New Tests at Grid-Connected PV Inverters: Overview over Test Results and Measured Values of Total Efficiency η_{tot}

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ABSTRACT: In 2005, at the 20th EU PV conference in Barcelona, we presented the new quantity "total efficiency η_{tot}", which is obtained as $\eta_{tot} = \eta \cdot \eta_{MPPT}$ from conversion efficiency η and MPP-tracking efficiency η_{MPPT}, which contains conversion efficiency and tracking efficiency in one value [1]. Besides the two inverters used as examples in [1], many more inverters of different manufacturers were tested at BFH's PV laboratory in 2004 - 2006: Sunways NT4000, Fronius IG30 and IG40, SMA SMC 6000 and SB3800, Sputnik SM2000E, SM3000E, SM6000C and SM25C and Convert 6T. First test results of a SMC 8000TL are also available.

At first an overview over the most important properties of these devices is given, considering conversion efficiency, MPP-tracking efficiency and total efficiency at three different voltage levels, rated power, galvanic separation, harmonic currents, EMC-behaviour on DC and AC side, voltage and frequency monitoring, islanding after loss of line voltage, sensitivity to telecontrol signals and dynamic tracking efficiency.

In the main part of the paper, conversion efficiency curves for three different DC voltages for the best inverter with and without galvanic separation measured so far will be indicated. Besides that, curves of total efficiency η_{tot} vs. offered MPP-power P_{MPP} will be shown for many inverter types at three different DC voltage levels.

KEYWORDS: Inverter, Grid-Connected, Efficiency, Performance.

1. Introduction

Last year at the 20th EU PV conference in Barcelona the new quantity „total efficiency η_{tot}“ was introduced, which can describe the static operating behaviour of a grid-connected PV inverter much better than conversion efficiency η alone. Total efficiency η_{tot} is the product of DC-AC conversion efficiency η and static MPP-tracking efficiency η_{MPPT} [1].

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 also makes 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.

In this paper, at first an overview over the most important properties of the tested inverters is given, considering conversion efficiency, MPP-tracking efficiency and total efficiency at three different voltage levels, rated power, galvanic separation, harmonic currents, EMC-behaviour on DC and AC side, voltage and frequency monitoring, islanding after loss of line voltage, sensitivity to telecontrol signals and dynamic tracking efficiency.

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In another contribution at this conference, dynamic MPPT-performance of these inverters will be discussed more in detail [2].

Extended test reports (in German) about the inverters tested are available on the internet under www.pvtest.ch

2. Overview over Test Results

In table 1 (on next page) the key specifications and main test results of the inverters tested by the PV laboratory of BFH in Burgdorf in 2004 to 2006 are listed. For all inverters, not only conversion efficiency, but sometimes also MPP-tracking efficiency depends on DC operating voltage (up to 2% and more) [1], [4]. Therefore it would be essential that manufacturers clearly indicate the DC voltage at which an efficiency value was measured in their data sheets. Some manufacturers indicate these values at least in their operating manuals.

European efficiency η_{EU} was calculated with the following formula (index value = percent of rated load):

$$\eta_{EU} = 0.03\,\eta_5 + 0.06\eta_{10} + 0.13\eta_{20} + 0.1\eta_{30} + 0.48\eta_{50} + 0.2\eta_{100}$$

3. Some Test Results in Detail

3.1 Highest values for DC-AC-conversion efficiency η measured until Aug. 2006

Good inverters without transformers have very high conversion efficiencies η (fig. 1). With the latest develop-ments, the difference in efficiency of 1 – 2.5 % between the inverters without and with galvanic separation remains in the same order of magnitude as it has been for many years. However, also inverters with galvanic separation now already have a very high efficiency (fig. 2). For both inverters, differences of efficiency of up to 2% due to variations of the DC operating voltage were registered.

