MPP VOLTAGE MONITORING TO OPTIMISE GRID CONNECTED SYSTEM DESIGN RULES

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ABSTRACT: It is most important to the design-quality of grid connected PV-systems, to find the optimum number of given serial connected modules feeding the inverter. Often, today's system design procedures do not fully take the input voltage for *optimum* inverter efficiency into account, thus causing avoidable losses of up to 3%. First, the question is answered, what are the operating DC-voltage and -power ranges for existing grid-connected plants over a whole year. The data is analysed in a surface-plot, which expresses the cumulative frequency curve of a certain energy output for certain intervals of voltage and power. Different characteristics are found e.g., between roof top systems and façade applications. Moreover, a non-optimum system design, caused by wrong numbers of serial connected modules, can be found in analysing the DC operating area's "footprint" in these plots. In such a case the distribution is located at the lower or higher MPP voltage limit of the inverter. Thus the manufactures of inverters are recommended to generally show the efficiency values of their products at relevant DC voltage ranges in their datasheets. It would also be helpful for increasing overall PV system efficiency, to include such information in their public system design software, which is widely used in practice. On the basis of the analysed in-field data, a possible refinement of the widely used EURO-efficiency definition for inverters, including voltage parameters is suggested.
Keywords: inverter efficiency, MPP voltage, performance,

1 INTRODUCTION

Three quarters of today's world-wide PV capacity installed are grid connected. One of the key factors for optimum design of these systems is the number of PV modules series-connected to the inverter input. Today, the majority of system designs is based on operating conditions derived from the modules MPP voltage at module temperatures between -10ºC and +70ºC. Inverter manufactures provide software tools [1] for finding an appropriate number of modules, that will make the strings fitting their inverters' input MPP-voltage range. They also use the above limits and sometimes do not distinguish between different geographical sites, module orientation, or tolerances of modules' temperature coefficients. Thus it can be assumed that the majority of today's grid connected systems are based on the above design rules which in fact are more like a rule of thumb.

A sub-optimum number of modules may lead to operating states, during which power losses occur due to string MPP voltages being out of the inverters' MPP voltage range. Increasing the number of modules to the real inverter MPP voltage maximum will lead to maximum PV electricity at the same inverter cost. Also the maximum DC-voltage occurring in the string, from the sum of the modules' open circuit voltages, must stay below the maximum DC input voltage of the inverter. Additionally, manufacturers' values of inverter efficiency are constricted to a certain optimum MPP voltage, which is not necessarily in accordance with the nominal inverter voltage.

Our approach in this paper is to elaborate about the real MPP voltage values and ranges of different grid connected PV systems, based on in-field monitoring data. The goal is to state more precisely the system design rules focussed on optimum MPP voltage. There exists considerable analytical monitoring data including voltage values, from PV systems world-wide, which can be used for such purposes.

Inverter efficiency changes of up to 3%-points within the upper and lower inverter MPP voltage limit are found [2]. Fig. 1 shows maximum and EURO inverter efficiency values as a function of MPP voltage. 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 a function of the DC input voltage.

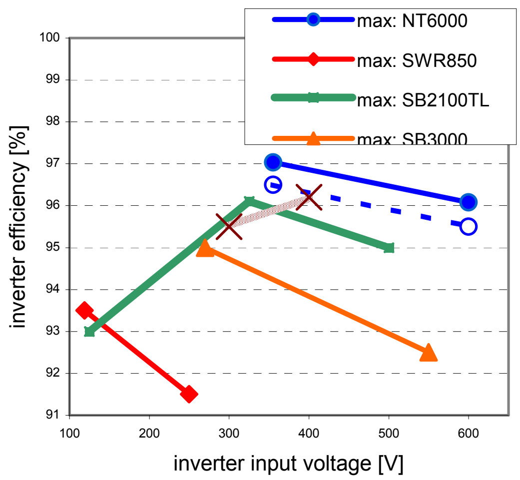

Figure 1: Inverter efficiencies versus inverter input voltage. The *maximum* efficiency values are marked with the prefix max in front of their product name, whilst the prefix euro stands for EURO-efficiencies. References for the data: [2] for the SMA products SWR850, SB2100TL and SB3000; [3] for the Sunways product NT6000; [4] for the Sputnik product SolarMax 6000E.

