STATUS AND RELEVANCE OF THE DC VOLTAGE DEPENDENCY OF THE INVERTER EFFICIENCY

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ABSTRACT: The efficiency characteristics and the "European Efficiency" of a grid connected inverter is dependent on the hardware topology and changes also significantly with varying input (DC) voltage. Therefore the energy yield of a PV-system based on an inverter with outstanding peak efficiency might be lower compared to a standard product, if an inappropriate voltage is chosen. Today, the PV system designer still faces a lack of data on this topic within most inverter data sheets provided by the manufacturer. For the same reason, most PV-simulation programs do not take this dependency into account. This paper summarizes previous work related to this topic and presents approaches on how to effectively model the voltage dependent efficiency. The resulting model parameters are presented for different inverter products available on the market and the individual average inverter efficiency is calculated for different DC voltage levels. Finally the authors strongly recommend to measure inverter efficiencies at independent test laboratories und publish the data. Round robin test for PV inverters have to be realized with partners form independent laboratories as well as partners from industry.

Keywords: inverter, efficiency, yield, economy

1 INTRODUCTION

The efficiency of a grid connected inverter depends not only on the actual power but also significantly on the level of the input (DC) voltage [1-4]. Today, most of the customers compare the performance of inverters only by one figure of merit, the weighted inverter efficiency i.e. the EURO efficiency η_{EU}. This may be a weak point in the design of the PV plant, because most of the manufacturer's data sheets don't give the DC voltage level used to determine the EURO efficiency value. Thus in most cases the information is not available, which is the optimum DC voltage level to select, in order to achieve the highest weighted efficiency. This lack of data concerning the DC voltage dependency of the efficiency directly influences the yield of the whole PV installation and thus the price of the inverter itself [6].

The published and recently measured inverters conversion efficiencies will be discussed together with the estimated measurement uncertainties. In a critical review it will be shown that published uncertainty values of efficiency below 0.1% are not feasible in today's inverter test laboratories [7]. A model is described which can be used to calculate the efficiency not only as a function of the power but also as a function of DC voltage. This is one of the preconditions to implement the inverter efficiency characteristics in the widely used PV design software tools [8].

2 INVERTER EFFICIENCY AND PRICE

A recent market survey of all PV inverters available in Germany resulted in an average efficiency of 93.1% when looking upon the weighted EURO efficiency value [9]. New products launched in 2007 offer an average Euro efficiency of 94.4%. The maximum EURO efficiency value is 97.7%. About 95% of all inverter products provide efficiencies within a range of +/- 3% around the average of 93.1% [9]. In a simplified manner the relation between efficiency and price is shown in table 1. In the used model the inverter accounts for 10% of the overall PV system costs.

Table 1 Relation between PV inverter EURO efficiency and specific costs. In the typical private house PV installation the inverter accounts for 10% of the overall system price [6,10].

efficiency difference between	relative efficiency change	Inverter price €/W
average efficiency value to highest efficient product	4.1%	41%
lower limit of efficiency and upper limit of efficiency of 95% of the market share	6.0%	60%
measurement uncertainty	+/- 0.5%	+/- 5.0%
maximum allowed deviation to the guaranteed efficiency according to IEC 61683	-1.3%	-13%

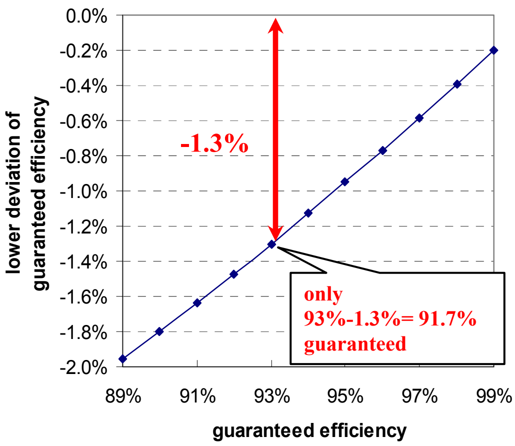

Fig. 1: Maximum allowed deviation to the guaranteed efficiency according to draft IEC 61683:1999 (according to the formula – 0.2 (1- η) η%) [10]

In table 1 it is shown that the best inverter in terms of efficiency, featuring 4.1% higher efficiency than an average product, may be 41% more expensive in terms of €/W when assuming the same generation costs of PV electricity.

