EURO REALO INVERTER EFFICIENCY: DC-VOLTAGE DEPENDENCY

F.P. Baumgartner
University of Applied Sciences Buchs NTB, Werdenbergstrasse 4, CH-9471 Buchs, Switzerland
web: www.ntb.ch/pv, email: franz.baumgartner@ntb.ch

ABSTRACT: The PV inverters efficiency ranking is commonly based on the EURO efficiency. The today's EURO efficiency calculation takes into account only the variation of efficiency as a function of power. State of the art inverters additionally exhibit an up to 3% efficiency change as function of DC voltage. Thus the traditional EURO efficiency values will not represent a realistic average inverter efficiency in the whole DC-voltage MPP range. Usually the inverter manufacturer doesn't show this voltage dependency of efficiency in their datasheets. Up to now also less information is found in literature on this topic. In the present paper the mapping of efficiency in the power voltage plot is given for six commercial PV inverters. A change in efficiency of up to 0.5% in a voltage interval of $100V_{DC}$ is typical for PV inverters with efficiency higher than 95%. Lower efficient inverters exhibit a much higher efficiency gradient of up to 2% at 100V. Two methods are presented to include the voltage dependency in the calculation of the average inverter efficiency. The results of the so called EURO REALO efficiency values are discussed. Due to the effect that few manufacturer started to hand over their efficiency values at several DC voltages this will led to more precise designing of the string voltage of PV plants with optimum over all system performance.
Keywords: Inverter, Grid-Connected, PV system,

1 INTRODUCTION

In 2004, two thirds of the PV inverters are marketed with EURO-efficiencies between 91% and 94% while the record products reaches efficiencies of 96%.[1] All of the inverter manufacturers still uses the calculation method of the EURO efficiency in their datasheets established about 15 years ago. [2] This approach takes into account the efficiency values of the inverter at part load conditions at a fixed DC voltage. These set of efficiency values are than multiplied by yearly average weighting factors [2] which originally were taken for the location of North Germany and still represent a so called standard on the international level.[12] Beside these EURO efficiencies values, the manufactures usually give no data sheet information about its DC voltage dependence. However measured inverter efficiency data show a significant change of up to 3% in respect to the inverters upper and lower MPP DC voltage limits. [1, 4] Five years ago it was suggested in the IEC 61683 standard to measure the inverter efficiency values at least at three DC voltage values. [3] But there was no consequent effect for the customers to find this complete information about the voltage dependency of inverters efficiency in the relevant datasheets. A detailed efficiency analysis of state of the art PV-inverters on DC-voltage and power dependence is still missing in literature. In this paper such figures will be presented, especially due to the kindly support of measured efficiency data from some key market players.[5 - 11] Finally the economic aspects has to be pointed out concerning inverter costs and system performance. An increase of 2% in inverter efficiency will allow 20% higher specific inverter prices in €/W.[1]

2 MEASURED EFFICIENCY AND MODELLING

Inverter efficiency is mainly determined by the inverter topology, the power transistors, switching type, switching frequency and filters. In particular, the losses in the power switches are also a function of the DC input voltage and the current in the power transistors. The following well established simple model [13] of inverter losses will be used. With P representing 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}.

$$P_{losses} = c_0 + c_1 P + c_2 P^2 \qquad \text{(Eq.1)}$$

Together with equation 1 the inverter efficiency can be expressed by

$$\eta(P_{AC}) = P_{AC} \Big/ P_{AC} + c_0 + c_1 \cdot P_{AC} + c_2 \cdot P_{AC}^2 \qquad \text{(Eq. 2)}$$

Fig. 1 shows the capability of this simple efficiency model with standard deviations STD given in table 1 for the error between measurements and fitted values.

