Technological University Dublin
ARROW@TU Dublin

Conference papers | School of Civil and Structural Engineering

2016

Solar Photovoltaic System Control Topology Investigation for Power Source Mismatch

Lynette O'Callaghan
Technological University Dublin, lynette.ocallaghan@tudublin.ie

Follow this and additional works at: https://arrow.tudublin.ie/engschcivcon

Part of the Computational Engineering Commons, Electrical and Computer Engineering Commons, and the Energy Systems Commons

Recommended Citation

O'Callaghan, L. (2016) Solar Photovoltaic System Control Topology Investigation for Power Source Mismatch, *19th Sir Bernard Crossland Symposium and Workshop, Mecahnical Engineering.* Queens University Belfast, 27 th APRIL 2016

This Conference Paper is brought to you for free and open access by the School of Civil and Structural Engineering at ARROW@TU Dublin. It has been accepted for inclusion in Conference papers by an authorized administrator of ARROW@TU Dublin. For more information, please contact arrow.admin@tudublin.ie, aisling.coyne@tudublin.ie.

This work is licensed under a Creative Commons Attribution-Noncommercial-Share Alike 4.0 License
Funder: TECHNOLOGICAL SECTOR RESEARCH (2007) STRAND III

Solar Photovoltaic System Control Topology Investigation for Power Source Mismatch

Lynette O'Callaghan

School of Mechanical & Design Engineering
Bolton St.
Dublin Institute of Technology
Dublin, Ireland.

Dublin Energy Lab (DEL)

Abstract

An investigation into solar photovoltaic (PV) system control topology selection, when partial shade is anticipated in the solar array, is presented. As available area is maximised in Building Integrated PV (BIPV) systems, shading is an inevitable consequence. The presence of partial shading in a PV array leads to multiple power peaks in the power-voltage curve, due to bypass diode sections being triggered, and an increase in module mismatch losses in the array. A building energy design software, Integrated Environmental Solutions, is used to determine the shadowed area on PV modules throughout the year, incorporating the PV system location and geometrical models of obstacles around the array.

Photovoltaic system topologies incorporate the following device options: central inverters, a power converter for each series string of PV modules, and a Module Integrated Converter (MIC). A model has been developed to compare a DC-AC parallel MIC configuration with a series string DC to AC power inverter configuration, for a commonly occurring shading pattern, and a simulation is used to compare the power delivered by the topologies. The model is broken up into the following stages: i) geometric modelling of array and surrounding obstacles, ii) solar PV power characteristic model as a function of temperature and irradiance, and iii) inverter efficiency model for each topology. A shade scenario is outlined to present data from each stage of the model. A discussion is presented to critically assess the strengths and weaknesses of the model.

I. INTRODUCTION

Photovoltaic technology directly converts solar radiation into electricity, using semiconductor materials exhibiting the photovoltaic effect [1]. Building Integrated Photovoltaic (BIPV) products are designed to avail of existing space on a building that can be used to generate electricity for occupants and/or supply a grid, increase the user's self-sustainability, decrease their reliance on fossil fuels and reduce the building's carbon footprint. Buildings account for 40% of total energy consumption in the European Union, and this figure is set to increase. The reduction of energy consumption and the use of energy from renewable sources in the buildings sector constitute important measures needed to reduce both the European Union's energy dependency and greenhouse gas emissions [2]. The EU Energy Performance of Building Directive (EPBD) contains a large range of requirements to improve the energy performance of new and existing buildings. The context for the directive is to comply with the Kyoto Protocol to the United Nations Framework Convention on Climate Change. With the impending depletion of natural resources, such as fossil fuels, it is in economies interest to conserve energy, and reduce reliance on fossil fuels, by developing technologies to transform energy from the environment, and to sustain its generation for generations to come. The directive goals have a dual nature, i) the reduction in energy consumption of buildings and ii) increasing the use of energy from renewable sources. These goals play an important role in promoting security of energy supply, and also in promoting a sustainable energy supply. The Building Energy Ratings (BER) in Ireland is required under the European Communities (Energy Performance of Buildings) Regulations, 2006 (S.I. No. 666 of 2006). On-site electrical micro-generation can have a significant impact on a buildings carbon emissions and the use of PV will generally also give a significant boost to the BER, as it significantly influences two of the three factors that comprise the energy rating, namely the calculation of primary energy and carbon dioxide emissions [3],[4]

In 2008 global cumulative installation was approximately 16GW. Large drops in solar module price have seen an installed capacity reaching at least 178 GW by the end of the 2104, sufficient to supply 1 percent of the world's total electricity consumption of currently 18,400 TWh [5]. The price per watt of modules has fallen from $4 in 2004-2008 to $2 in 2009 to $1 in late 2011 [6]. However the price per watt measure does not translate directly into full installed costs. The reasons for the high costs are the distributor's margins in value-based pricing schemes, transportation to site costs, Balance Of System (BOS) components costs and installation costs.