If a manufacturer guarantees for example an inverter efficiency of 93% the customer can expect acutal efficiency values which may not be lower than 91.7% according to the IEC 61683 [10]. An efficiency 1.3% lower than its nominal value corresponds to a decrease in inverter prices of 13%. (Fig. 1)

3 UNCERTAINTY OF MEASURED EFFICIENCY

Always, measured values have to be discussed with regard to their measurement uncertainties. The state of the art in measurement uncertainty of inverter efficiency has to be highlighted before drawing conclusions based on fractions of a percent in inverter efficiency. Since 1993 the international "Guide to the Expression of Uncertainty in Measurement" (GUM) is an international standard and must also be applied to efficiency measurements of PV inverters [11]. Based on GUM, table 2 reports the comparison of the type B uncertainty budgets of two different inverter efficiency measurements setups, respectively power analyzers. The uncertainty of the inverter efficiency u(η) is given by the combined uncertainty of the DC power measurement $u(P_{DC})$ and the AC power measurement $u(P_{AC})$ applying

$$u(\eta)^2 = u(P_{DC})^2 + u(P_{AC})^2 \, . \qquad \text{Eq. 1}$$

Type B uncertainties in table 2 and 3 were estimated by considering the combined uncertainty of the accuracy values relative to the reading and relative to the full scale value, as given in the data sheets.

The values in table 2 show that the measurement uncertainty of each efficiency value strongly depends on the actual power reading relative to full scale. Values between 0.2% and 0.5% are good estimates. Thereby the DC power measurement dominates the whole type B uncertainty budget.

Uncertainty contributions of external current sensors must also be taken into account. Both systems compared in table 2 are equipped with shunts. In table 3 the uncertainty budget of DC and AC power is reported for the D6000 power analyzer. For this particular case it is evident, that the main contribution is not caused by the shunt but by the uncertainty of the DC voltage measurement from the external current sensor as well as by the inverters DC voltage reading.

According to GUM the influence of the measurement statistics concerning the actual reading, known as type A uncertainty contribution, has to be combined with the type B contribution as given in table 2. The type A uncertainty contribution which corresponds to the standard deviation of the means can also be in the range of some tens of a percent. It strongly depends on the stability of the working point, the active MPP tracking, the DC source of the inverter and the update interval during the measurement procedure.

Impacts on the uncertainty of the AC measurements may occur due to the active inverters impedance measurement (ENS). Thereby the ENS control system has to generate periodically significant current peaks as shown in Fig. 2. This may cause an automatic change of the current measurement range during a typical inverter test sequence. This leads to a deterioration of the uncertainty values because then the actual reading is much smaller compared to full scale (see Tab. 2)

When comparing the measurement results of different laboratories on the same DUT the whole set of uncertainty contributions must precisely be taken into account. Relative changes of efficiency values during an individual test sequence typically show a significant resolution between 0.1% and 0.05% when performed by qualified laboratories.

In conclusion, the overall measurement uncertainty of the inverter efficiency will be in the range between 0.2% and 0.6% of reading based on a 95% confidence (GUM k=2). The uncertainty of the AC power should be a good estimate when focussing only on the significance of the relative change of efficiency, for example as it occurs when the inverters DC voltage is altered. Thus relative changes of the inverter efficiencies with a significant resolution between 0.05% and 0.15% may be expected when the test are carried out by personnel in qualified laboratories using state of the art advanced standard equipment.

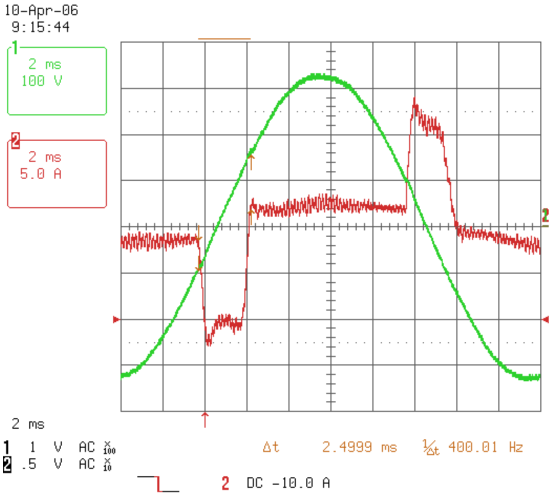

Fig. 2:

Time response of AC voltage and current of an SB3800 inverter while a current test impulse of the impedance measurement occurs every second at the zero-crossing of the voltage operating at relatively low power ($P_{AC} \approx$ 450 W) [18].