The Sunways NT6000 product, with maximum efficiency of 97%, exhibits the smallest change in efficiency of about 1%-point within the whole MPP voltage range. Other products like the SB2100TL allow a broader input voltage range, especially at lower input voltages. Thus at input voltages below 320V, an internal DC voltage up-converter is needed to feed the DC-AC converter, resulting in a decrease of efficiency of up to 3%-points (Fig. 1). For other inverters, similar efficiency decreases of around 3%-points were measured over voltage ranges from 200V to 80V by independent laboratories. [5] Two thirds of the inverters are marketed with EURO-efficiencies between 91% and 94% (Fig. 2). Together with these efficiencies, the manufactures usually give no data sheet information about its voltage dependence.

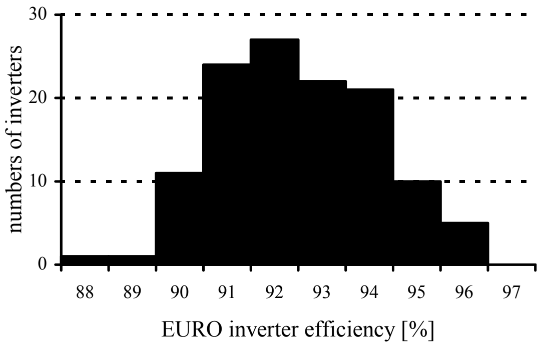

Figure 2: Distribution of EURO efficiency values of 122 inverters (below 10kW nominal power) available on the German Market 1994; average efficiency at 92.6% [6]

An inverter with 3% better efficiency will lead to 3% gain in energy production of the PV-system. Thus the overall investment costs can also be 3% higher. Representing a share of ca.15% of the whole PV system costs, such a more efficient inverter allows for 20% higher Euro per W price.

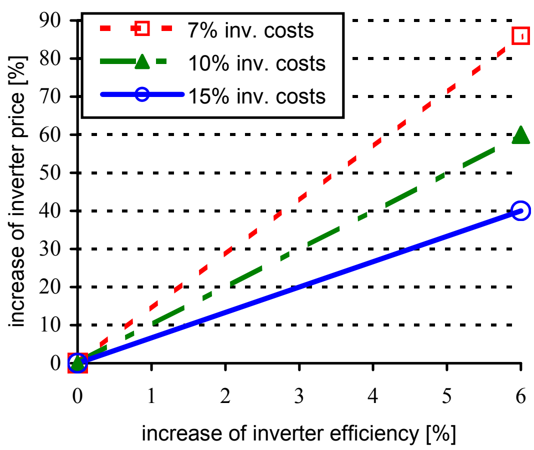

Figure 3: showing that more efficient inverters allow for higher specific Euro/Watt inverter prices at same overall PV system cost. The lines represent different values of inverter cost-share in the total PV system costs. A 7% inverter cost-share can be found in large scale PV plants (0.3 to 1MWp size) [7].

Taking the most efficient inverter with 96% efficiency and comparing it to a less efficient type of around 90% (see Fig. 2), the same simple estimate would allow for a 60% higher Euro per Watt price (see Fig. 3). Therefore, PV system plant designers have to take a close view on the in-field inverter efficiency for an overall cost-effective system solution. Still, most of the PV system design software does not take the voltage dependence of the inverter efficiency into account, because of the lack of inverter efficiency data.

The aim of the present work is to focus on the MPP voltage monitoring data of different PV-grid connected systems in Europe. A simple analysis method is introduced to categorise the PV systems with regard to their behaviour of the MPP voltage and the DC power.