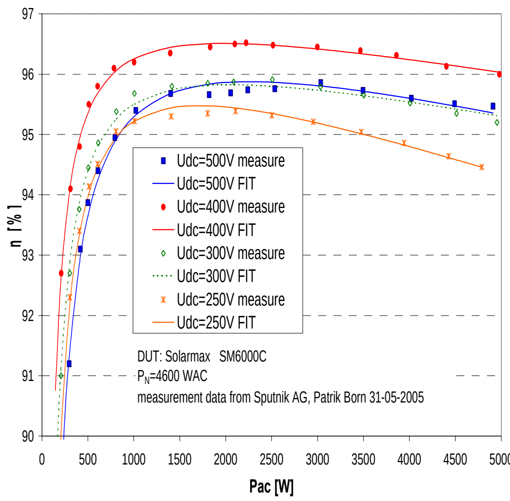

Fig. 1: Measured inverter efficiencies versus output power at four different input voltages V_{DC} of the SolarMax SM6000C PV inverter. (Based on manufacturers data [10]). The continuous lines show the fitted results of efficiency based on values in table 1.

Table 1 Fitted coefficients of Solar max SM6000 C based on equation 1, 2 and measurement values of Fig. 1.

V_{DC} [V]	500	400	300	250
c_0 [W]	20.453	11.249	13.836	16.816
c_1	0.02499	0.02483	0.03005	0.02775
c_2 [W^{-1}]	3.974E-06	2.856E-06	3.299E-06	5.725E-06
STD [%]	0.11	0.06	0.12	0.07

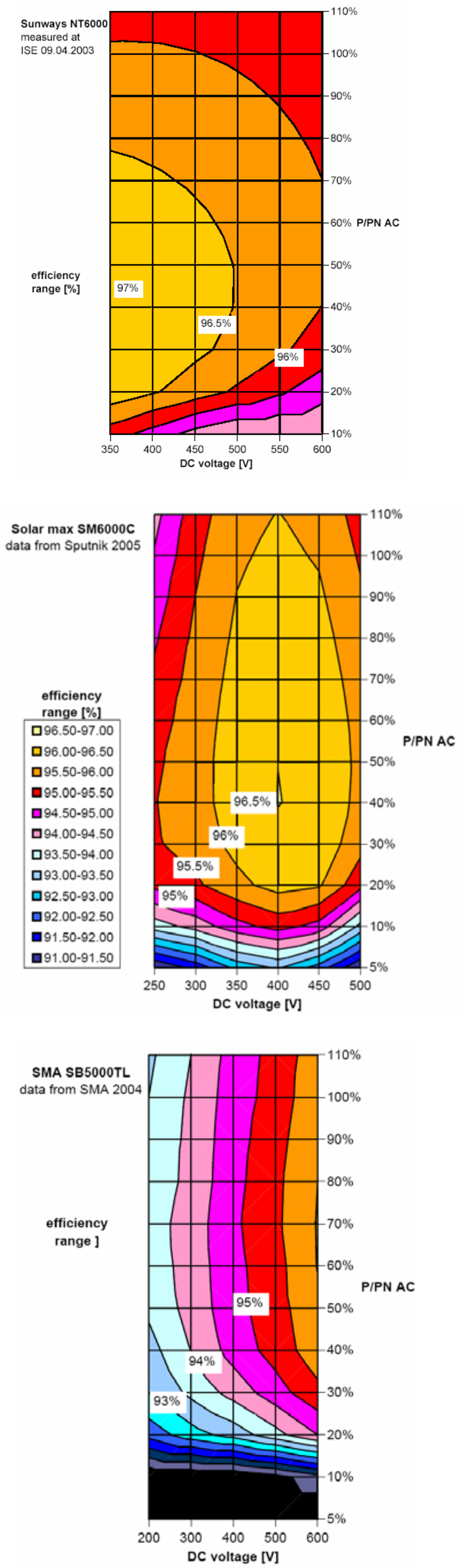

Fig. 2: Measured efficiency values of transformer less type inverters (P_N=4.6kW) drawn in the DC voltage / power plot. (data supplied by the manufacture [4, 5, 6])

