connected PV inverter always operates at the MPP.

However, depending on the MPP-tracking algorithm used by the inverter, at certain power and voltage levels more or less significant deviations from the MPP may occur, which can reduce energy yield of the whole PV plant up to a few % .

If η and η_{MPPT} are known, total efficiency $\eta_{tot} = \eta \cdot \eta_{MPPT}$ can be calculated. As the actual input quantity to the inverter is P_{MPP} offered by the PV array or PV array simulator, it makes sense to indicate η_{tot} not vs. P_{DC}, but η_{tot} vs. P_{MPP}. Then examples for measured curves of η_{tot} at different DC voltage levels for two inverters will be shown.

For PV modules there is a tendency to improve specifications in a way that not only power specifications at STC (and at lower irradiance levels) are indicated, but also energy yields measured during a certain time period under real weather conditions. It is hoped that this will make possible an improvement for the calculation of the DC-energy yield of a PV array. But if energy losses caused by poor MPP-tracking of the inverter are not considered, another essential uncertainty for accurate determination of the energy yield of a grid-connected PV-plant remains. The introduction of η_{tot} described in this paper will resolve this problem.

2. Examples for voltage dependency of DC-AC-conversion efficiency η for 2 inverters

Inverters without transformers (fig. 1) have very high conversion efficiencies η, which may be up to a few percent higher than those of comparable devices with galvanic separation (fig. 2). However, for both inverter types differences of efficiency of up to 2% due to variations of DC operating voltage were registered.

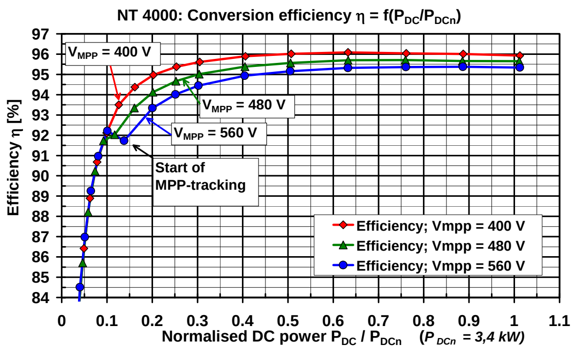

Fig. 1: Measured conversion efficiency of an inverter NT4000 without transformer at three different DC-voltages (P_{DCn} = 3,4kW).

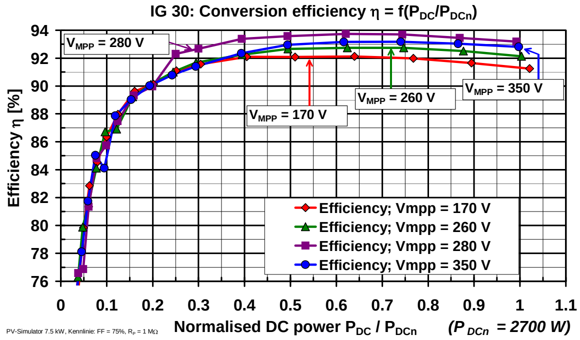

Fig. 2: Measured conversion efficiency of an inverter IG 30 with galvanic separation (thus a little lower η) at four different DC-voltages ($P_{DCn} \approx$ 2,7 kW).

3. Measurements of static MPP-tracking efficiency η_{MPPT}

For accurate and reproducible measurements of static MPP-tracking efficiency η_{MPPT}, PV array simulators with high stability are necessary [3, 5]. The diode chain simulators, which are in use at many test laboratories, have an inherent thermal stability problem and are limited to the fill factor of the diode chain used, therefore they are not sufficient for this purpose. With PC-controlled PV array simulators many different quantities can be measured on a given power level (e.g. η, η_{MPPT}, cosφ, harmonics of current), and by means of automatic variation of the current on a given I-V-curve automatic measurements are possible.