2 METHOD OF ANALYSES

The first question is what typical voltage versus power profile is fed into the inverter DC input. The measured data will be filled into a matrix, where the value of the individual matrix element is given by the produced DC energy. This energy value is expressed in numbers of nominal hours, equal to the time the PV-system would have to run with nominal STC module power ('yield').[8] The x- an y-categories of the matrix are steps of normalised system DC voltage and DC power. The step width is typically chosen to be 3% of the nominal STC MPP voltage and 10% of STC module power. The covered voltage range is 76% to 103% of the MPP-STC-voltage. The power axis is simply run from 0% to 100% of STC power. Derived surface plots of such a matrix are shown in Fig. 4 to 9. They show energy frequency vs. voltage and DC power, and are called EVP plots for short.

The grid lines indicate the centre of the individual matrix elements e.g. 80% stands for all values, which are within the interval of 75% and 85%. Therefore, the 2.5% indicator at the lower end of the power axis stands for all power values, which are between 0% and 5% of STC power.

3 THE DATASET: ANALYSED PV PLANTS

The data analysed here is derived from analytical monitoring data, which was averaged to 10-minute mean values. Three roof systems (R1…3) and three façade systems (F1…3) are analysed, details are given in table I

Table Ia: General parameters of the PV-plants

Plant#	location	installation	orientation		field	Ref.
R1	Buchs, CH	roof ontop	30°	-14°	f3	[9]
R2	Baden, CH	roof ontop	45°	+15°		[10]
R3	Amersfoort, NL	roof ontop	20°	+7°	L3	[11]
F1	Winterthur,CH	façade	90°	-30°		[10]
F2	Steckborn, CH	façade	86°	-23°		[10]
F3	Amersfoort, NL	façade	90°	0°	n9	[11]

* first value of orientation of the module plane is given relative to horizontal plan, second value to south (negative value east direction)

Table Ib: Manufactures data of PV-roof top plants

Plant #	R1	R2	R3
Pdc STC power [kWp] *	4.5	2.5	2.1
Umpp of the string [V] **	96	104	102
Inverter voltage lower limit***	75%	67%	65%
Inverter voltage upper limit***	129%	134%	118%
Inverter voltage maximum***	153%	153%	
Solar cell type****	mono Si	mono Si	mult Si
Module manufactures	GPV	Arco	Shell
Module type	110	M55	RSM75
Cell voltage TC [%/K]		-0.44	-0.46
Cell power TC [%/K]		-0.37	-0.40
Inverter manufactures	Schmidh.	Solcon.	Master
Inverter type	P420	3000	2500
Pn_AC,inv/P_STC*****	111%	118%	117%

* STC power on the input of one inverter
** strings can be parallel on the inverter input
*** voltage values are given relative to the string Umpp
**** mono Si: mono crystalline silicon modules
mult Si multi crystalline silicon modules
***** ratio of inverter nominal versus module nominal power

Table Ic: Manufactures data of PV-facade plants

Plant #	F1	F2	F3
Pdc STC power [kWp] *	67.4	19.4	2.6
Umpp of the string [V] **	686	783	131.2
Inverter voltage lower limit***			67%
Inverter voltage upper limit***			122%
Inverter voltage max***			152%
Solar cell type****	mono Si	mono Si	mult Si
Module manufactures	Solution	Fabri	Pilk.
Module type	128	M65	Shell
Cell voltage TC [%/K]			-0.46
Cell power TC [%/K]	-0.35		-0.40
Inverter manufactures	Sputnik	Invertom.	Master
Inverter type	max50	Ecop.15	2500
Pn_AC,inv/P_STC*****	79%	77%	94%

* STC power on the input of one inverter
** strings can be parallel on the inverter input
*** voltage values are given relative to the string Umpp
**** mono Si: mono crystalline silicon modules
mult Si multi crystalline silicon modules
***** ratio of inverter nominal versus module nominal power