Galvanic separation seems to have also some advantages. Based on the experience in our long-term monitoring program with more than 60 inverters over many years, it seems that inverters with transformers have a somewhat higher long-term reliability.

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Inverter Type	Test Year	S_N [kVA]	Trafo	MPP-Voltage [V]	η_{EU} [%]	η_{MPPT_EU} [%]	η_{tot_EU} [%]	Dyn. MPPT-Behaviour	Harm. of Curr. (0.1 – 2kHz)	EMC AC	EMC DC	Telecontrol Sensitivity	Frequency Monitoring	Voltage Monitoring	Islanding
Sunways NT4000	04	3.3	TL	400 *480* 560	95.4 *94.9* 94.6	99.5 *99.0* 98.0	94.9 *94.0* 92.6	+	+	0	+	++	--	++	++
Fronius IG30	04	2.5	HF	170 *280* 350	91.0 *92.1* 91.6	99.8 *99.7* 99.5	90.8 *91.8* 91.2	0	++	+	+[4)]	+	++	+	+
Fronius IG40	04	3.5	HF	170 *280* 350	91.1 *92.5* 91.8	99.9 *99.6* 99.5	91.1 *92.2* 91.3	-	++	++	+[4)]	+	++	+	+
Sputnik SM2000E	05	1.8	TL	180 *300* 420	92.4 *93.4* 94.0	99.9 *99.7* 99.2	92.3 *93.1* 93.2	*0* **	++	0[1)]	+[4)]	++	++	++	+
Sputnik SM3000E	05	2.5	TL	250 *330* 420	93.5 *94.0* 94.7	99.5 *99.4* 99.7	93.0 *93.4* 94.4	*0* **	+	0[1)]	++	++	++	++	+
Sputnik SM6000E	05	5.1	TL	250 *330* 420	94.3 *94.8* 95.2	99.8 *99.9* 99.6	94.1 *94.6* 94.9	*0* **	-	0[1)]	++	+[3)]	++	++	++
Sputnik SM6000C*	05	4.6	TL	250 *330* 420	94.5 *95.1* 95.4	99.7 *99.6* 99.5	94.2 *94.7* 95.0	+	+	0[1)]	++	+	++	+	+
Sputnik SM25C	05	25	LF	490 *560* 630	93.1 *93.1* 92.9	99.6 *99.5* 99.7	92.7 *92.6* 92.6	+	++	0[1)]	+[6)]	++	+[7)]	++	+[8)]
ASP TC Spark	05	1.4	LF	160 *190*	90.0 *90.4*	99.7 *99.8*	89.8 *90.3*	++	++	0[1)]	++	0	+	+	0[5)]
SMA SB3800*	05	3.8	LF	200 *280* 350	94.8 *94.2* 93.5	99.6 *99.7* 99.7	94.4 *93.9* 93.2	+	++	++	++	++	++	++	+
SMA SMC6000	05	5.5	LF	280 *350* 420	94.7 *94.1* 93.7	99.6 *99.6* 99.7	94.3 *93.8* 93.4	*0* **	++	++	++	+	++	++	+[2)]
Convert 6T	06	5.0	TL	630	94.7	99.8	94.5	+	++	++	+	++	+[7)]	++	0

++	**Very good**	**1)**	Higher than limits for frequencies < 300kHz
+	**good**	**2)**	Operation only with activated MSD (ENS)
0	**sufficient**	**3)**	Relatively sensitive to telecontrol signals with f=200Hz
-	**not sufficient**	**4)**	Higher than limits for frequencies < 200kHz
--	**bad**	**5)**	Older model, complies only to old MSD (ENS) standard
*	***η measured with new power meter***	**6)**	Higher than limits for frequencies < 400kHz
		7)	High frequency shutdown a little over limits acc. to new VDE126-1-1
		8)	Test power a little too low due to power limit of PV simulator
**	***measurements somewhat too stringent***		

Table 1:
Key specifications and main test results of the inverters tested by the PV laboratory of BFH in 2004 – 2006.
Transformer type: LF = low frequency, HF = high frequency, TL = transformerless (no transformer).

