PERFORMANCE ANALYSIS OF SHADED PV MODULE POWER ELECTRONIC SYSTEMS

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ABSTRACT: In the last decade decentralized Modul Level Power Electronics (MLPE) equipment has gained tremendous market share due to the potential to operate each Photovoltaic (PV) module in their optimum power point even in partial shading condition. The total losses of the group of decentralised DC/DC converter combined with the coupled centralised DC/AC inverter not always offer an advantage to the standard String Inverter System (SINV), like in the unshaded moments of high-power operation of a PV system at noon. The customer expects a clear answer about the quantified gain in annual power of a roof top system either operated by MLPE or SINV. Today, even the experienced planner is not able to elaborate these numbers in an economic efficient way. This is the case due to a lack of complex geometrical data of the shading obstacles and absence of software tools which are able to simulate the MLPE and SINV by calculating the shade of each solar cell in all PV modules together with an appropriate loss model of all used power electronic components. Up to know no standards exist to measure the set of MLPEs in the lab and the manufactures have not proposed detailed loss models up to now, whereas only max efficiency number of the MLPE are stated in their data sheets. This paper shows that detailed loss measurements performed in the lab, provided up to three percent higher losses of the MLPEs in the relevant operation area commonly used through a year of operation. It is recommended to use a very narrow range of numbers of MLPE in the string for high efficiency power conversion, due to the fact, that losses increase by 1.5% if the input/out voltage ratio of MLPE differ 5% from unity. A concept is presented to estimate the final so-called shading adaption efficiency which is based on the efficiency measurement of the MLPE in the indoor lab at a few operation points and by using weighting factors. Thus, the comparison of the shading adaption efficiency is given, either for different MLPEs or SINVs power electronic systems for a typical PV system with shading, relative to the same aggregated sum of maximum decentralised DC power at the PV Modules. Finally, one example of a tilt PV roof top system with partial shading of a chimney is given, were the standard SINV shows 1.2% percent higher losses estimated for a whole year of operation compared to a MLPE system. This value will change if the number of MLPE in the string is modified.

Keywords: inverter, optimizer, power electronic, MLPE, performance, measurement, shading losses, SINV

1 INTRODUCTION

Today, several millions of MLPE components are in operation worldwide, with still very high growth rates in the markets of PV systems on rooftops. Their unique ability to operate each single PV module in the individual absolute maximum power point, under different shading conditions of each module, is the most important door opener in the market. In literature, we are not able to find clear evidence to prove typical numbers of annual performance increase of such PV rooftop systems equipped with MLPE in the double-digit range relative to standard SINV. Surveys have been published on the topic of testing of typical row shading in outdoor conditions for the purpose of large-scale greenfield installations.[1,2] Outdoor comparison of smaller roof top PV systems is critical, because the expected yield difference is a low one-digit number, which is close to the outdoor measurement uncertainties. Additionally, having an equal diffuse light condition on both installations MLPE and SINV is challenging.

Back in 2007, the relevance of about 3% difference in annual inverter efficiency on the market was demonstrated due to the dependency on the chosen DC generator voltage of a single inverter. Due to the cost share of the inverter of about 10% of total system costs this was leveraged to about 30% of specific inverter prices.[5] As a follow up, the market player promoted development of standards [6] and today in the inverter data sheets we will find the difference of annual inverter efficiency at different DC voltage levels without any simulation needed for the planers/customers decision. Today each qualified PV planer must also quantify the benefit in yield of MLPE versus SINV, conventional serial connected PV modules to feed standard string inverter for each PV roof top system. Two types of MLPE are available on the market, the buck-boost converter, and the buck converter. The latter easily may be added to very few numbers of PV modules in a conventional SINV string, beneficial to get out most of the power. This works, even at the high string currents of the inverter, in some cases of partial shading as it is shown in the right part of Fig. 1 without activating the PV module by-pass diodes. That simple concept without any further control and communication within the DC string needed will fail for higher numbers of partial shaded modules, which may lead to a final DC string voltage which is below the limit of the input stage of the DC/AC inverter itself.