4 ANALYSES OF DC OPERATING AREA

4.1 PV Roof top systems

Fig. 4a shows the system R2 only for January, where most of the energy output of the PV array occurs in the interval between 50% and 70% of P_{STC}, at DC voltages from 94% to 100% of U_{mppSTC}. In July however, (see Fig. 4b) the range of its operative states is much more extended. Due to the higher module temperature, the voltage range for most of the energy production is then shifted to lower values, centred at 70% of STC power and 86% of STC voltage. In the plot for a whole year, the different seasonal operation states sum up to a typical 'footprint' for a rooftop PV-system. The sum of all energy values in the matrix elements is equal to the so-called array yield Y_a.

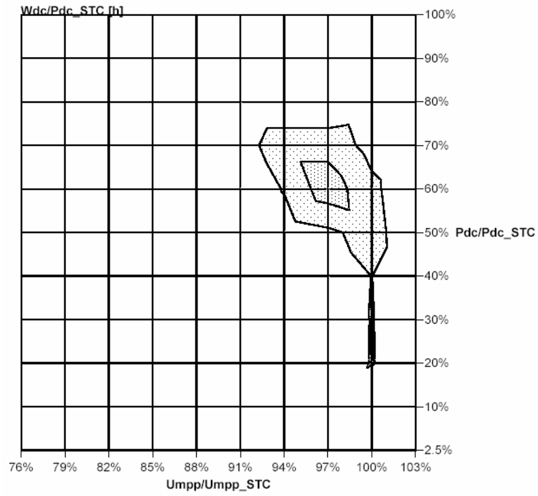

Figure 4a: EVP plot summing up to a monthly array yield Ya=42h; data from PV-roof plant R2 (see Tab. I, II) in Jan 1999; the energy step per contour line is 2 nominal hours per mesh. (Mesh size: 3% voltage and 10% power.)

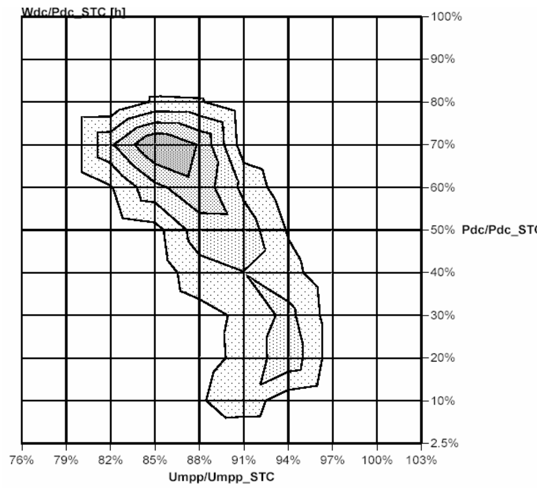

Figure 4b: EVP plot summing up to a monthly array yield of Ya=108h; data from PV-roof plant R2 in July 1999; (see Tab. I, II)

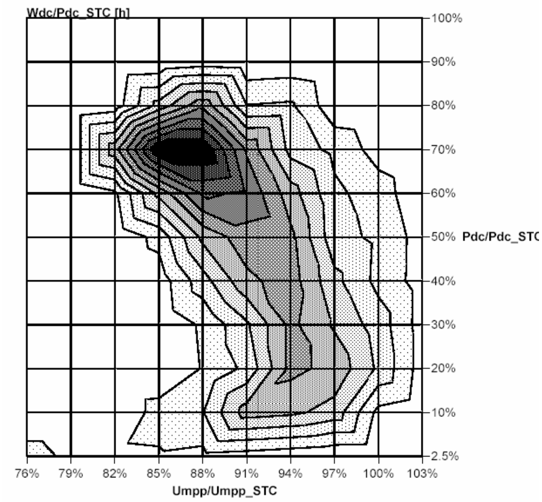

Figure4c: EVP plot summing up to a yearly array yield of Ya = 877h; data from PV-roof plant R2 in all 1999; yearly final yield Yf=827h; reference yield Yr=1164h; PR=71.0%; The energy step per contour line is 5 nominal hours per mesh.