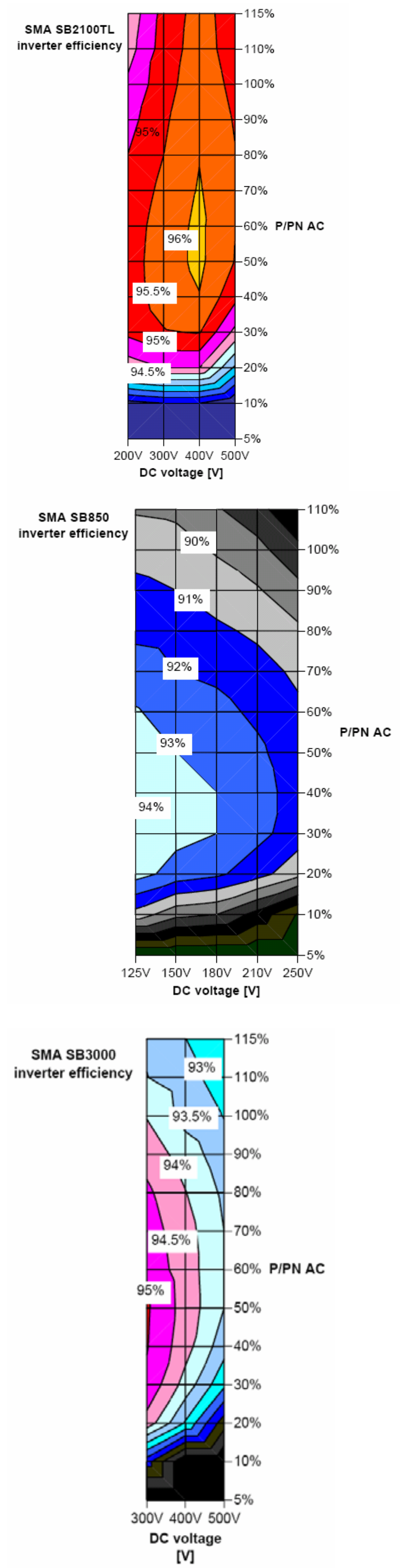

Fig. 3: Measured efficiency values of transformer less type inverters drawn in the DC voltage / power plot. The data supplied by the manufacture [5]

The measurement results show that the efficiency characteristics significantly changes with the DC voltage leading to other fitted coefficients c_0, c_1, c_2 given in table 1. An explicit formula of the inverter efficiency [13] can be found by fitting the losses coefficients in equation 1 versus DC voltage by the following polynomial form

$$P_{losses}(P,V) = (c_{0,0} + c_{0,1}V + c_{0,2}V^2 + c_{0,3}V^3) + (c_{1,0} + c_{1,1}V + c_{1,2}V^2 + c_{1,3}V^3)P + (c_{2,0} + c_{2,1}V + c_{2,2}V^2 + c_{2,3}V^3)P^2 \quad \text{(Eq.3)}$$

Thus the resulted set of 12 coefficients $c_{i,j}$ in table 2 describes the characteristics of inverter efficiency $\eta(P,V)$ as a function of power P_{AC} and voltage V_{DC} . Measurement results at more than at least four different DC voltage values are required to fit this number of coefficients. A reduced set of only 9 coefficients (with $c_{0,3} = c_{1,3} = c_{2,3} = 0$ see Eq. 3) derived from the measurement in Fig. 1 is given in table 3. This reduced set revealed a higher standard deviation between fit an measurement values of 0.19% compared to 0.9% using the 12 coefficients in table 2. Additionally table 3 lists the $\eta(P,V)$ coefficients of the Sunways NT6000 fitted to the efficiency measured at the ISE, Freiburg [8] (see Fig. 2).

Table 2 Fitted coefficients $c_{i,j}$ of SolarMax SM6000C according to Eq. 2 to describe the voltage and power dependency of the inverter efficiency; data $P>5\%P_N$ used; standard deviation fit to the measurement in Fig. 1 STD =0.09%; units P_{AC} [W] and V_{DC} in [V] see Eq. 3, 2

$c_{0,0}$	$c_{0,1}$	$c_{0,2}$	$c_{0,3}$
4.825E+00	2.470E-01	-1.161E-03	1.458E-06
$c_{1,0}$	$c_{1,1}$	$c_{1,2}$	$c_{1,3}$
-1.436E-01	1.495E-03	-4.162E-06	3.693E-09
$c_{2,0}$	$c_{2,1}$	$c_{2,2}$	$c_{2,3}$
6.577E-05	-4.647E-07	1.114E-09	-8.628E-13

Table 3 Fitted coefficients $c_{i,j}$ of SolarMax SM6000C and in the second row NT6000 according to Eq. 2, 3 to describe the voltage and power dependency of the inverter (all data P>5% P_N) ; units of power values P_{AC} in [W] and V_{DC} in [V]. The fit of the sunways NT6000 coefficients based on measurement values at the fixed DC voltages 355 V, 418, 500V and 600V at each 23 power values.