However, commercial PV planning tools using efficient annual yield simulation are facing two relevant challenges. First, the measurement of all the shading obstacles on the roof or nearby objects must be transferred into the 3-dimensonal model which takes typically several hours. Second, commercial PV planning tools apply annual yield simulation generally in a one-hour simulation time steps and are typically not able to analyse partial shading of all solar cells individually on each PV module and do not provide an appropriate loss model of the different types of MLPEs. Finally, on the planer side, this effort to perform this PV fine planning in manpower and equipment if e.g., drones are used, will exceed the value of the today's typical margin of a single-family solar roof installers.

Thus, other practical solutions will be developed to take the limited budget of the final customer for this MLPE versus SINV decision into account as it will be presented in this paper.

2 APPROACH - COMPARISON SHADING LOSSES

In this paper we are proposing to quantify the annual improvement in performance of different power electronic components on some representative typical shading cases on single family PV rooftop systems with defined obstacles. The applied method is based on indoor measurement of the power optimizers and string inverter using solar array simulator for the partial shading emulation of each PV module. In detail, the analyses need the entanglement of indoor efficiency measurement of all the MLPE components of the system that are individually powered by several DC power supplies emulating the shaded set of PV modules in a minute time interval. Thus, the parameter settings of this power supplies are calculated from ray simulations as shown in Fig. 1 with a high-precision surface resolution of the shadow on top of each solar cell of all modules. This leads to the individual PV module current voltage characteristics.[3]

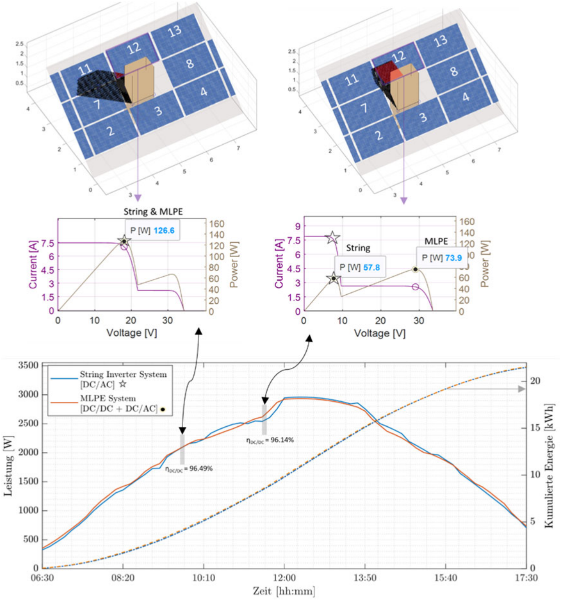

Figure 1: Two examples of the IV characteristics of shaded module no. 12 with a beneficial gain of MLPE on the right side relative to the operation point of the conv. SINV.

3 MEASUREMENT SETUP INDOOR LAB

In the subsequent laboratory performance measurement of the string inverter systems and MLPE systems, both systems are powered by the same current voltage characteristics settings of the power supplies, representing the individual shaded PV modules on a roof top installation. To test and develop these procedures, the ZHAW IEFE laboratory equipment consists of 10 Keysight E4360 SAS and several Newtons4th precision power analyzers of type PPA1500 and PPA5500. Notably, with this setup and the direct power measurement capability of the PPAs, the efficiency of the Device under Test (DUT) can generally be tested and measured with a GUM uncertainty of below ±0.5% (k=2) at standard operating conditions of most MLPE (50W<P<400W, 20V<U<100V, 1A<I<10A). Accordingly, this approach offers better reproducibility and lower uncertainties compared to outdoor measurements.

As an example, for such a laboratory analysis, the MLPE could be tested at different operation condition not only partial load but also ratio of DC input versus DC output voltage. The results offer much lower efficiency values around 97% than the given values of 99% in the manufactures data sheet, although operated in the permitted working range of the number of optimizers.[4] A MLPE loss model will be presented based on the input current and the voltage ratio of the DUT.