The DC voltage power plot of two other rooftop PV-systems are shown in Fig. 5 and 6. A second maximum of the produced energy occurred in Fig. 5 at low power, which indicates that the inverter starts the MPP tracking at a certain voltage, here it was 97% of nominal STC MPP voltage. Fig. 6 shows a different ‘footprint’ of the energy frequency distribution, with the appearance of a straight line on the left side indicating that the inverter is limiting the voltage of the array at 85% of the STC MPP voltage. In this case, increasing the string voltage by adding another module into the string would have lifted that limitation, and would have increased system efficiency.

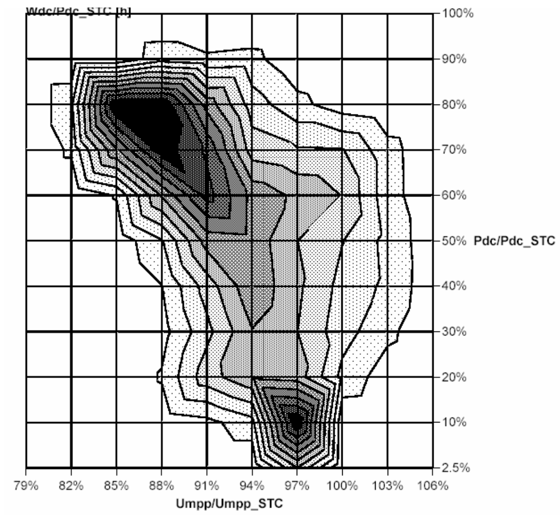

Figure 5: EVP plot summing up to a yearly array yield of Ya=966h; data from PV-roof plant R1 in all 1999; (PR=71.9% incl. all 4 fields of each 4.5kWp); the energy step per contour line is 5 nominal hours per mesh.

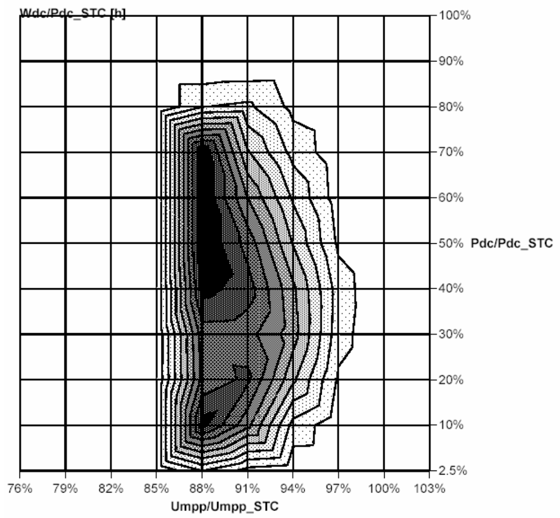

Figure 6: EVP plot summing up to a yearly array yield of Ya= 790h; data from PV-roof plant R3 in 2001; energy step per contour line is 5 nominal hours per mesh. (July data is missing)

4.2 PV Façades

For the façade applications, the plots of the energy frequency distribution (see fig. 7 to 9) have their most often occurring operation states at lower power values

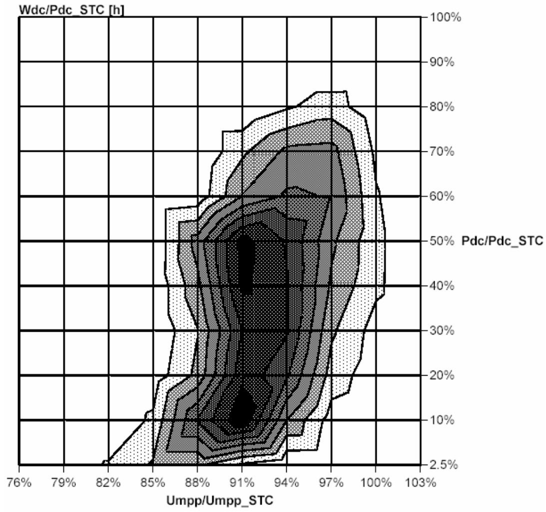

Figure 7: EVP Plot summing up to a yearly array yield of Ya= 618h for all 2001; data from plant F3; energy step per contour line 5 nominal hours per mesh.