Table 2 Uncertainty budget of inverter efficiency measurement setups given for an expanded uncertainty level of k=2 (95% confidence, see type B contribution) based on two different power analyzers. The manufacturer's data sheet accuracy specification a_x was used to calculate the GUM uncertainty by the well known formula 2 a_x / √3 [11, 12]. The uncertainty values are given at 3 different actual reading values relative to full scale.

Relative uncertainty power analyzer 30A range	System I D6000* LEM Norma	System II WT3000** Yokogama
actual power readings at full scale		
$u(P_{DC})$	0.26%	0.13%
$u(P_{AC})$	0.13%	0.05%
$u(\eta)$ for k=2	0.29%	0.14%
actual power readings at 1/2 of full scale		
$u(P_{DC})$	0.28%	0.24%
$u(P_{AC})$	0.14%	0.10%
$u(\eta)$ for k=2	0.31%	0.26%
actual power readings at a quarter of full scale		
$u(P_{DC})$	0.37%	0.47%
$u(P_{AC})$	0.16%	0.19%
$u(\eta)$ for k=2	0.40%	0.50%

D6000* accuracy values guaranteed for 24 months
WT3000** accuracy values guaranteed for 6 months

Table 3 Uncertainty budget of inverter efficiency measurement setups given for an expanded uncertainty level of k=2 (95% confidence, see typ B contribution [11], based on power analyzers data sheet accuracy specification, only internal current sensors used). Here, the actual measured values should be at a quarter of the full scale reading.

power analyzer D6000 shunt-triax 0.1 to 30A	actual readings at	
	full scale	a quarter of full scale
Uncertainty budget of the DC power measurement		
u(voltage signal DC)	0.18%	0.22%
u(current signal DC)	0.18%	0.29%
u(shunt-triax)	0.03%	0.03%
$u(P_{DC})$ for k=2	0.26%	0.37%
Uncertainty budget of the AC power measurement		
u(voltage signal 50Hz)	0.05%	0.07%
u(current signal 50Hz)	0.05%	0.10%
u(shunt-triax)	0.03%	0.03%
u(real power calc.)	0.10%	0.10%
$u(P_{AC})$ for k=2	0.13%	0.16%

4 EFFICIENCY VERSUS DC VOLTAGE LEVEL

The conversion efficiency of an individual grid connected inverter significantly depends on AC power and DC voltage. Fig. 3 and 4 show the two different plots of this dependency of two different products on the market. The typical dependence of the widely used transformer-less inverter topology is shown in Fig. 4 as a mapping plot of the efficiency versus power and voltage.

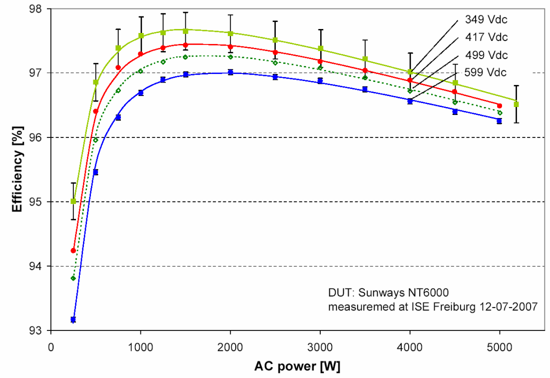

Fig. 3: Measured conversion efficiency of an inverter shown as a function of AC power at four different DC-voltages. In the upper curve a measurement uncertainty of +/-0.3% is indicated by the error bars. The DUT was a NT6000 new version since June 2007 an inverter without transformer (www.sunways.de). The maximum efficiency of 97.7% was measured at a MPP voltage of 349Vdc. The measurement was performed at the ISE Test Laboratory using a D6000 power analyzer using a DC power supply in the constant voltage mode (see also Table 2, 3 and Fig. 10).

