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OUTDOOR CHARACTERIZATION OF THREE PV ARCHITECTURES UNDER CLEAR AND SHADED CONDITIONS

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ABSTRACT: Building Integrated and Building Applied Photovoltaic (BIPV, BAPV) systems often suffer from low performance due to partial shading. New system architectures have been proposed to optimize the energy yield. The common approach of these new architectures is to track the Maximum Power Point (MPP) of every solar module individually. Three independent PV systems were installed in Eindhoven, a reference string inverter system, a power optimizer (PO) system and a micro inverter system. We designed a sophisticated monitoring system that allows for a detailed comparison of the three PV systems. We calculated system and component efficiencies and found a good agreement with data sheets provided by the manufacturers. Additionally, we analyzed the performance ratio for DC and AC of the systems for different weather types based on the clearness index. A pole shading covering 1 to 2% of the total system surface has been used to evaluate system performance under a specific type of partial shading. Module Level Power Electronics (MLPE) are capable of increasing the Performance Ratio (PR) up to 35% under certain partial shading conditions. However, the string inverter system outperformed MLPE under unshaded operation conditions.
Keywords: MLPE, partial shading, BIPV, BAPV, outdoor testing, micro-inverters, power optimizers

1 INTRODUCTION

Penetration of solar PV systems in the Netherlands and worldwide has remarkably increased the past years and it is forecasted to keep growing in the future. Particularly the application of BIPV and BAPV systems are projected to thrive in the following years as a result of increasing electricity prices and decreasing PV component costs and zero energy building regulations.

Residential and small commercial PV systems are typically installed in an urban environment. Roofs and terraces are often affected by shade coming from the close proximity of buildings, poles, antennas, dormers etc. Shading operation of traditional PV systems has been studied by various researchers in the past [1]-[2] but the quantitative impact of shade in different PV architectures remain unclear.

Several approaches have been proposed to mitigate these types of heterogeneous circumstances. A common feature of these approaches is to bring maximum power tracking at the module level. These are called MLPE devices and can be distinguished into two main categories: micro-inverters and power optimizers. The power optimizer category consist of several DC/DC converter topologies such as: buck, boost and buck-boost converters. On the other hand, traditional central and string inverters are evolving and offering high performance, hybrid MPPT techniques, detailed monitoring capabilities etc.

Figure 1: Residential PV system shaded by a lighting mast

Traditionally, solar panels are connected in series forming strings. The strings are then connected in parallel forming arrays. The total DC power of the array is then fed to a power electronic device (inverter). Usually, the inverter is connected to the grid and is equipped with a maximum power point tracking algorithm in order to extract the maximum available power from the solar panels. However, in order to maximize the energy fed to the grid, other system topologies have been introduced in the past years such as string inverters, micro-inverters and power optimizers [3]. The initial purpose of introducing different system topologies was to minimize the so called “mismatch losses”.

Electrical mismatch losses are generally caused by manufacturing tolerance, heterogeneous irradiation conditions, panel degradation and thermal mismatch of the solar panels. Manufacturing tolerance has been improved significantly in the past years. Due to the vigorous testing during manufacturing the quality of the solar panels has been improved significantly.

Solar panels are connected in series and thus sharing the same current in a string. This topology is prone to power losses if the solar cells are not operating under the same conditions thereby reducing the current of the whole string. Shaded solar cells become reverse biased because of the series connection and thus act as a load consuming the power that is generated by the unshaded cells. Two negative effects occur from partially shaded operation of a PV system: power loss and increased temperature on the shaded cell (hot-spot). By-pass diodes have been applied in solar panels to prevent power consumption from shaded cells and to prevent hot-spots by by-passing the shaded substrings of the solar panel. Most of the solar panels include one by-pass diode connected anti parallel per 16-24 cells [4]. Even shading 50% of a typical crystalline solar cell in a module can activate the by-pass diode that protects the shaded cell and the assigned group of cells resulting in a reduction of 1/3 of the module power [5].

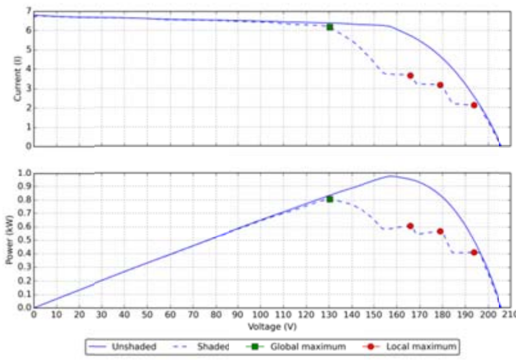

Figure 2: Measured IV and PV curve of an unshaded and partially shaded PV system with a pole. In this case three local maxima and a global maximum peak can be observed. Traditional MPPT techniques have difficulties tracking the dynamics of partially shaded series connected PV modules.