Before the measurement of static MPP-tracking efficiency, a stabilization period of at least 60 s (for inverters with slow MPP-tracking up to 300 s) is needed. Then during a subsequent measuring period T_M, DC-current I and DC-voltage V is sampled simultaneously at a relatively high sampling rate (e.g. 1000 to 10000 samples per second) often followed by subsequent averaging during 50 ms or 100 ms to reduce the number of data points and to eliminate the influence of the 100 Hz ripple on the DC side of single phase inverters. Static MPP-tracking efficiency η_{MPPT} is the ratio between DC energy effectively absorbed during measuring period T_M divided by DC energy $P_{MPP} \cdot T_M$ offered to the inverter in T_M.

Static MPP-tracking efficiency or MPP-tracking accuracy η_{MPPT} can be determined as follows:

$$\eta_{MPPT} = \frac{1}{P_{MPP} \cdot T_M} \int_0^{T_M} v_A(t) \cdot i_A(t)\,dt \qquad (1)$$

where
$v_A(t)$ = array voltage at inverter input.
$i_A(t)$ = array current at inverter input.
T_M = duration of measurement (started at t = 0). Recommended: 60s to 300s per power level.
P_{MPP} = available maximum PV power at MPP of array.

Conventional high precision power meters are usually too slow to determine MPP-values with sufficient accuracy, therefore the sampling and averaging method described above proved to be much more significant and effective. The data points obtained can be displayed in a so called "cloud diagram" (see fig. 3 and 4).

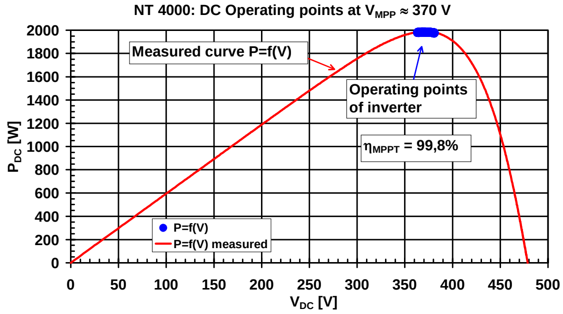

Fig. 3: Cloud diagram of an inverter NT4000 at $P_{MPP} \approx$ 2 kW and $V_{MPP} \approx$ 370 V. Measured η_{MPPT} is 99,8%, MPP-tracking is very good here.

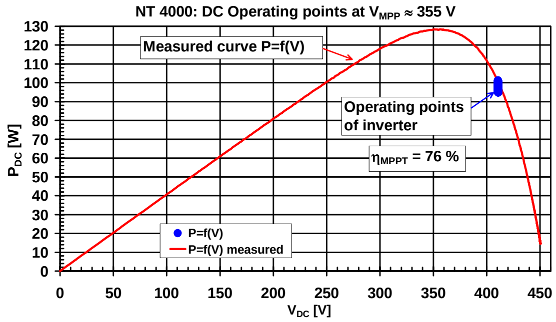

Fig. 4: Cloud diagram of an inverter NT4000 at $P_{MPP} \approx$ 130 W and $V_{MPP} \approx$ 355V. The inverter operates at $V_{DC} \approx$ 410 V far away from the MPP. Measured η_{MPPT} is 76%, MPP-tracking is rather bad here.

In order to show the exact MPP tracking behaviour at different power levels, it is useful to display not only η_{MPPT} vs. offered MPP power P_{MPP}, but also to indicate (for each power level P_{MPP}) in the same diagram on the second y-axis the true, measured value of the MPP voltage V_{MPP} on the I-V-curve and also the average value of the DC input voltage V_{DC}, on which the inverter was actually operating on the I-V curve (see fig. 5 and 6).

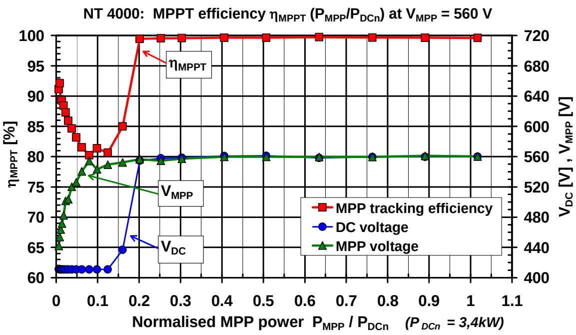

Fig. 5: MPP tracking efficiency η_{MPPT} of an inverter NT4000 vs. normalised MPP-power P_{MPP}/P_{DCn} at $V_{MPP} \approx$ 560 V. As the inverter operates at low power levels at the lower voltage $V_{DC} \approx$ 410 V, η_{MPPT} is lower there. For higher power levels, η_{MPPT} rises towards 100%, as $V_{DC} \approx V_{MPP}$.