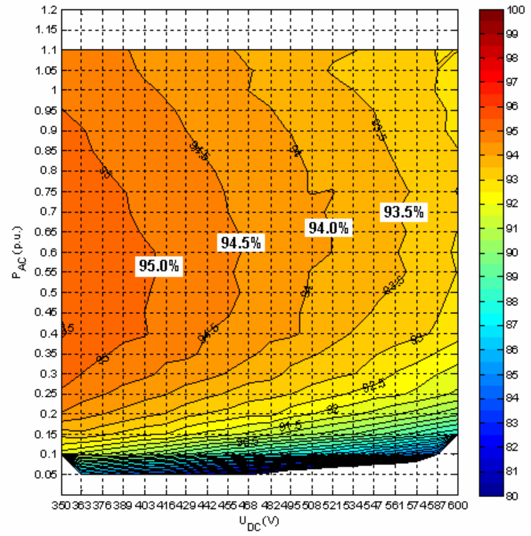

Fig. 4: Measured conversion efficiency of an inverter shown as mapping plot in the AC power versus DC voltage plane. The DUT was a standard inverter without transformer. The plot is based on 440 individual efficiency measurements at 20 different DC voltage levels (350V – 600V) and AC power values (plotted relative to P_N=2.6kW). The measurement was performed at the arsenal research [12] using a D6000 power analyzer (see also Table 3 and Fig. 8)

The maximum efficiency of 95.5% was measured at the lowest DC voltage value of 350V at about 40% of nominal power. The efficiency drops to 93% at the upper limit of the DC voltage range.

Similar efficiency characteristics of other transformer-less products (Sunways NT6000, SMA SB850) were published at previous conferences in the same AC power /DC voltage plot [1]. However differences in maximum efficiency of up to 3% were found. The dependency of efficiency with DC voltage is found to be less than 1% for inverters with record maximum efficiency of ≥ 97%. Transformer less inverters with maximum efficiency values ≤ 95% exhibited a significantly higher voltage dependency of about 2.5% [1] similar to recent results shown in Fig. 4.

There is no general rule about the dependency of inverter conversion efficiency on DC input voltage. There are inverters that have their maximum efficiency at low voltages like those shown in fig 3, 4, 5 and 6, but there are also inverters that have their top efficiencies at high voltages (e.g. Solarmax 6000C, SB5000TL Multistring) and also inverters that have their maximum efficiencies at a medium DC voltage (e.g. Fronius IG30 and IG40 [2], Magnetek power one). Due to the commonly used topologies of transformer-less inverters they will reach their maximum of efficiency at a DC voltage level close to the peak value of the AC voltage. Inverters setup with a transformer tends to increase efficiency at lower DC voltage levels.

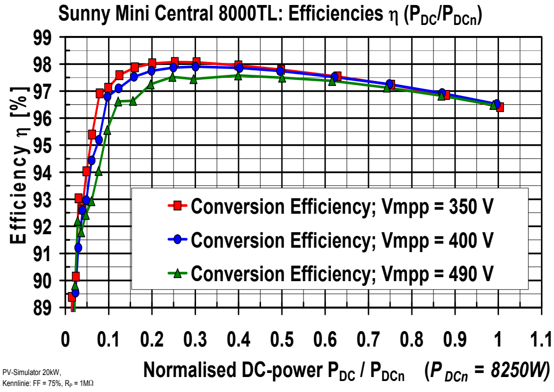

Fig. 5: Highest measured *conversion efficiency at a prototype of an inverter without transformer* at three different DC-voltages (SMC 8000TL, P_{DCn} = 8.25 kW) [2]. At low power the efficiency shows a considerable voltage dependency. With increasing power this dependency decreases and at the highest power levels efficiency is virtually independent on the DC voltage.

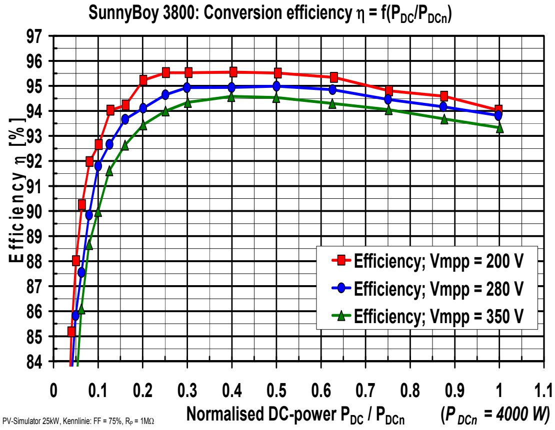

Fig. 6: Measured *conversion efficiency of an inverter with transformer* at three different DC-voltages (SB 3800, P_{DCn} = 4 kW) [2]. At all power levels, conversion efficiency depends somewhat on the DC voltage. At low power, this difference is up to 4%, whereas at high power, it reduces to about 1%.