The distinctive I-V and P-V pattern of a partially shaded and an unshaded string of PV modules can be seen in Figure 2. In this case there are four local maxima, but only one is the true global maximum. Since the inverter can operate at any given time with only one MPP, it has to decide which one of these four maxima will operate. Usually solar inverters are using the “Hill climbing method” or Pertrub and Observe (P&O) algorithm because of its simplicity and low cost implementation. However, the tracking efficiency of the algorithm is slow under rapidly changing irradiance and especially when multiple power maxima are present [6].

The concept of the micro inverter or AC module has been introduced in the past years and many pilot projects have been realized with satisfying results. Distributed MPPT strategy has been proposed by many authors to be beneficial in terms of increased yield where high mismatch losses are present. Additionally such distributed architectures offer detailed monitoring capabilities per module and increased safety due to the lack of high DC voltages. Maintenance disturbances can also be minimized. At the moment there are at least 15 companies active in the micro inverter market [7].

Power optimizers (DC/DC converters) have been proposed by several authors in order to mitigate partial shading problems and they come in three different topologies: buck, boost and buck boost. In this paper only boost DC/DC converters will be discussed. Power optimizers are installed per solar panel. The output of the power optimizers is then connected in parallel to a DC bus with 380V. A centralized inverter is used without MPPT since this operation is now performed on module level. In this way, the inverter can be simplified and always operated at a fixed voltage regardless of ambient temperatures and bypassed substrings.

Traditional string and central inverters for PV systems have reached maturity. Inverter manufacturers launch new products with high efficiency and innovative topologies. Transformer-less topologies have already been commercialized with success by major inverter players [8]. In addition, new MPPT algorithms are used in an effort to optimize performance. Hybrid P&O MPPT strategies including IV scanning in short intervals have been implemented and commercialized by various inverter manufacturers such as SMA (Optitrac) and Mastervolt (Intellishade). In this way the global MPP can be easily determined in a string of panels and thus optimize the performance under partially shaded conditions.

2 EXPERIMENTAL SET-UP AND METHODOLOGY

2.1 System set-up

The aim of our field test is to compare three different PV system architectures under the same operation conditions. For this purpose PV systems with 30 degrees inclination angle and 165 degrees azimuth (SE) have been built. The field-test site is situated 40 meters above sea level at 51,4 degrees northern latitude and 5,48 degrees eastern longitude. Every system consists of the same installed capacity (1.59kWp) with solar panels of the same power class and manufacturer installed at two successive rows per system as seen in the Figure 3.

For the field test the Yingli Panda 265Wp modules have been selected for their high efficiency and absense of Light Induced Degradation. The panels consist of 60 series connected mono-crystalline n-type cells. Every sub-module of 20 cells is assigned to one by-pass diode connected anti-parallel. Flash data of the solar panels was available by the manufacturer, however, the modules were additionally flashed by a PASAN IIIB solar simulator. On average the maximum power was 98,4% of the provided Pmax by the manufacturer. Note that the solar panels have been distributed randomly throughout the field test.

The string inverter system has been fitted with a commercially active inverter from Mastervolt (Soladin 1500 Web). The string inverter has a nominal output of 1500W and is fitted with a high frequency transformer. The micro inverter system consists of 6 micro inverter prototypes from Heliox rated at 250W AC while the power optimizer system consists of 6 power optimizers with nominal power of 310W and an inverter of 2,4kW with fixed input at 380V. The power optimizer system including the inverter is supplied by Femtogrid Energy Solutions.

Figure 3 : Impression of the field test. Every PV system consists of two successive rows of three solar panels. On the right side is the micro inverter system while in the middle is the reference string inverter system. On the far left is the power optimizer system. The measuring equipment and inverters are located in the cabinets behind the panels.

The front rows of the PV systems are shaded during winter months by a wall situated at the south side of the plant while there is also partial shadowing from row to row. Additionally neighboring buildings are situated on the east and west side of the PV systems further reducing the horizon view and thus the available irradiation. Since the goal of the field test is to make a direct and absolute comparison of the three PV systems, a shading analysis was done to determine which parts of the day there is uncontrolled shade.