Historically, modules formed 60% of the total system costs [7], however BOS components are now the majority share of the total capital cost-per-Watt, representing one of the main potential sources for further cost reductions [8]. Average costs of BOS including installation in 2012 ranged from $1.6/W for a ground-mounted system to $1.85/W for a rooftop system [9].

There is a desire by architects and buildings owners to mount modules at non optimal orientations, especially with the reduction in module cost to below $1/W, and the implication for the energy rating and hence value of the property. As available area is maximised in Building Integrated PV (BIPV) systems shading is an inevitable consequence. BIPV products include transparent PV for use as windows, photovoltaic roof tile, and façade mounted panels, leading to differing power characteristics due to modules being mounted at different orientations: known as power source mismatch. Average losses from BIPV systems are approximately 20 to 25%, due to shade, mismatch, differences in orientation and inclination, and temperature effects [10]. When shade impacts a PV array, even by a small amount, the power losses have been measured and evaluated at 7.1%, 11% and 35% [11], [12], [13]. Shade manifests as cell mismatch and this loss, calculated through simulation, has been shown to be responsible for losses up to 10% of total generated power [14]. More accurate procedures are required in order to accurately estimate energy payback for PV systems operating under non-optimal operating conditions, in particular those conditions manifesting as power source mismatch. This will facilitate the more accurate calculation of return on investment.

Aims and Objectives

Limitations in the accuracy of evaluating the total power harvested by PV systems operating under realistic conditions, can be due to weather conditions, design details, surrounding obstacles and geographic location [15]. One of the most significant factors is the effect of the partial shading condition on PV arrays, and a more realistic calculation method needs to be developed to represent such impacts while evaluating efficiency of a PV system [16]. Evaluating the total power harvested enables i) a more accurate estimation of payback time for an investment in a PV system, and ii) a more accurate estimation of the size of a PV system to meet a required energy demand. The research aims to develop a validated model to estimate and compare the annual energy generated by shaded PV modules, operating within two common power converter topologies.

In order to prevent over-proportional power losses due to shade, power converter software and hardware need to be designed effectively to minimize power source mismatch losses. The choice of the inverter (DC – AC power converter) influences yield losses due to shade and effective inverters should have the following characteristics: i) a broad input voltage range to adjust the optimal operating point, ii) the ability to control the modules at series string level or module level to operate optimally during partial shading and avoid most losses, and iii) a Maximum Power Point Tracking (MPPT) control algorithm that recognizes the existence of several operating points for partially shaded strings [17]. An accurate simulation model of the PV Arrays power voltage output characteristic is required to enable a robust design for MPPT controllers, especially in the case of changing environmental conditions and in particular so that the controller can minimize the substantial drop in power yield during partial shading [18]. An aim of the research is to model PV power voltage output characteristics as a function of irradiance and temperature for the purpose of locating all potential power peaks available.

To obtain meaningful conclusions regarding the power-voltage characteristics within the PV array it should be known which PV modules are shaded [19]. In order to manage shadow effectively through system design, it is important to determine i) the proportion of the shaded PV modules in relation to the total generator and ii) the course of shadows over time, to determine what length of time the shadow is impacting the system throughout the year [17], A mathematical procedure to determine the shadowed area on PV modules throughout the year, depending on PV system location and the geometrical modelling of obstacles is presented in [15]. The present investigation explores the use of commercial software Integrated Environmental Solutions to achieve that goal. The software is used for the design of energy efficient buildings, and has in-built solar shading analysis tools. The aim of the research is to coordinate the specific shade area data obtained from the IES with the model of PV Power in order to enable the calculation of annual energy of PV systems operating with power source mismatch due to shade.

The objective of the paper is to present a framework for investigation through simulation of the behaviour of i) an AC modular inverter configuration, and ii) the series string inverter configuration. A simulation of DC electrical characteristics of PV modules connected in a series under partial shade conditions [20] is extended in this paper to include inverter efficiency curves derived and extrapolated from experimental data, enabling AC power predictions. Combining the ability to calculate the shaded area using IES, and the power performance of the PV modules and power converters, enables a platform to compare through simulation, two of the leading configurations in PV systems today. The objective is to provide simulated results for an instantaneous shade scenario, in order to highlight the processes occurring within the model.

Photovoltaic system topologies and the problem description are outlined in section II. A model has been developed to compare a DC-AC parallel Module Integrated Converter (MIC) configuration with a series string DC to AC power inverter configuration, undergoing shading. The Model is presented in Section III, and is broken up into the following stages: i) geometric modelling of array and surrounding obstacles, ii) solar PV power characteristic model as a function of temperature and irradiance, and iii) inverter efficiency model for each topology . Discussion of simulation results for a shade scenario is presented, and a discussion of the variables for further analysis is presented in section VI.

II. Photovoltaic System Topologies and Problem Description

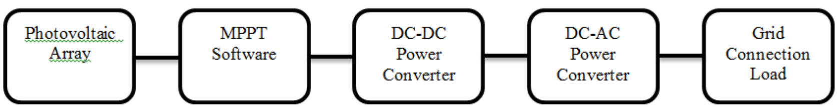

Figure 1 PV System Components.