4.1 CUSTOMERS NEED RELIABLE INFORMATION ABOUT INVERTER EFFICIENCY!

In the last years the state of California started the well recognized solar initiative promoted by governor Arnold Schwarzenegger. Since 2005 lists are published of eligible PV products, like inverters, PV modules by the California Customer Energy Center [15]. There the customer will find detailed information for example on the inverter efficiency of up to 170 PV inverters available on the US market. Among that list some products with a nominal power of 5kW are listed in table 4. In Dec 2006 the California Energy Commission published the final guidelines, describing the criteria to be listed as an eligible product [16]. One of the criteria is the publication of measured inverter efficiency values at least for 3 different DC voltages. Furthermore the tests must be performed by an independent laboratory.

The compilation of this list since 2005 was necessary to provide the customer with transparent and independent information about the inverter efficiency beyond the efficiency values stated in the marketing documents from the manufactures.

The establishing of such an independent list would be also highly desirable for the European market. First steps are done by the magazine Photon [7] published the results of the author's publication [1], a mapping plot of the efficiency versus power and voltage, together with their yearly inverter market survey in 2005 [19]. This was very helpful to bring that topic to a broader audience. The magazine Photon started in January 2007 to publish in each monthly issue measurement results of one individual inverter product with focus on the DC voltage dependency.

Table 4 Weighted inverter efficiency values measured at independent US test laboratories according to the Guidelines given by the California Customer Energy Center [16]. Only inverters suitable for the US market are listed with nominal power 5kW and DC voltage above 100V. The measurement uncertainty is not given. They may not be directly compared to products of the same company available on the European market due to other grid frequency, voltage level and other design features. The weighted efficiency values are shown for 3 different DC voltage values. (The US weighting factors to calculate the average inverter efficiency are given at the end of the this table)

Product	Company	$V_{DC,min}$	$V_{DC,nom}$	$V_{DC,max}$
SB5000US-240V	SMA	96.4%	95.9%	94.6%
GT 5.0 – POS	Xantrex	95.6%	95.5%	95.2%
PVP 5200	PV Power	96.4%	96.2%	95.5%
SUNString 5000	Sunset	93.8%	93.7%	93.3%
PVI 5000, US240V	Power One	96.1%	96.7%	96.1%
IG 5100	Fronius	94.2%	94.9%	93.7%

According to the CA guidelines [16] the weighting factors to calculate average efficiency are: 10% 0.04; 20% 0.05; 30% 0.12; 50% 0.21; 75% 0.53; 100% 0.05

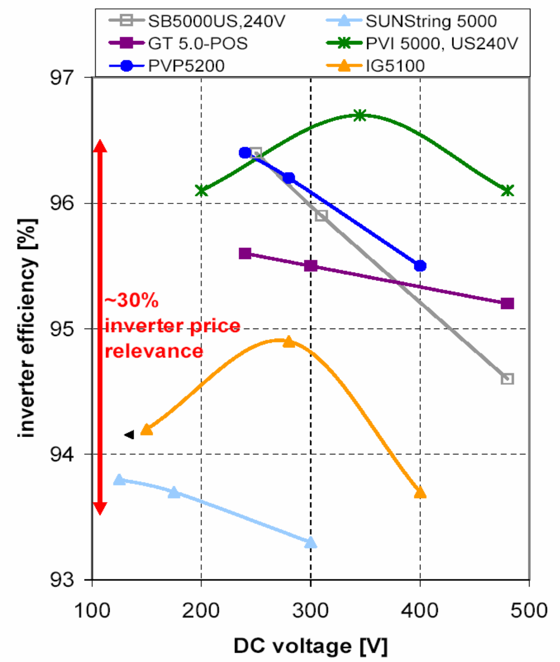

Fig. 7: Weighted efficiency of inverters available in the US as a function of DC voltage according to the measurement results published by the California energy commission see table 4.

4.2 MANUFACTURERS INFORMATION ON DC VOLTAGE DEPENDANCY

Seven years ago it was suggested in the IEC 61683 standard to measure the inverter efficiency values at least at three DC voltage levels. [10] Today in most of the manufactures datasheets this information is lacking. Typically the manufacturers only give one single weighted efficiency value, typically the European efficiency η_{EU} without specifying the corresponding DC voltage. A few manufactures like Sputnik (www.solarmax.com) list the η_{EU} at two different DC voltage values in their datasheets [1].

This is particularly interesting to the fact, that for example a 2% lower actual efficiency on the same DC voltage level lead to a 20% lower specific price of the inverter (Table 1). Maybe the PV plant designers did not request that information and create their purchase decision only on the simple average Euro- efficiency values.