Note: Some of the *dynamic MPP-tracking tests* performed before April 2006 had a somewhat too high variation in MPP-voltage between the high and the low power level. If possible, the measurements have been replaced by measurements with a realistic MPP-voltage variation since May 2006. However, for some inverters this was no longer possible, therefore their dynamic MPP-tracking results may be worse than they would have been with the typical voltage variation of only a few percent for crystalline silicon. These measurements are marked with ** in table 1. All other measurements (also the other measurements of the corresponding inverters) were not affected.

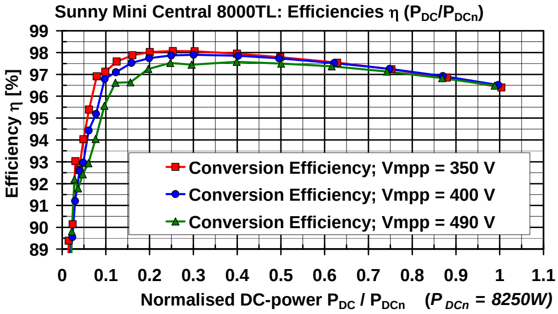

Fig. 1:
Highest measured *conversion efficiency* **at a prototype** of an inverter ***without transformer*** at three different DC-voltages (SMC 8000TL, P_{DCn} = 8.25 kW).

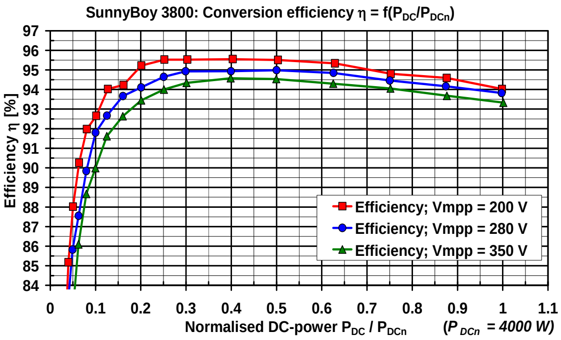

Fig. 2:
Highest measured *conversion efficiency* of an inverter ***with transformer*** at three different DC-voltages (SB3800, P_{DCn} = 4 kW).

3.2 Measured curves for total efficiency η_{tot} for some inverters

The following diagrams show $\eta_{tot} = \eta \cdot \eta_{MPPT}$ as a function of normalised MPP-Power P_{MPP}/P_{DCn} (P_{DCn} = rated DC power of the inverter under test). 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_{AC} or P_{DC}, but η_{tot} vs. P_{MPP}. Measured curves for 3 different DC voltage levels are shown.

Note: $P_{AC} = \eta \cdot P_{DC} = \eta \cdot \eta_{MPPT} \cdot P_{MPP} = \eta_{tot} \cdot P_{MPP}$ [1].

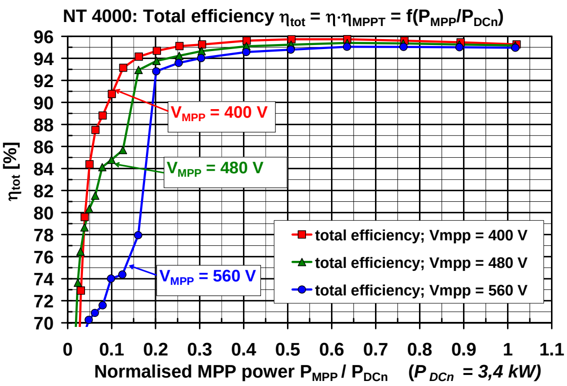

Fig. 3:
Total efficiency η_{tot} of a NT4000 (without transformer) vs. normalised MPP-power P_{MPP}/P_{DCn} at 3 different MPP voltages. Due to the relatively low η_{MPPT} at low power levels and higher values of V_{MPP}, despite the high conversion efficiency η the device has a quite low η_{tot} there.