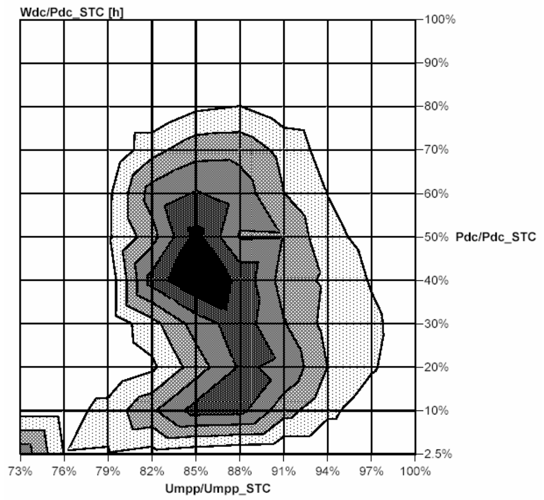

Figure 8: EVP plot of 1999 summing up a yearly array yield Ya=635h; data from plant F1; reference yield was Yr=796h; (final yield Yf=546h; PR=68.6% [10]) An energy step per contour line is 5 nominal hours per mesh.

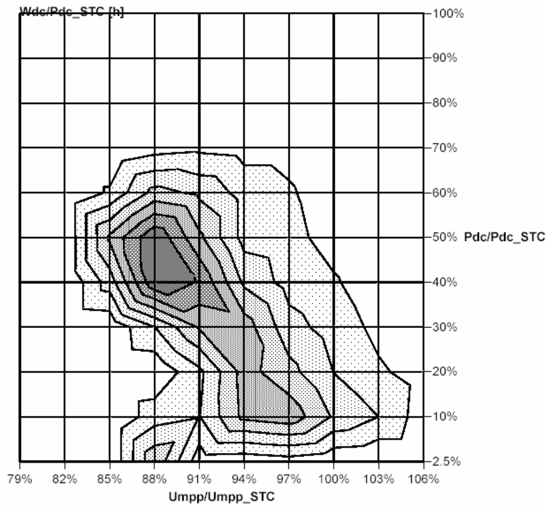

Figure 9: EVP plot of 1999 summing up a yearly array yield Ya=537h, data: plant F2; ref. yield Yr=748h; final yield Yf=546h; PR=60.3% [10]) A step per contour line is 5 nominal hours per mesh (3% voltage, 10% power).

than with the roof top applications, namely at only 40% to 50% of the STC power. Moreover, these plots suggest by their maximum footprint extension on the power axis to 80% or even only 70% of the STC power, that for façade applications, the choice of nominal inverter power could be some 10% lower.

4.3 Module temperature indications

Even without measuring exactly the module temperatures, it can be estimated from the described EVP plots. In Fig. 4c e.g., the lowest measured operational voltage at high DC power is found at 81% of the STC MPP voltage, due to the decrease of MPP voltage with temperature. Based on the temperature coefficient of the module, given by the manufacturer datasheet (-0.44%/K in table Ib), the maximum module temperature is estimated to be 65ºC. This estimation fits well with the in-field measured temperature values by a PT100 sensor as can be seen in Fig. 10. This simplified estimation works, however, only under the assumptions of neglecting wiring losses and a perfect MPP-tracking.