Up to now the most comprehensive information about $\eta_{EU}(P,V)$ are available from Sunways about their inverters [7]. On their datasheet the plots of $\eta_{EU}(P)$ at three DC voltage levels are shown. Additionally Sunways present a numerical listing of their typical measurement results on the same datasheet. They are in comparison with the measurement at the ISE test laboratories as shown in Fig. 3.

In Fig. 8 the characteristics of the maximum efficiency at different DC values are given, according to a detailed technical documentation of the market leader SMA which was requested [14]. This was for the last years one of the only information's on that topic. Recently SMA also gives the efficiency characteristics as a function of part load at 3 DC voltage levels to their customers.

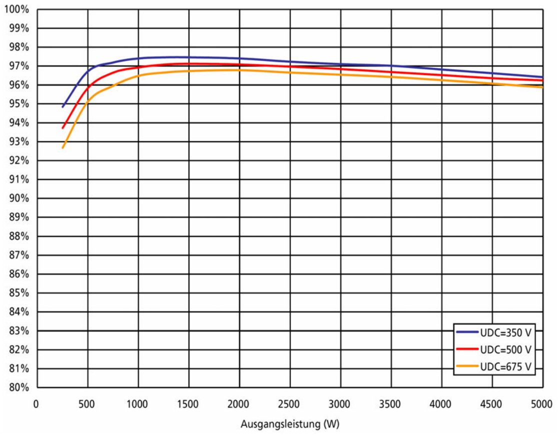

Fig. 8: An excellent example of detailed information available on the manufactures datasheet shown here for the NT6000 inverter version 06/2007 from Sunways. Also the numeric values of the measurement results are given (www.sunways.de). (see Fig. 3.)

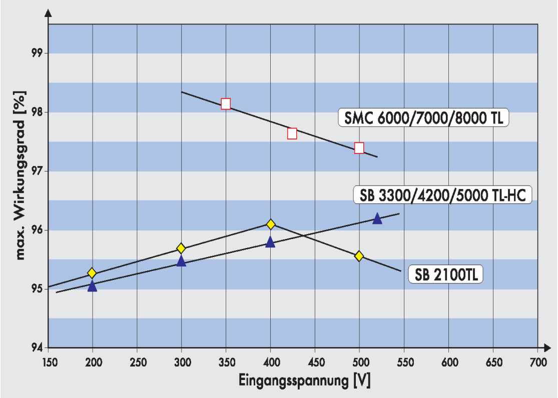

Fig. 9: In the last years only the dependency of the maximum efficiency on DC voltage was given from the manufacturer SMA to their customers. [14]

5 MODELLING CONVERSION EFFICIENCY VERSUS VOLTAGE AND POWER

Inverter efficiency is mainly determined by the inverter topology, the power transistors, modulation method, switching frequency and filters. Moreover, the losses in the power switches are a function of the DC input voltage and the current in the semiconductors and filters. The following simple model [1, 5] of inverter losses will be used. It has to be noted that this model is not appropriate to be applied to inverters which uses internally switching of general parts of the power electronic circuits (Fronius IG, SMC8000, Solarmax E series, Danfoss…) In the following P represents the output AC power of the inverter and c_0, c_1, c_2 are constant coefficients for a certain DC input voltage V_{DC}. Together with equation 1 the inverter efficiency can be expressed by

$$\eta(P_{AC}) = \frac{P_{AC}}{P_{AC} + P_{loss}(P_{AC}, V)} \quad , \qquad \text{(Eq. 2)}$$

$$\begin{aligned} P_{loss}(P,V) \;=\; & (c_{0,0} + c_{0,1}\,V + c_{0,2}\,V^2 + c_{0,3}\,V^3) + \\ & + (c_{1,0} + c_{1,1}\,V + c_{1,2}\,V^2 + c_{1,3}\,V^3)P + \\ & + (c_{2,0} + c_{2,1}\,V + c_{2,2}\,V^2 + c_{2,3}\,V^3)P^2 \;. \end{aligned} \qquad \text{(Eq.3)}$$

Table 5 Fitted coefficients $c_{i,j}$ of Sunways inverter NT6000 measured in 2003 and a the new NT6000 version 2007 (Fig.2) measured recently. The fit performed according to Eq. 2, 3 and describes the voltage and power dependency of the inverter (data P>5% P_N); units of power values P_{AC} in [W] and V_{DC} in [V]. The fit of the Sunways NT6000 version 2007 coefficients based on measurement values at the fixed DC voltages 349 V, 417V, 499V and 599V at 13 power values each.