The most challenging part is the selection of typical shading cases and typical partial shaded PV roof top systems. In practice, these approaches are not independent of the type of PV power electronics chosen. Installers will typically increase the number of PV modules on the roof top by using MLPE but are not able to guarantee a certain yield number. Using string inverter during the design stage the number of PV modules is expected to be smaller, and thus the shading rate will be lower, in most of the cases. The millions of MLPE customers are facing this problem today. It is not very likely that these detailed analyses will be performed by the installer business because of the excessive measurement effort of all the relevant shading objects and correct orientation of each single PV module in the simulation. The process of selecting the relevant typical shading cases must consider the experience of several groups in different countries. Our concept of performance comparison is intended to be further developed within international collaborations like the IEA and others.

Finally, these collaborations should lead to typical shading cases, with a few selected solar array simulator DC settings of involved PV module, respectively. Thus, PV power electronic components either MLPE or string inverter will be tested on the same settings and the results as number of annual performance shading losses, could be compared by the customers. Nevertheless, some individual shading situation of a specific customer with the most matching typical cases will be analysed in this work and therefore, the customers will receive useful practical information.

4 RESULTS

First results from typical moderate shading conditions, such as that of a chimney on a single-family solar roof, show a shading performance gain of about two percent relative to the string inverter. But, for low shading conditions the annual performance of conventional high-efficient string inverter systems is higher, if the number of chosen MLPE DC/DC converter is not optimized for an input to output voltage ratio of 1. This mismatch configuration leads to MLPE efficiency values nearly 2% lower compared to the given efficiency number in the data sheet.

Our finding should be a starting point for comparing these kinds of results throughout independent research and test labs using the same methodology. This should lead to more reliable performance data of MLPE, as well as to a fairer and more understandable comparison to string inverter under partial shading condition.

4.1 MLPE single component characteristics

The losses in the power electronic converters arises in the individual components such as

- passive components in the inductors and capacitors by the ohmic losses
- semiconductor switches by ohmic and switching losses
- socket losses due to power supply of all other components of drives and control circuits

In Fig 2 the characteristics of the losses are shown as a function of input current of the DC/DC converter with socket losses of below 2 W for the buck mode. Fig. 3 shows that additionally the ratio of input to output voltage is needed to optimize the simple loss model as given in equation (1) where the coefficients are polynomials of U_{in}.

$$P_{loss} = c_0 + c_1 I + c_2 I^2 \qquad (1)$$

Generally, it is well known that a set of small power electronic components will lead to higher total losses compared to a single device e.g. DC/DC converter as it is implemented in a SINV. Improvements of MLPE efficiency with high bandgap semiconductors can reduce the gap.