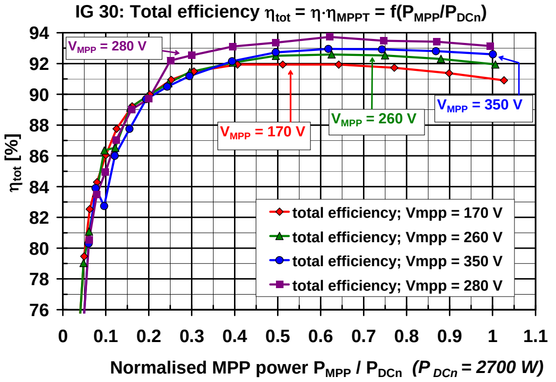

Fig. 4:
Total efficiency η_{tot} of an IG30 (with galvanic separation) vs. normalised MPP-power P_{MPP}/P_{DCn} at 4 different MPP voltages. At low power, owing to the good MPP-tracking, for η_{tot} the device can compensate most of the lower conversion efficiency.

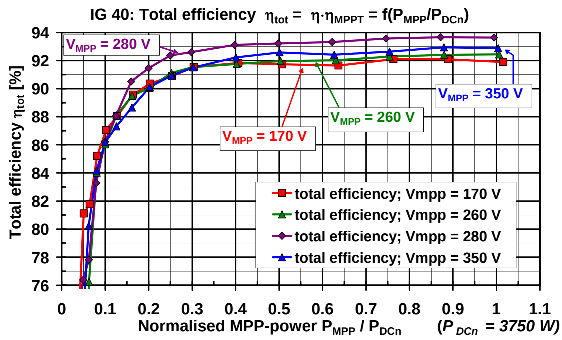

Fig. 5:
Total efficiency η_{tot} of an IG40 (with galvanic separation) vs. normalised MPP-power P_{MPP}/P_{DCn} at 4 different MPP voltages. With this device, efficiency at medium DC-voltage is highest. It is astonishing that a small increase of the DC voltage from 260V to 280V causes a significant increase of η_{tot}.

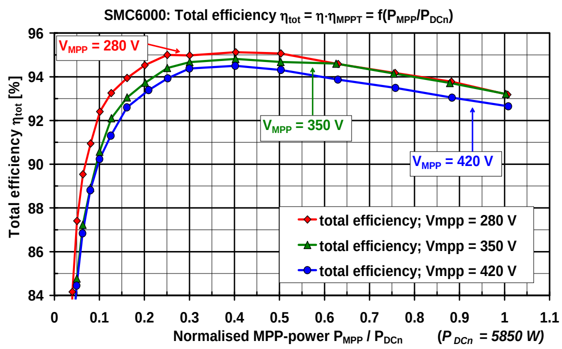

Fig. 6:
Total efficiency η_{tot} of an SMC 6000 (with transformer) vs. normalised MPP-power P_{MPP}/P_{DCn} at 3 different MPP voltages. This device has a very high efficiency for an inverter with transformer, which depends only slightly from DC voltage. Highest efficency is obtained here at the lowest DC voltage.

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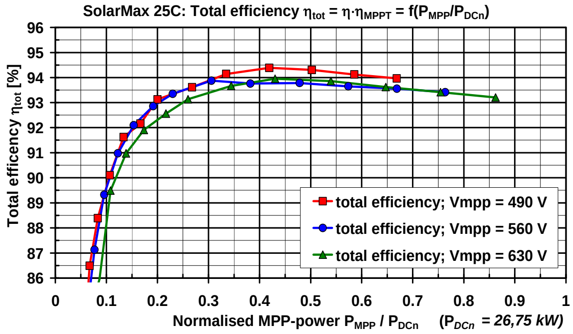

Fig. 7:
Total efficiency η_{tot} of a Solarmax 25C (3-phase, with transformer) vs. normalised MPP-power P_{MPP}/P_{DCn} at 3 different MPP voltages. This device has the highest efficiency at low DC voltages.