For this purpose we used the Suneye from Solmetric. By means of a fisheye camera with integrated compass and GPS, one can determine the exact time and date that a specific point of the PV system is shaded. Several skyline pictures have been taken from all the module sub strings of the systems and superimposed to the sun path in order to determine which part of the PV generator is shaded and when this happens. In this way a "clean measurement time" has been determined where shadeless operation takes place.

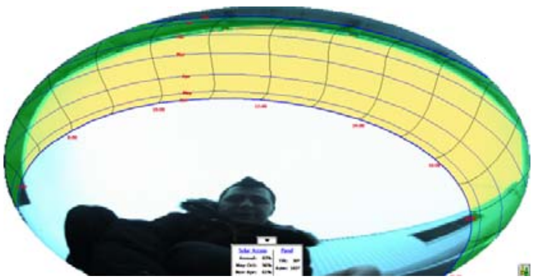

Figure 4 : Skyline picture shoot from the micro inverter system facing south-east. Clearly visible is the wall on the south side of the solar panels highlighted with green colour. Additionally the east and west neighboring building can be seen. An average solar access of 83% has been calculated for the specific location.

DC and AC electrical parameters are monitored with high accuracy power analyzers from Yokogawa(WT-1800). In total 7 power analyzers with 6 inputs per device have been used. Through a wired network the power analyzers are synchronized providing data capture simultaneously for all channels. Logging interval is per second for all inputs to assure detection of even the fastest transient phenomena. Thermocouples are used to measure module and ambient temperature while 2 ISO secondary standard pyranometers measure in plane irradiance. Logging of the temperatures and irradiance is via a MW100 data logger that is also synchronized with the power analyzers. All measuring equipment is housed in weather proof cabinets including the devices under test. All in all more than 130 parameters with 1 second resolution are monitored in order to evaluate system performance.

2.2 Analysis software and calculation routines

We developed a software package in Python to automatically perform calculations reducing manual errors. Daily 'control graphs' are generated and analysed for quick inspection of the ongoing measurements. Intermediate performance steps for the three systems are calculated according to figure 5.

The general equation for the performance ratio is given in equation 1 [9].

$$Performance\ Ratio = \frac{\sum_{t_0}^{t_{end}} power}{P_{STC}} \cdot \frac{G_{STC}}{\sum_{t_0}^{t_{end}} G_{POA}} \quad (1)$$

Where the summation of power over a given time period is substituted for DC power, PO power or AC power to calculate respectively the DC ratio, PO ratio or PR. P_{STC} and G_{STC} are the rated system power and the irradiance under STC conditions. G_{POA} is the measured irradiance in plane of array.

The European and CEC inverter efficiencies are calculated according to equations 2 and 3

$$\eta\ Euro = 0.03 \cdot \eta 5 + 0.06 \cdot \eta 10 + 0.13 \cdot \eta 20 + 0.1 \cdot \eta 30 + 0.48 \cdot \eta 50 + 0.2 \cdot \eta 100 \quad (2)$$

$$\eta\ CEC = 0.04 \cdot \eta 10 + 0.05 \cdot \eta 20 + 0.12 \cdot \eta 30 + 0.21 \cdot \eta 50 + 0.53 \cdot \eta 75 + 0.05 \cdot \eta 100 \quad (3)$$

Where $\eta\, x$ is the inverter efficiency at x % of the maximum power.

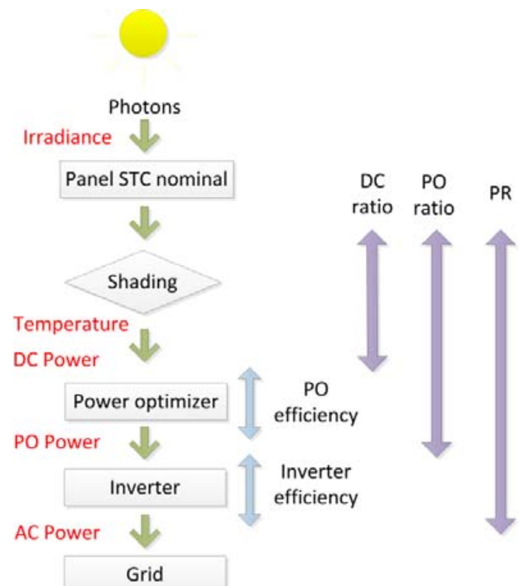

Figure 5. Schematic rep of the path from sunlight into grid injected AC power, showing the monitored parameters in red and the definition of the DC ratio, PO ratio and PR on the right hand side by blue and purple arrows

3 CHARACTERIZATION UNDER OPERATING CONDITIONS

3.1 String inverter

The string inverter chosen for the task is a new generation low power inverter fitted with a HF transformer. It includes a shadow function which can be switched on from the internal settings of the device. Note that the inverter is supplied with the shadow function deactivated by default. Experiments with a pole shadow have been performed both with the shadow function activated and deactivated.