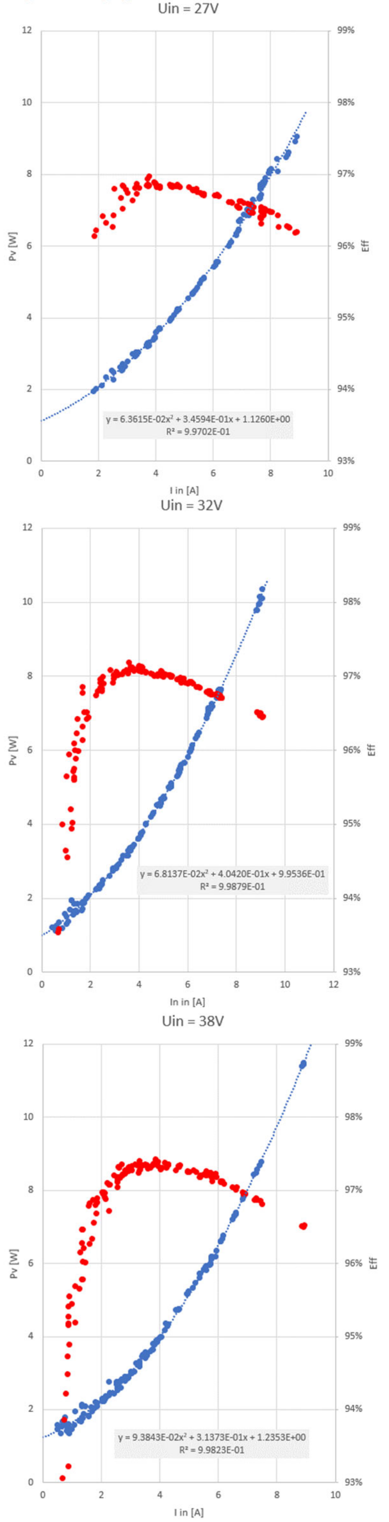

Figure 2: The measured losses at the ZHAW IEFE lab are strongly correlated to the input current of the DC/DC optimizers for the buck converter mode. [9]

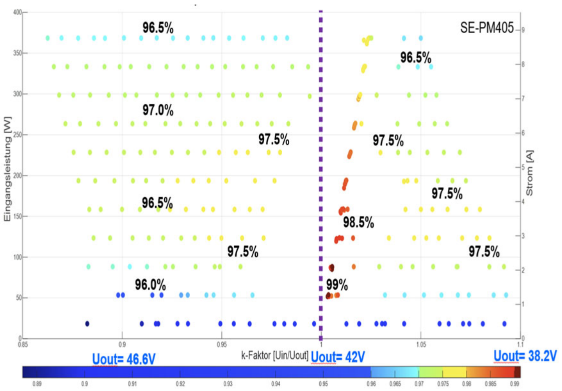

Figure 3: Measured efficiency of MLPE is between 96% and 97.5% at constant input voltage of 42V at an input power level between nominal 400W and 10% of nominal power and a DC/DC voltage ratio is about +/-10% around unity for most of the typical operating points (P405, Solar Edge data sheet efficiency 99%).[7]

5 QUANTIFY PV EFFICENCY AT SHADING

First results from typical moderate shading conditions, such as that of a chimney on a single-family solar roof, show a practical shading performance gain of MLPE of about two percent relative to the SINV systems. Here an approach is presented to quantify the electrical output of the system relative to highest possible DC input power, which is reached if all PV modules individually are operated at their MPP each.

5.1 SHADING ADAPTION EFFICIENCY

By using the equation (1) the annual DC/AC efficiency is calculated for PV power electronic system *a* consisting of a set of shading objects. (Fig. 3) The so-called shading adaption efficiency gives the ratio of output AC power versus the maximum available sum of aggregated DC power from each of the k PV modules in the string if all of them are operated in their individual absolute MPP. This hypothetical DC power is generated by 100% efficient DC/DC converters and will not be reach in real systems. In laboratory setups, as described in chapter 3, this $\eta_{shad,a}$ will be calculated by the measured P_{ac} power at a characteristically shading situation *a* which leads to a specific IV characteristic of each PV module. If the real MLPE is able to track the PV module in this absolute MPP this DC input power, according to equation (2), will be measured in the lab and summed up to the total DC input power of all *i* PV modules, used in the denominator of that equation. Testing SINV systems the measured DC input power on the plugs of the inverter could be smaller than the term $\sum_{i=0}^{k} P_{mod,i}$ for at situations, where the string DC current will not lead to operate each PV module in their absolute MPP. In that case the value of the denominator is modified.

$$\eta_{shad,a} = \frac{P_{ac}}{\sum_{i=0}^{k} P_{mod,i}} \qquad (2)$$

The annual average $\eta_{shad,a}$ will be found by applying the concept of weighting factors for a few typical shading moments in a year. Thus, the weighting factors $a_{shad,a,n}$ are multiplied by the measured efficiency $\eta_{shad,a,n}$ of MLPs or SINV inverter systems in the laboratory, at that limited set of operating points *n*, at a characteristically shading situation *a* as given in equation (3).

$$\eta_{shad,a} = \sum_{n=1}^{N} a_{shad,a,n} \cdot \eta_{shad,a,n} \tag{3}$$

The binning of this characteristically shading situations a will be found at several moments n in the annual mapping as it is shown in Fig. 4 and illustrated by the numbers therein. The weighting factors are representing the energy amount during the year at similar shading adaption efficiencies which are different for MLPE and SINV.