	Sunways NT6000 version 06/2007 (meas. in 2007)	Sunways NT6000 Ref. [1] (meas. in 2003)
η max	97.7%	97.0%
$c_{0,0}$	-1.195E+00	4.848E+00
$c_{0,1}$	4.508E-02	1.504E-02
$c_{0,2}$	-3.251E-05	2.368E-05
$c_{1,0}$	8.060E-03	6.740E-03
$c_{1,1}$	-4.161E-06	1.037E-05
$c_{1,2}$	2.859E-08	2.716E-08
$c_{2,0}$	3.530E-06	8.934E-06
$c_{2,1}$	5.667E-09	-1.254E-08
$c_{2,2}$	-8.161E-12	6.378E-12

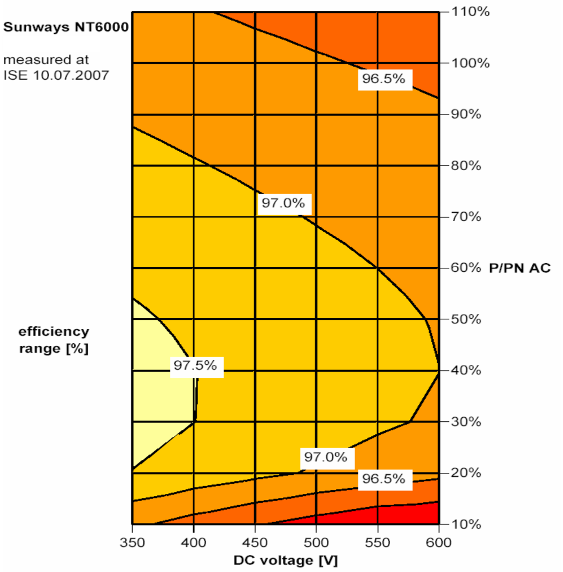

Fig. 10 Measured conversion efficiency values of the transformer-less inverter Sunways NT6000 advanced version 06/2007. The mapping plot is based on the fitted values given in table 5.

The following expression represents the power looses model proposed by ISE as a function of AC current I_{AC} and DC voltage V_{DC}.[17]

$$
\begin{aligned}
P_{loss}(I,V) = {} & P_0(V_{DC}) + U_0(V_{DC})\, I_{AC} + R_0(V_{DC})\, I_{AC}^2 = \\
= {} & (a_{0,0} + a_{0,1} V_{DC} + a_{0,2} V_{DC}^2) + \\
& + (a_{1,0} + a_{1,1} V_{DC} + a_{1,2} V_{DC}^2)\, I_{AC} + \\
& + (a_{2,0} + a_{2,1} V_{DC} + a_{2,2} V_{DC}^2)\, I_{AC}^2
\end{aligned}
\qquad \text{(Eq.4)}
$$

The first term P_0 represent the losses at vanishing output power at I_{AC}=0. Fig 8a shows the dependency of P_0 as a function of DC voltage. In Eq. 4 this characteristics is described by a second order polynomial term with the corresponding 3 fitted coefficients $a_{0,0}$, $a_{0,1}$ and $a_{0,2}$ given in table 6. The second part of the losses is proportional to the current leading to the coefficient U_0. In that model U_0 will describe the sum of all the voltage drops over the power semiconductors in the inverter. The last group of losses are attributed to the over all ohmic losses represented by the coefficient R_0 which is also fitted by three coefficients (Eq. 4 and table 6).

Together with the nine coefficients of table 6 and the AC current, which may by calculated as a function of the AC power at a fixed AC voltage the efficiency is defined as a function of DC voltage and AC power.

Both equation 4 and 5 uses the same type of polynomial descriptions of the DC voltage dependency but the coefficients are different. The advantage of the model based on Eq. 5 is to check the quality of the fitted results of P_0, V_0 and R_0 individually as can be seen in Fig. 11a-c. Thus bigger deviations between fit and measurement are noticed and detailed analyses for example of the measurement uncertainties at lower AC power values may be performed.