As the actual input quantity for the inverter and especially for MPP-tracking is not P_{DC}, but P_{MPP} offered by the PV array or PV array simulator at MPP, it makes sense to indicate η_{MPPT} not as a function of P_{DC}, but of P_{MPP}. To compare the behaviour of inverters of different size, it is useful to normalise P_{MPP} to rated DC power P_{DCn}, i.e to indicate η_{MPPT} as a function of P_{MPP}/P_{DCn} like in fig. 5 - 8.

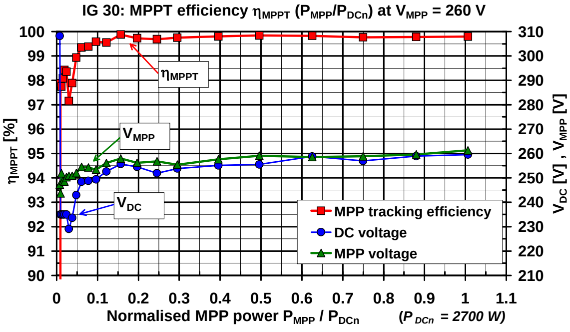

Fig. 6: MPP tracking efficiency η_{MPPT} of an inverter IG30 vs. normalised MPP-power P_{MPP}/P_{DCn} at $V_{MPP} \approx 260$ V. Even at low power levels, the deviation of V_{DC} compared to V_{MPP} is low, therefore static MPP-tracking behaviour is very good also there.

As shown in fig. 5, at low power levels many inverters operate on a fixed voltage level, because interferences caused by the internal PWM switching frequency may affect the recognition of the current signal that is quite low at low power, which makes it difficult to find the exact location of the MPP. Owing to this approach, operation at low power is still possible, but depending on the actual position of V_{MPP}, a certain amount of energy that would be available from the PV array is wasted, especially if this fixed voltage is far from the effective V_{MPP} like in fig. 5. The inverter shown in fig. 6 has a much better static MPP tracking behaviour, its operating voltage V_{DC} is very close to V_{MPP} even at low power, the available power is used better and therefore η_{MPPT} is much higher there. Fig. 7 and 8 show static MPP tracking efficiency η_{MPPT} of an inverter NT4000 and of an IG30 as a function of P_{MPP}/P_{DCn} at three (NT4000) and four (IG30) different MPP-voltages. At low power, static MPPT-behaviour of the IG30 is much better.

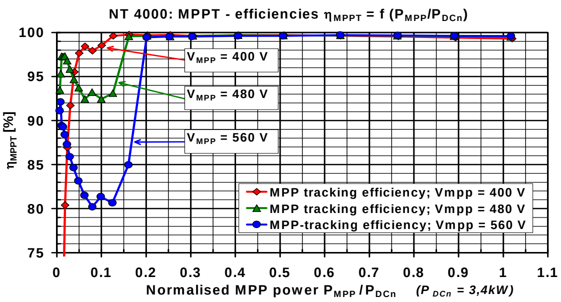

Fig. 7 Static MPP tracking efficiency η_{MPPT} of a NT4000 vs. normalised MPP-power P_{MPP}/P_{DCn} at 3 different MPP voltages. As the device operates at a fixed voltage $V_{DC} \approx 410$ V at low power, η_{MPPT} is lower than 100% there (depending on actual location of V_{MPP}).