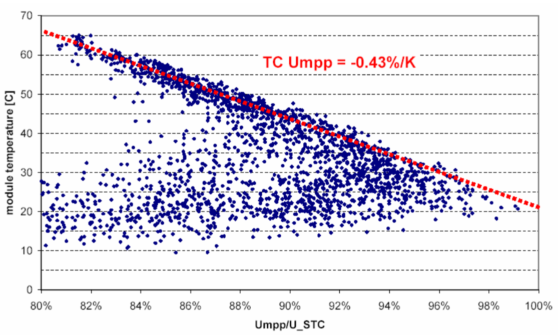

Figure 10: Module temperature versus MPP voltage in July 1999 of Plant R2 (see Table I) The slope of the upper limit, indicated by the dashed line, gives the measured temperature coefficient of the MPP voltage, here α= -0.43%/K.

5 REFINEMENT OF EURO INVERTER EFFICIENCY DEFINITION

Summing up the yields in each row of the EVP-plot, we receive the distribution over DC-power classes as shown in Fig. 11 and 12. Such power densities served as the basis for the definition of the EURO-inverter efficiency coefficients in 1990. [12] Given the fact, that different types of PV-systems (e.g., façades and rooftops) are featuring different DC power distributions, we can derive better fitting coefficients (or "weighting factors" k) for the definition of the inverter efficiency. In Fig. 11 it is noteworthy, that the in-field behaviour of e.g., PV-plants R1 and R2 are fitting quite well the Freiburg reference plant [13], but not so well the EURO-efficiency definition coefficients [12]. However, in the case of the facades (see Fig. 12), even the Freiburg distribution does not model well the real situation. Therefore, we suggest differentiating between facades and roofs when choosing the coefficients k for calculating the overall inverter efficiency, as is exemplified in table II. Theoretically, there exists an exact solution:

$$\eta(P,V)=k_1\cdot\eta_1(P_1,V_1)+ k_2\cdot\eta_2(P_2,V_2)+ \ldots + k_i\cdot\eta_i(P_i,V_i)$$

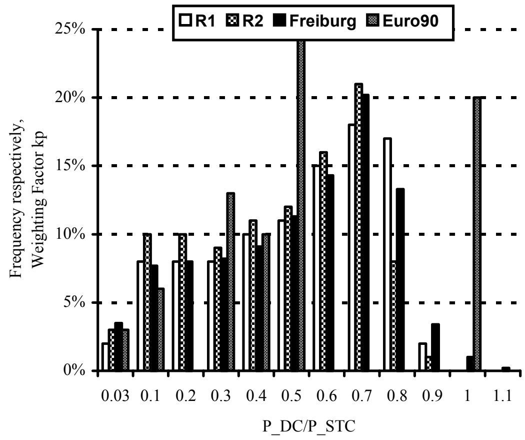

Figure 11: DC power classes distribution of PV-roof plants R1 (see Fig. 5) and R2 (see Fig. 4a-c). Also the coefficients for Freiburg, Germany are shown [13]. The EURO efficiency definition is shown (remark: value of 48% at 0.5 P_DC/P_STC are out of scale)

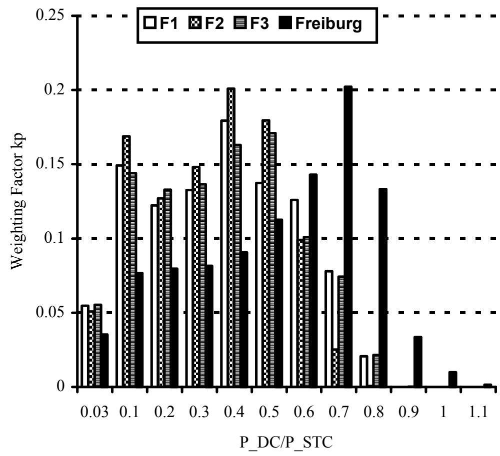

Figure 12: DC power classes distribution of PV-facades plants R1 (see Fig. 7) and R2 (see Fig. 4-6). Also the data from Freiburg, Germany (see legend) are shown [13].