Table 6 Fitted coefficients to calculate the efficiency based on the measurement results shown in Fig. 4 according to Eq. 4 (details see also Fig. 11)

$a_{0,0}$	$a_{0,1}$	$a_{0,2}$
19.259	-0.065	$1.737 \cdot 10^{-4}$
$a_{1,0}$	$a_{1,1}$	$a_{1,2}$
0.846	0.015	$-1.104 \cdot 10^{-5}$
$a_{2,0}$	$a_{2,,1}$	$a_{2,2}$
0.612	$-7.75 \cdot 10^{-4}$	$1.519 \cdot 10^{-6}$

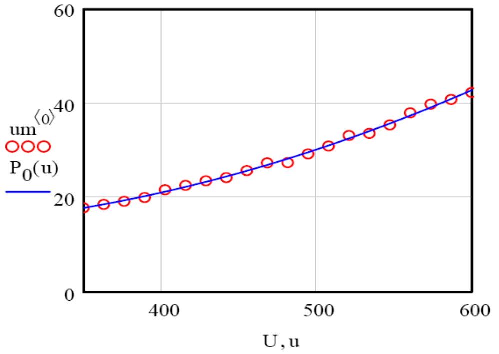

Fig. 11a: Extracted coefficient of the power losses at I_{AC}=0 as a function of DC voltage shown together with the fitted curve according to Eq. 4 and Tab. 6. Data are based on the measurement results at 20 different DC voltage values shown in the efficiency mapping in Fig. 4. (Fit performed by ISE, measured at arsenal research)

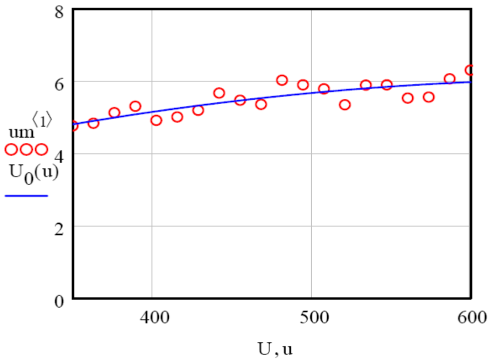

Fig. 11b: Extracted coefficient of the constant voltage U_0 as a function of DC voltage shown together with the fitted curve according to Eq. 5. (see Fig. 11a)

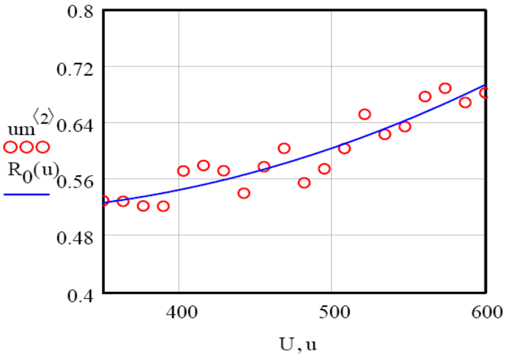

Fig. 11c: Extracted coefficient of the constant loss resistance R_0 as a function of DC voltage shown together with the fitted curve according to Eq. 5. (see fig. 11a)

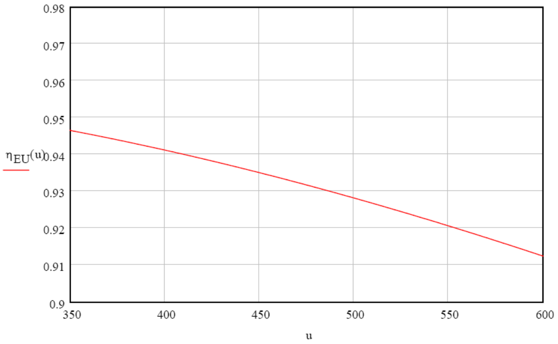

Fig. 11d: Calculated weighted efficiency of the transformer-less inverter according to the efficiency model described also by Eq. 5 and the EURO efficiency weighting coefficients [6]. (Measurement shown in Fig. 4; details see Fig. 11a-c and Tab. 6)

6 CONCLUSION and OUTLOOK

It is strongly recommended to establish and publish a list of weighted inverter efficiency values at different DC voltages for the European market(s). Similar to the very successful California list the inverters have to be examined by independent laboratories.

Based on this list and further measurements the dependence of efficiency on power and DC voltage should be modelled and implemented in the common PV System design software products.

These software products could also offer the function of a simple economic estimate comparing the inverter price in €/W to overall PV system price taking into account the influence of the resulting weighted efficiency of the final design.

A round robin test of inverters at different independent laboratories should be performed in the near future.

Also the deviation in inverter efficiency of a given production line is of high relevance especially for the inverter manufacturer and the guaranteed efficiency values on the market.

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