	Sputnik SM6000C	Sunways NT6000
$c_{0,0}$	7.485E+01	4.848E+00
$c_{0,1}$	-3.517E-01	1.504E-02
$c_{0,2}$	4.851E-04	2.368E-05
$c_{1,0}$	3.374E-02	6.740E-03
$c_{1,1}$	-2.065E-05	1.037E-05
$c_{1,2}$	4.669E-09	2.716E-08
$c_{2,0}$	2.434E-05	8.934E-06
$c_{2,1}$	-1.105E-07	-1.254E-08
$c_{2,2}$	1.399E-10	6.378E-12

The explicit formula of $\eta(P,V)=f(P_{AC}, V_{DC}, c_{i,j})$ is plotted in Fig. 2 as lines of constant efficiency values in the voltage power plot. The $\eta(P,V)$ contour plots of three high efficient transformer less inverters are shown. This plots are based on measurements results supplied by the manufactures.[8,9,10] The region of the maximum efficiency values is found at the lower MPP voltage limit of the Sunways NT6000. In contrast the SolarMax SM6000C shows the efficiency maximum at the center and the SMA SB500TL at the upper MPP voltage limit. The gradient of the efficiency versus voltage near the region of the efficiency maximum is roughly 0.5% at a 100V voltage interval. At nominal power all three inverters show efficiency values of roughly 96% at a voltage of 500V.

Fig. 3 shows the $\eta(P,V)$ contour plots of less efficient inverters. The plot of the SMA SB850 points out an efficiency gradient of up to 2% in a voltage interval of 100V.

5 AVERAGE INVERTER EFFICIENCY - THE EURO REALO CALCUATION METHOD

In-field performance data of several grid-connected PV systems are analysed in [1] with respect to calculate the average inverter efficiency. Fig. 4 shows a typical surface-plot, which expresses the cumulative frequency curve of a certain energy output for certain, intervals of DC voltage and DC power. This cumulative frequency values are characterized by 10 weighting coefficients k_i found in the table of Fig. 4 [1]. Again it has to be noticed that in contrast to the conventional EURO efficiency calculation [2] the present formula takes into account the inverter efficiency not only as function of power but also at different DC voltage values V/V_{STC}. In Fig. 4 these values are expressed in relative numbers to the modules STC values.

To make the calculation more convenient the numbers of weighting factors k_i are reduced to six as it is proposed by an IEC document. [3] These values of the weighting factors k_i are given in table 4. They are still based on the performance analyses in [1]. The power is expressed relative to the AC nominal power with the corresponding DC power at the modules side of $P_{DC}=P_{AC}/\eta$ which is not equal to modules STC power.

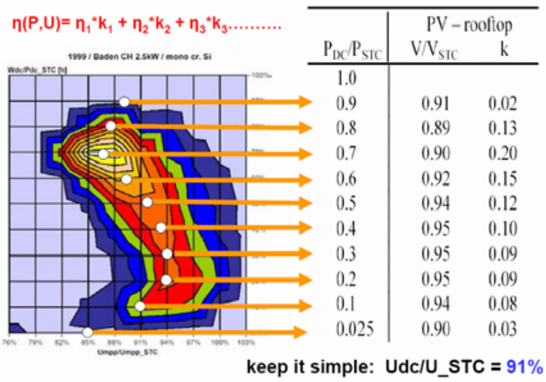

Fig. 4 Surface-plot of the cumulative frequency curve to operate a PV roof-top system in the given intervals of DC voltage and DC power expressed relative to the STC module power (location Switzerland – details see [1]). The derived weighting factor k_i are given in the right part.