Table II: Definition of a new "EURO-Realo" inverter efficiency coefficient k for rooftop and façade PV-systems; P_{DC} inverter input power; P_{STC} modules STC power; inverter DC voltage relative to module STC MPP voltage; weighted average of the voltage in both cases 91%.

	PV – rooftop		PV-facade	
P_{DC}/P_{STC}	V/V_{STC}	k	V/V_{STC}	k
1.0				
0.9	0.91	0.02		
0.8	0.89	0.13	0.93	0.01
0.7	0.90	0.20	0.92	0.06
0.6	0.92	0.15	0.91	0.11
0.5	0.94	0.12	0.90	0.16
0.4	0.95	0.10	0.90	0.18
0.3	0.95	0.09	0.92	0.14
0.2	0.95	0.09	0.93	0.13
0.1	0.94	0.08	0.91	0.15
0.025	0.90	0.03	0.84	0.06

in which every partial load P_i the real inverter efficiency η_i would depend on its DC-voltage V_i. We recognise, however, that this would become impractical. In order to keep it simple for the end-user, we suggest using all the inverter efficiencies η_i for the partial loads at a representative voltage of 91% of the array MPP STC voltage. These inverter efficiencies have to be given by the inverter manufacturer.

In designing the overall DC-voltage level of the array within the allowed inverter MPP voltage range, the inverter efficiency may be changed significantly (see Fig. 1). Therefore in practice, the above formula has to be applied for at least three DC-voltage levels (say, bottom, mid and top) of the allowed inverter MPP voltage range, using:

$$\eta(P,V_a)=k_1\cdot\eta_1(P_1,V_a)+ k_2\cdot\eta_2(P_2, V_a)+ \ldots + k_i\cdot\eta_i(P_i, V_a)$$

$$\eta(P,V_b)=k_1\cdot\eta_1(P_1,V_b)+ k_2\cdot\eta_2(P_2, V_b)+ \ldots + k_i\cdot\eta_i(P_i, V_b)$$

$$\eta(P,V_c)=k_1\cdot\eta_1(P_1,V_c)+ k_2\cdot\eta_2(P_2, V_c)+ \ldots + k_i\cdot\eta_i(P_i, V_c)$$

with V_a ,V_b and V_c being each 91% of three representative array's MPP STC voltages. Additional, if the array STC power is lower than the maximum allowable one, the inverter will work mainly in the lower efficient partly load condition and the averaged EURO efficiency may decrease (see rows additional two rows in table II.) Based on that extract of data the system designer chooses the optimum synthesis of high efficiency including the criterion of the maximum possible DC input power.

Table III: Example for a possible EURO-efficiency data-sheet of an inverter, relative to the STC voltage and power values of the array. (EURO–Realo efficiency values calculated using above set of formulas with k coefficient from table II respectively)

	$V_{a,STC}$ bottom	$V_{b,STC}$ mid	$V_{c,STC}$ top
1 P_{STC}		95%	93%
0.8 P_{STC}	91%	94%	92%
0.6 P_{STC}	90%	93%	92%

Ideally, the inverter efficiency at single DC-voltage and DC-power operation points, not averaged values like in table II, could be given to the PV-system designer as a surface plot of inverter efficiency, graphically similar to the EVP-plots given above. Thus the advanced system designer how wants to fully optimise inverter efficiency together with the maximum array power will apply the exactly formula of EURO-Realo efficiency together with table II or with better matched expected power density plots and coefficients for his particular location and system type.

Another promising approach to optimised PV system design will be to integrate the voltage dependent inverter efficiency characteristics into existing PV design software tools.

6 OUTLOOK

The graphical analysis method using the normalised DC-voltage and –power as plotting base will be easily extended to inverter efficiency, final yield, reference yield, and thus Performance Ratio (PR) [14]. All this approach is only a first step, to better optimise PV system design and behaviour using in-field data. Admittedly, other parameters affecting the inverter efficiency, like MPP-tracking quality, inverter temperature, and variations of the grid AC-voltage have to be considered in future.

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