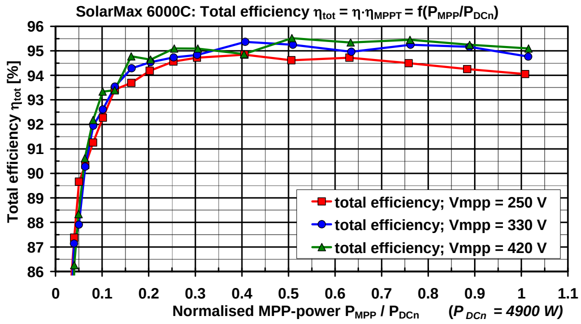

Fig. 8:
Total efficiency η_{tot} of a Solarmax 6000C (without transformer) vs. normalised MPP-power P_{MPP}/P_{DCn} at 3 different MPP voltages. This device has the highest efficiency at high DC voltages.

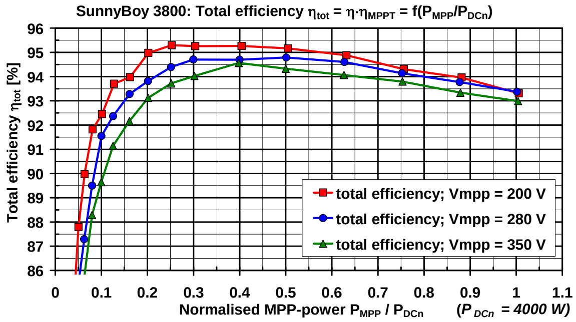

Fig. 9:
Total efficiency η_{tot} of a SB3800 (with transformer) vs. normalised MPP-power P_{MPP}/P_{DCn} at 3 different MPP voltages. This device has also a very high efficiency for an inverter with transformer. Highest efficiency is obtained here at the lowest DC voltage. At higher power levels, efficiency depends only slightly on DC voltage.

4. Conclusions

Compared to measured efficiencies of some older inverter models indicated in [2], European efficiencies for inverters of the same technology could be increased again by about 1% - 3%.

Measurements have also shown that most inverters have a quite good static MPP-tracking. Therefore total efficiency η_{tot} is often very close to conversion efficiency. However, to verify inverter quality, it makes sense to perform actual measurements by independent test institutions.

In the past, our measurements have shown that inverter efficiences indicated by many manufacturers in their data sheets often contained exaggerated values with 1 – 2% "marketing overtip". As efficiency measurements become more difficult and require very expensive measuring equipment the closer they come to 100%, it is very difficult for the average consumer to verify this. A similar situation has existed (and partly still exists) with module specificiations. However, some inverter manufacturers now indicate real efficiencies on their data sheets that can actually be confirmed by measurements with high-precision instruments in the laboratory. This is very good for plant designers and plant owners and for the further evolution of the PV market.

Notes:

- A proposed measuring procedure and some measuring results for measurements of *dynamic MPP-tracking behaviour* are presented in another contribution [3].
- Extended test reports (in German) are available under www.pvtest.ch > Wechselrichter-Testberichte.

Important Notice

Acknowledgements

Thanks go to all the institutions that gave financial support for this project. The work described in this paper was carried out in the project "PV system technology 2003-2006" under a contract with the Swiss Federal Office of Energy (BFE). Other parts of this project were co-funded by Localnet AG Burgdorf, GMS, c/o BKW, Bern and EBL, Liestal.

References:

[1] H. Haeberlin, L. Borgna, M. Kaempfer and U. Zwahlen "Total Efficiency η_{tot} – a new Quantity for better Characterisation of Grid-Connected PV Inverters ". Proc. 20th EU PV Conf., Barcelona 2005.

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