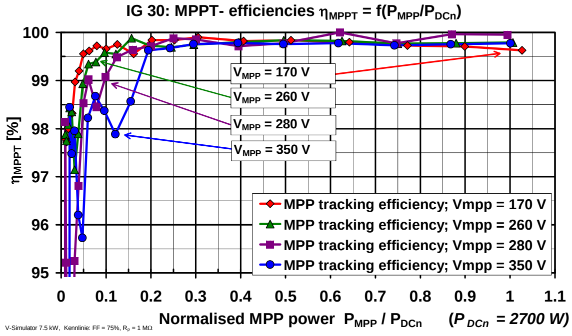

Fig. 8: Static MPP tracking efficiency η_{MPPT} of a IG30 vs. normalised MPP-power P_{MPP}/P_{DCn} at 4 different MPP voltages. Compared to fig. 7, the scale for η_{MPPT} is considerably extended. Static MPP tracking of this device is very good also at low power levels.

4. Introduction of total efficiency η_{tot}

With a more basic approach, the new quantity “total efficiency” η_{tot} can be introduced (see fig. 9):

According to the actual in-plane irradiation G and the module temperature T, a PV array always offers a certain DC-power P_{MPP}. However, under steady-state conditions, the inverter can extract only $P_{DC} = \eta_{MPPT} \cdot P_{MPP}$ and converts it to $P_{AC} = \eta \cdot P_{DC}$.

Therefore a new quantity, the total efficiency of a grid-connected inverter, can be defined:

$$\eta_{tot} = \eta \cdot \eta_{MPPT} = P_{AC} / P_{MPP} \qquad (2)$$

With η_{tot}, under steady-state conditions P_{AC} can be obtained directly from P_{MPP}:

$$P_{AC} = \eta \cdot P_{DC} = \eta \cdot \eta_{MPPT} \cdot P_{MPP} = \eta_{tot} \cdot P_{MPP} \qquad (3)$$

Total efficiency η_{tot} is therefore a direct indication of the quality of an inverter, which has a higher relevance for practical energy yield than the DC-AC conversion efficiency η alone. Like η and η_{MPPT} also η_{tot} depends on P_{MPP} and V_{MPP} and has to be determined by means of appropriate measurements.

Fig. 9 and 10 show total efficiency η_{tot} calculated according to (2) for the two inverters as a function of normalised MPP power P_{MPP}/P_{DCn} at three and four different MPP voltages.

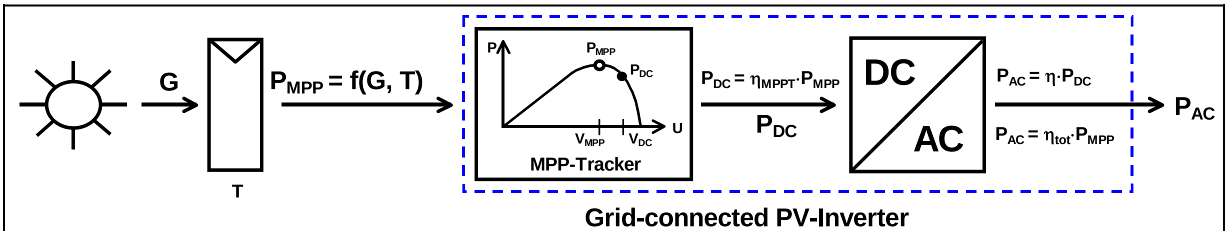

Fig. 9: Determination of total efficiency η_{tot} of grid-connected PV inverters:
A grid-connected inverter consists of two main parts, the MPP-tracker, which has to extract always the maximum available power P_{MPP} from the array (varying according to irradiance G and module temperature T), and the DC-AC converter, which has to convert the available DC power P_{DC} to AC power P_{AC} as efficiently as possible.

	NT4000			IG30			
V_{MPP}	400 V	480 V	560 V	170 V	260 V	280 V	350 V
η_{EU}	95,3%	94,8%	94,3%	90,9%	91,4%	92,0%	91,5%
$\eta_{MPPT\text{-}EU}$	99,5%	99,0%	98,0%	99,7%	99,8%	99,8%	99,5%
$\eta_{tot\text{-}EU}$	94,9%	93,9%	92,5%	90,7%	91,2%	91,7%	91,0%

Table 1: Average efficiencies for η , η_{MPPT} and η_{tot} (weighting factors according to formula for European efficiency) for the inverters NT4000 and IG 30 at three and four different MPP-voltages.