Here the mapping shows the difference of efficiency of MLPE versus SINV relative to the annual energy DC output of MLPE. The value of the individual weighting factors $a_{shad,a,1}$ and $a_{shad,a,2}$ to $a_{shad,a,n}$ are found by the aggregation over the whole year at this typical shading situation a including several PV modules and MLPEs or SINV in the plant. A similar approach is found by the established calculation of the average string inverter efficiency according to the standards, based on the irradiance binning at different locations, known as the EUR efficiency or California inverter efficiency.[6]

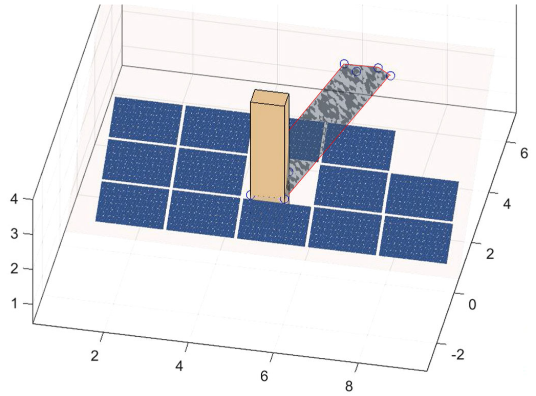

Figure 4: Ray trace simulation of direct and diffuse irradiation on each part of a single solar cell on all PV modules in the south oriented roof top PV systems a consisting of chimneys shading obstacle. [4, 7]

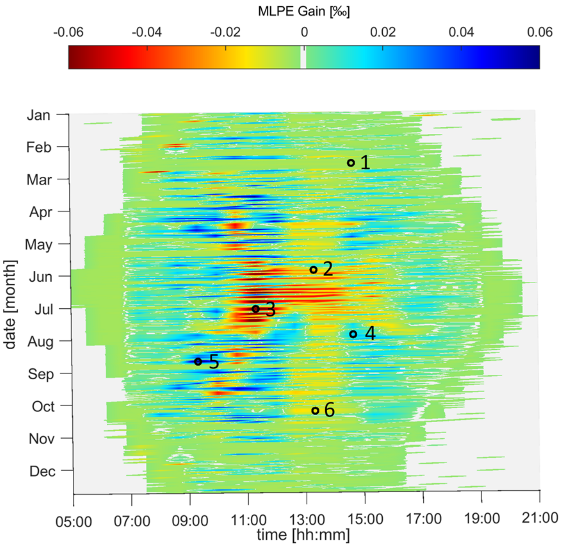

Figure 5: Mapping of power gain of MLPE versus SINV DC/AC Systems for hours and das over a year for the roof top PV systems system a consisting of the shading object chimneys as shown in Fig. 3. Each marked point 1 to 6 could by one of n characteristic test set ups for each module for the efficiency test in the indoor lab – equation (2). [4, 7]