It can be seen in figure 6 that when the inverter is operating with the shadow function disabled and there is partial shading present, it chooses a local maximum from the lumpy PV curve of the series connected modules. When the shadow function is activated, the inverter is scanning the MPPT every 15 minutes and can correctly track the global maximum and hence improve the extraction of the available power.

Depending on the system size and the shading conditions and due to the operation of the shadow mode, the inverter can easily fall below the MPPT voltage range specified by the manufacturer occurring additional energy harvesting losses. The string inverter can be shadow tolerant but the amount of shading coverage of the modules must be considered in advance.

The peak efficiency of the inverter is at 25% of the power output and ideal for central European climate with a lot of overcast days throughout the year.

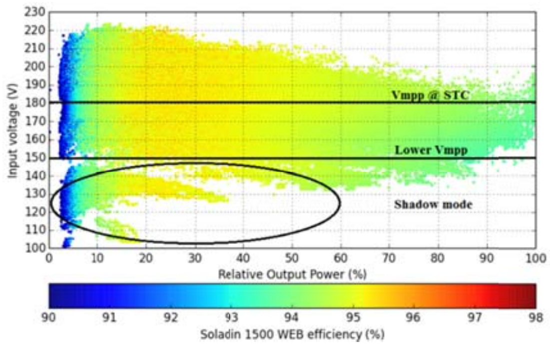

Figure 6: Relation of input voltage with efficiency and power output during 5 months of operation under clear and partially shaded conditions. Note that the input voltage is reduced significantly during shade mode operation under partially shaded conditions.

3.2 Micro inverter system

The system consists of six micro inverter prototypes supplied by Heliox. The micros are rated at 250W with resonant and soft switching power conversion to achieve high efficiency.

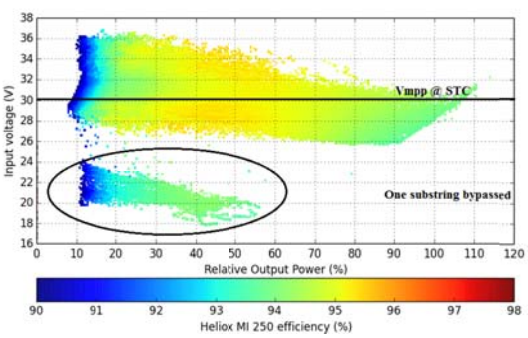

Figure 7:. Relation of input voltage with efficiency and power output during 5 months of operation under clear and partially shaded conditions. The micro inverter includes a hybrid P&O MPPT algorithm which can track global maximum by performing regularly IV scans.

The micro inverter has a wide range of MPPT voltage (16-48V) and in combination with frequent IV scans can track the global maximum point under certain conditions. Only when the shadow covering the solar module is beyond 1 substring the micro inverter MPP voltage (Vmpp) is out of range and has to operate at high voltage and low current. It can be seen in figure 7 that there is a voltage dependency in the efficiency while peak efficiency is achieved at around 40% of power.

3.3 Power optimizer system

The power optimizer system performs MPPT on a module level and utilizes a central inverter with fixed voltage input. The benefit of the power optimizer system is the wide voltage operation and the hybrid P&O MPPT.

The boost converter used at the Femtogrid system can operate from as low as 8V with its maximum MPPT efficiency. As it can be seen in figure 8 the PO310 can operate even under extreme shading conditions covering 2/3 of a typical 60 cell crystalline solar module. However, the efficiency of the boost converter drops from 98% to 95% at low voltages.

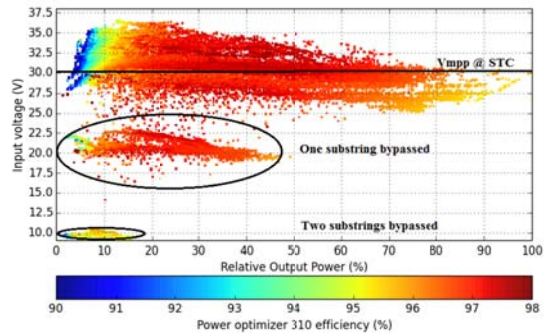

Figure 8: Relation of input voltage with efficiency and power output during 5 months of operation under clear and partially shaded conditions. The PO310 can operate even with one illuminated substring and thus track the global maximum even at extreme shading conditions.