The EURO REALO efficiency is calculated using the coefficients in table 4 and the individual calculated efficiency values as a function of power and DC voltage (see Eq. 3 and table 3). This method is applied to the data of the NT6000 and the SM6000C. The results are given in Fig. 5, 6. If one wants to simplify the calculation method further, the inverter efficiency at a constant average DC voltage (e.g. $0.91 \cdot V_{MPP,STC}$) will be taken together with the k_i values of table 4. The results of this simplified method are also given in Fig. 5,6. The differences of the both methods are to be neglected for the NT6000. In contrast the results of the SM6000C exhibit a deviation of up to nearly 0.2% which can be not neglected. Thus it is recommended to us the more accurate method and not only calculates the EURO efficiency at a constant DC voltage.

Table 4: Weighting coefficients k_i to calculate an average EURO REALO efficiency according to the formula [3,1]
$\eta(P,V)= \eta_1 \cdot k_1+\eta_2 \cdot k_2+\eta_3 \cdot k_3+\eta_4 \cdot k_4+\eta_5 \cdot k_5+\eta_6 \cdot k_6$
data based on crystalline silicon modules temp. coeff.

$P_{AC}/P_{N,AC}$	$V_{DC}/V_{MPP,STC}$	k_i
1.00	0.91	0.05
0.75	0.89	0.4
0.50	0.94	0.27
0.25	0.95	0.18
0.10	0.95	0.08
0.05	0.92	0.02

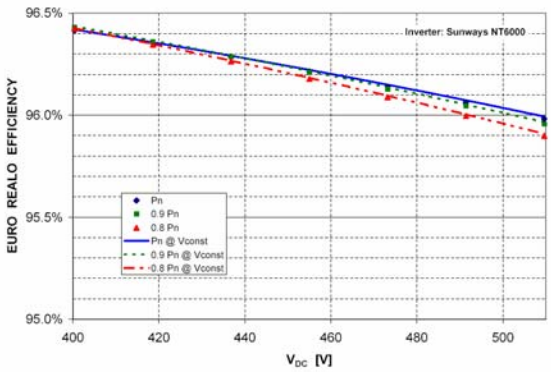

Fig. 5 EURO REALO efficiency of the Sunways NT6000. The DC voltage V_{DC} corresponds to 91% of modules MPP voltage at STC.(see tab. 4)

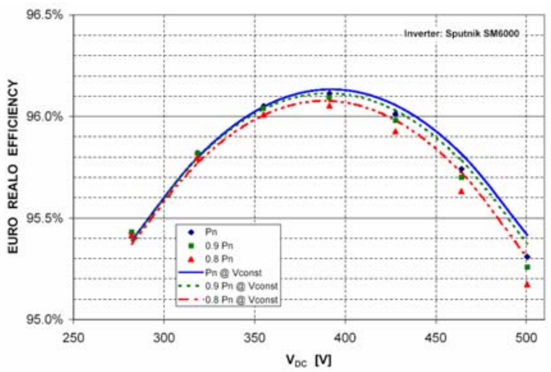

Fig. 6 EURO REALO efficiency of the SolarMax SM6000C. The DC voltage V_{DC} corresponds to 91% of modules MPP voltage at STC. (see tab. 4)

Table 5a Proposed Sunways NT6000 datasheet.

Euro Realo efficiency	U_{DC}=400V	U_{DC}=460V	U_{DC}=510V
$P_{N,AC}$	96.4%	96.2%	96.0%
0.8 $P_{N,AC}$	96.4%	96.2%	95.9%

Table 5b Proposed Sputniks SM6000C datasheet.

Euro Realo efficiency	U_{DC}=300V	U_{DC}=400V	U_{DC}=500V
$P_{N,AC}$	95.6%	96.1%	95.3%
0.8 $P_{N,AC}$	95.6%	96.1%	95.2%

To give the customer access to the clear information about the inverters efficiency the data sheet should consist of at least the six average efficiency values proposed in table 5a, 5b.[12] Today Sputnik is the only inverter company how shows the EURO efficiency in their datasheets at two different DC voltages.[7] These values are in agreement within ±0.1% to the values shown in table 5b. All the above discussed facts are only based on static inverter efficiency values. Other important effects on the performance of inverters in real life have also to be considered, like MPP tracking errors and the influence of heating effects of the power electronic components.

5 CONCLUSION

A method is presented to compare the average efficiency of inverters by calculating the EURO REALO efficiency values at the relevant DC voltage values.

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