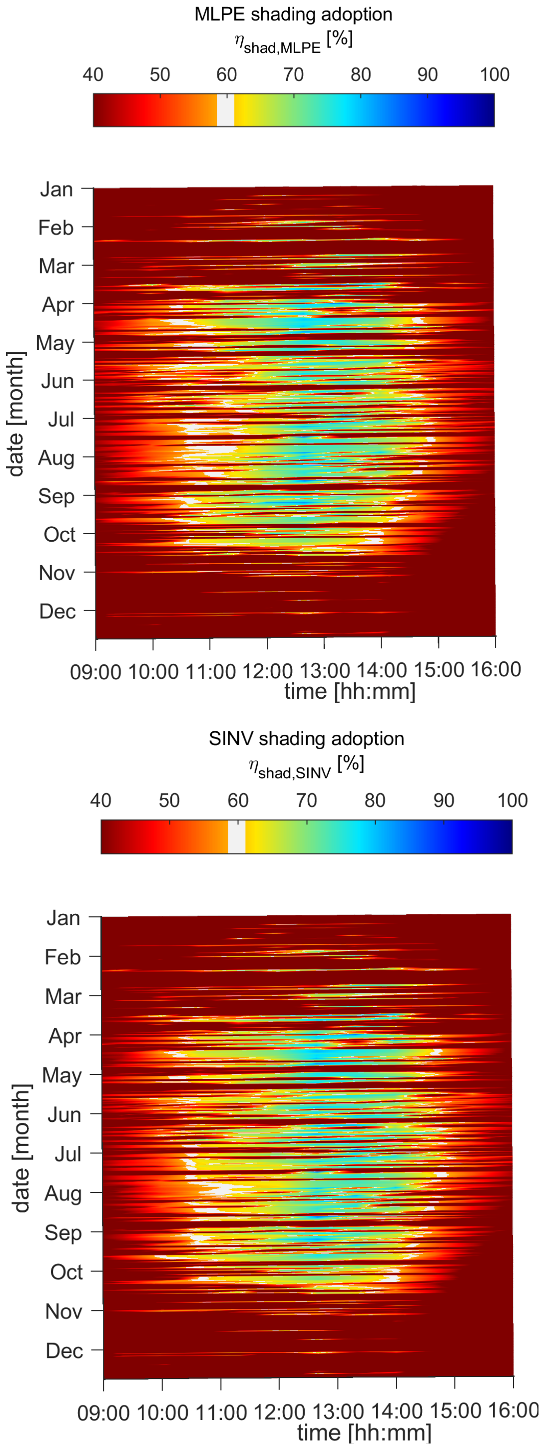

Figure 6: Mapping of the annual shading adaption efficiency, relative to the nominal PV generator power for the MLPE and below for the string inverter system SINV for the shading system given in Fig. 3 using equation (1).

Each PV system consists of number i of PV modules. The concept is looking forward using several limited measurement moments in the lab e.g. 10 to by performed with the power electronic equipment to by applied by the different weighting factors for several other shading types a.

Other laboratories are invited to perform their test on other MLPE equipment or extend the concept to other shading systems. Table I should be extended in sizes of the PV systems, like different number of PV module on single-family houses and other shading objects like, dormer, other chimney, venting pipes, trees, neighbouring buildings.

Table I: Annual average shading adaption efficiency for a few typical shading objects *a* and commercial MLPE or SINV products used in the single family roof top system according to equation (2) and (3) with the defined weighting factors based on the laboratory tests of the commercial equipment. The used string inverter for II shows an average euro efficiency of 97.5%.

Systems of PV and shading cases	Shading objects *a*	I MLPE	II SINV
Single roof tilt chimney	1	96.6%	95.8%
Single roof tilt dormer	2	x	x
Single roof tilt tree	3	x	x
Flat roof Ventilation pipe	4	x	x

6 CONCLUSIONS AND OUTLOOK

Indoor laboratory measurements of the efficiency of a commercial DC/DC MLPE shows more than 1.5% higher losses than the data sheet value if the voltage ratio input to output differ more than 5% from unity. This leads to the recommendation to the PV planers that only a certain number of optimizers, plus minus one will lead to low losses compared to SINV systems in the unshaded case e.g. at noon.

First results from typical moderate shading conditions, such as that of a chimney on a single-family solar roof, show a shading performance gain of MLPE of 1.2% to the SINV. But, for low shading conditions the annual performance of conventional high-efficient string inverter systems is higher, if the number of chosen MLPE DC/DC converter is not optimized for an input to output voltage ratio of close to unity. This mismatch configuration leads to MLPE efficiency values up to 3% lower compared to the given efficiency number in the data sheet.

This research work will by continued for the next two years at ZHAW IEFE within the national research project EFFPVSHAD and within the follow up for the new IEA PVPS Task 13 international collaboration on MLPE activities is requested. [9, 4] Our findings could be a starting point for a systematic comparison of the performance of MLPE versus SINV to engage other independent research and test labs to compare results by similar methodology. This should lead to more reliable performance data of MLPE versus SINV on their manufactures data sheets, as well as to a fairer and more understandable and thus, economical comparison of PV output under partial shading condition.

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