3.4 Efficiency during operation

In table I the calculated efficiencies of the three system components can be seen. Equations 2 and 3 have been used to calculate the η. Note that the Femtogrid system has two conversion stages which are not shown in figure 8 and table I. For comparisson of the total system efficiency the inverter efficiency of the power optimizer system has to be taken into account.

The measured parameters are very well correlated with the data sheet values provided by the manufacturers of all three systems.

Table I: Calculated and measured parameters from the outdoor field test

Device	Voltage range	Max power measured	$\eta_{Euro measured}$	$\eta_{CEC measured}$	η_{Max}	η Max @ power%	$\eta_{Euro\ datasheet}$	$\eta_{Max\ datasheet}$
Femtogrid PO 310	30 ± 0.2	293 DC	96.56	96.67	97.5	39.93	97	>97
Soladin 1500 WEB	180 ± 0.2	1568 AC	94.74	94.65	95.4	25.38	95	95.6
Heliox SMI250	30 ± 0.2	270 AC	94.33	94.65	95.2	40.37	94.5	95.5

4 PERFORMANCE RATIO ANALYSIS DURING CLEAR AND PARTIALLY SHADED CONDITIONS

Based on equation 1, the PR of the three systems is calculated daily for the clean measurement time. Moreover, the clearness index (Kt) is calculated daily based on global irradiance measurements in close proximity of the field test. The clearness index is defined as the ratio of the measured horizontal global irradiance on earth and the extraterrestrial irradiance available outside the atmosphere. Weather classification can be done based on the clearness index as follows: Kt<0.2 overcast, Kt=0.2-0.6 partly cloudy and Kt>0.6 clear [10].

A pole has been positioned on the south side of the front row of each system blocking direct irradiance. This results in shading of cells in different substrings of modules. The poles have been positioned at the exact same height, length and width from the setups to provide equal shading among the three systems. The pole dimensions are:

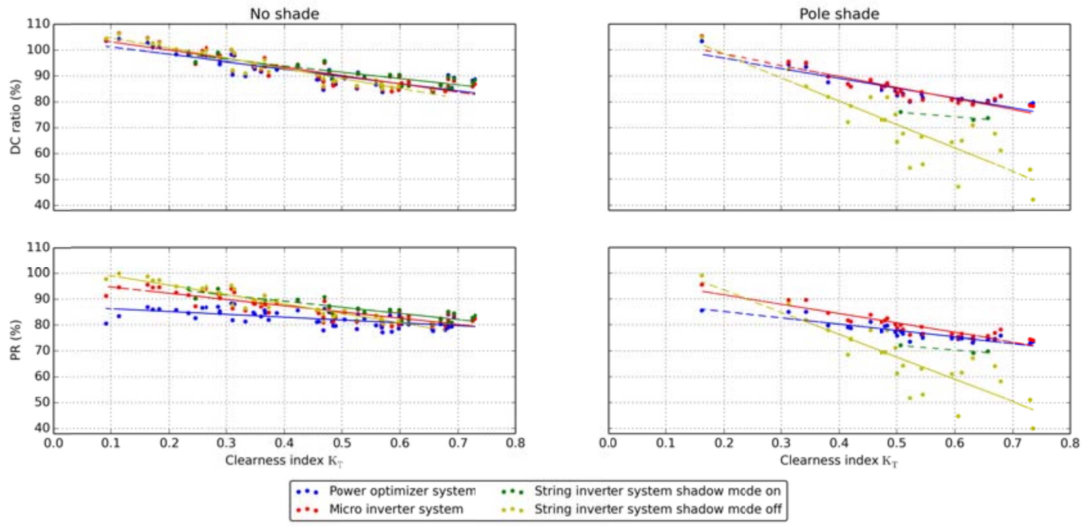

Figure 9: Daily calculated PR and DC ratio versus average clearness index of the day for unshaded and partially shaded operation of the three systems with a pole shading 1-2% of the total PV system surface. Data presented at the graph are calculated during spring months.

146cm height, 12.5cm diameter and have been positioned 69cm away from the middle solar module of the front row.

On days with overcast weather where the largest part of the light consists of diffuse irradiance, the pole has no effect on the PR of the three systems. PRs of more than 100% can be seen due to lower temperatures from STC conditions. However, when Kt increases, the benefit of distributed MPP tracking under partial shading can be seen in figure 9.