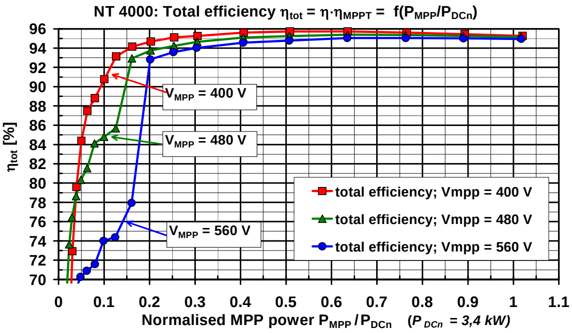

Fig. 9: Total efficiency η_{tot} of a NT4000 vs. normalised MPP-power P_{MPP}/P_{DCn} at 3 different MPP voltages. Because of the relatively low η_{MPPT} at low power levels and higher values of V_{MPP}, despite the high conversion efficiency η the device has a relatively low η_{tot} there.

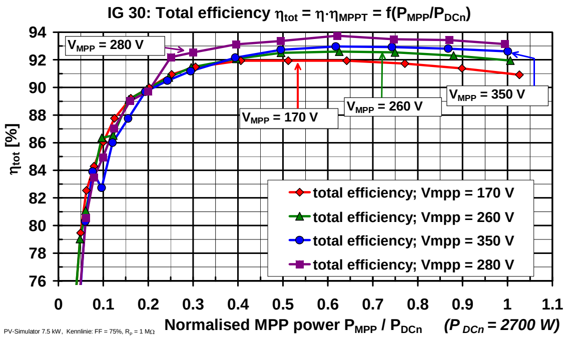

Fig. 10: Total efficiency η_{tot} of an IG30 vs. normalised MPP-power P_{MPP}/P_{DCn} at 4 different MPP voltages. At low power, owing to the good MPP-tracking, for η_{tot} the device can compensate most of the lower conversion efficiency.

In order to characterise the overall static behaviour of an inverter with a single value, also for η_{tot} and η_{MPPT} an average efficiency (e.g. European efficiency) can be calculated. Note: $\eta_{tot\text{-}EU}$ is not exactly $\eta_{EU} \cdot \eta_{MPPT\text{-}EU}$, as η_{EU} is not referred to P_{MPP}. Table 1 (at the top of this page) shows these average efficiencies at different DC voltages for the two inverters tested.

5. Conclusions

The new quantity „total efficiency“ η_{tot} introduced in this paper can describe the static operating behaviour of a grid-connected PV inverter much better than conversion efficiency η alone. Manufacturers should indicate η_{tot} at different voltages in their data sheets. Thus inverters would be better specified and PV planners and simulation programs could design more optimum PV plants.

At locations, where there are often variable cloudy conditions, besides static behaviour also the dynamic MPPT-behaviour has to be considered.

Inverters with a fast MPP tracker have higher energy yields under quickly changing irradiance than devices with slow MPP tracking. For the two examples of inverters described here, static MPPT-behaviour of the IG30 is better, but its MPP tracker is slow and therefore dynamic MPPT performance is rather poor. Static MPPT-behaviour of the NT4000 is not so good at low power and high voltage, because it operates on a fixed and relatively low voltage there, but its MPP-tracker is fast and dynamic MPP tracking is good. Due to space limitation, dynamic MPPT performance of the two inverters can not be discussed here, some general examples can be found in [5]. More detailed reports (in German) are available under www.pvtest.ch > Wechselrichter-Testberichte.

Based on the measurements performed, it can be concluded that for optimum overall results for a NT4000 V_{MPP} at rated power should be chosen between about 400 V and 460 V, for an IG 30 between 280 V and 330 V.

Important Notice

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Further information about the research activities of the PV laboratory of HTI (former name: ISB) can be found on the internet: **http://www.pvtest.ch.**