With the shadow mode of the string inverter deactivated, there is an absolute 35% improvement under certain shading conditions on the PR (Kt=0,74) for the MLPE. The string inverter MPP tracker follows a local maximum point of the IV curve, while the micro inverters and power optimizers operate the unshaded parts of the system at MPP and mismatch losses are restricted to the affected module. However, when the shadow mode of the string inverter is activated and the MPP tracker of the inverter tracks the global maximum the difference between the string inverter and MLPE on absolute PR is almost 5% in favor of the MLPE. Thus, it is recommended to activate the shadow function (if any) of the string inverter when partial shading is expected. The fine tuning and optimization of the MPP tracker scan intervals during shadow mode needs to be further investigated.

During shadeless operation the energy gain of MLPE solutions seems limited and in some cases negative. The multiple conversion stages and the oversized inverter in the case of the power optimizer system and the low efficiency under low power input of the micro inverter yield additional losses in power production. These loses can be better seen with low Kt values (0,1-0,3) resulting in significantly lower PRs than the string inverter system.

5 CONCLUSIONS

Module Level Power Electronics have entered the market the past years and are considered to be one of the most dynamic sectors of the PV industry. On the other hand, the mature inverter industry shows continuous improvement on performance and cost effectiveness.

In this work, string and distributed MPP architectures have been compared and evaluated under unshaded and partially shaded conditions which are often found in the urban built environment. Results show that the outdoor measured efficiencies of the devices for nominal operation are in good agreement with the data sheets provided by the manufacturers. During operation under shaded conditions the efficiency of the MLPE devices is reduced by 1 to 2% depending on the voltage input . On the system level, traditional architectures seem to perform better in unshaded conditions whereas MLPE solutions offer up to 35% more yield at certain partially shaded conditions. With advanced MPPT techniques string inverters reduce the MLPE advantage to 5%. For this is suggested to activate the shadow function of the string inverter if applicable. Depending on the seasonal changes of the shade extension at the installation location, MLPE can be an interesting solution to consider. In this paper the investigation was limited to a single string of modules. In case of parallel strings assigned to the same MPPT the advantage of MLPE solutions maybe larger.

Further investigation is needed to assess additional performance criteria in relation with investment costs. The next step is to perform shading experiments with different shade types throughout a full year.

6 ACKNOWLEDGEMENT

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7 REFERENCES

[1] Shahab Poshtkouhi, Vishal Palaniappan, Miad Fard, Oliver Trescases 'A general approach for quantifying the benefit of distributed power electronics for fine grained mppt in photovoltaic applications using 3-D modelling' in Proc IEEE on Power Electronics vol.27, No 11 page 4656-4666

[2] Woyte A. , Nijs J. , Belmans R. 'Partial shadowing of photovoltaic arrays with different system configurations: literature review and field test results' Solar Energy 74 (2003) p. 217-233

[3] Koirala B.P. , Sahan B. , Henze N. 'Study on MPP mismatch losses in photovoltaic applications' Proc. of 24th European Photovoltaic Solar Energy Conference 2009

[4] Silvestre S., Boronat A., Chouder A., "Study of by-pass diodes configurations on PV modules" Applied Energy 2009

[5] Deline C. 'Partially shaded operation of a Grid Tied PV System'34th IEEE Photovoltaic specialists conference, 2009

[6] Sanchis P., Lopez J., Ursua A., Gubia E., Marroyo L., 'On the testing, characterization and evaluation of PV inverters and dynamic Mppt performance under real varying operation conditions' Progress in Photovoltaics, Prog. Photovolt. Res. Appl. 2007; 15:541–556

[7] Sinapis K., Folkerts W., "MLPM Benchmark report 2013", Solar Energy Application Centre, available online http://www.seac.cc/fileadmin/seac/user/doc/SEAC_External_Benchmark_Report_MLPM_2013.pdf

[8] Poliseno M.C. , Mastromauro R.A. , Liserre M. 'A performance comparison of high efficiency transformer-less PV inverters' Proc 27th European Solar Energy Conference 2012

[9] Reich N.L., Muller B., Armbruster A., Kiefer ., van Sark W.G.J.H.M., Reise C. 'PERFORMANCE RATIO REVISITED:ARE PR>90% REALISTIC' Proc 26th European Solar Energy Conference 2011

[10]Reindl D.T., Beckman W.A., Duffie J.A. 'Diffuse Fraction Correlations' Solar Energy Vol 45 No1, pp 1-7, 1990