Figure 1 shows the typical components in a grid connected PV system. The power converters convert the DC power from the PV modules to AC power to be injected into the grid. The MPPT control algorithm is a searching algorithm aiming to obtain maximum power transfer from the PV, which is operating in a dynamic environment of changing irradiance and temperature. All modules are assumed to be mounted in fixed and stationary orientation. The typical PV system topology is the central-inverter topology, where strings of modules are wired in series, and the strings are connected in parallel to a central inverter using a single MPPT algorithm, as seen in Figure 2(a). A more sophisticated version of this topology is the string inverter topology, where each string is controlled by its own MPPT algorithm, seen in Figure 2(b). Clever installation is recommended to reduce the impact of expected shade [17] around unavoidable objects like chimney stacks, which causes array capture losses to occur in the array, called current and voltage mismatch losses.

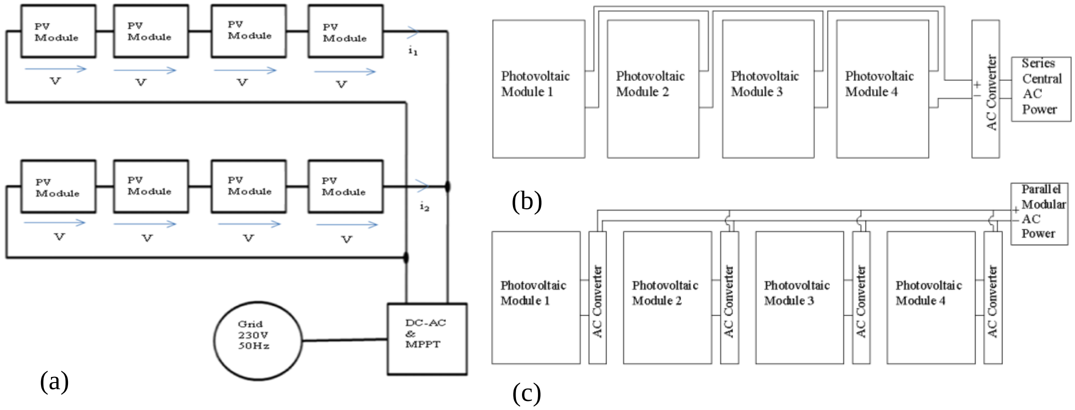

Figure 2 (a) Series/parallel PV array with central grid inverter, implementing array level control. (b) Series configuration of modules with a central AC converter (b) Parallel bus configuration of PV modules and modular AC converters

Current and Voltage Mismatch Loss

As with all series connections of power sources, the element with the lowest current defines to total current. This is termed current mismatch loss in the series string, and the shaded module, generating the lowest current, will dictate the current in the circuit. The higher currents are dissipated using bypass diodes to prevent heat damage to the cells. However, if the inverter has superior mpp intelligence, the shaded module can be bypassed in favour of letting a higher current flow in the circuit. As with all parallel connections of power sources, the element with the lowest voltage defines to total voltage. If two strings are operating at differing voltages, the lowest voltage dictates and the excess voltage is dissipated as loss. This is known as voltage mismatch loss.

Bypass diodes

Bypass diodes typically subdivide cells in groups of between 12 and 24, and the number of bypass diodes on a PV module varies typically from one to three. The presence of bypass diodes creates multiple power peaks in the power curve of the array, as can be seen in figure 7. In order to prevent damage to shaded cells, due to the sinking of the other modules power in the form of heat, groups of cells are fitted with bypass diodes to protect the mismatched cells from experiencing potential failure. The location and number of bypass diodes effects the location of the power peaks when shading occurs. The factors that influence the system maximum peak of available power are: irradiance, temperature, shading pattern, and array configuration [29].

The influence of hardware location, and hence software capability, within the array has a great impact on the ability to minimise array capture losses when mismatch is occurring in the array. Modular power converters offer module level Maximum Power Point Tracking (MPPT), which can result in a 25% energy enhancement [21], allowing each module to operate at its MPP. Modular power converters can be 1) DC –DC in series, 2) DC-DC in parallel or DC – AC in Parallel, however series connected modular converters also experience module mismatch losses, due to current mismatch. DC or AC parallel wired modular converter systems feeding a constant bus do not suffer from module mismatch losses [22], as the configuration removes current and voltage mismatch between modules. This paper investigates the AC power output of an AC Module Integrated Converter (MIC) configuration wired in parallel, as design facilitates the optimal coupling between the DC-DC and DC-AC stages as shown in Figure 1. This configuration is shown in fig 2(c).

III. MODELLING

A. Geometric Modelling of Array and Surrounding Obstacles

Integrated Environmental Solutions (IES) is commercial software accredited for calculating Energy Ratings for non-domestic compliance in the Republic of Ireland of EPBD [23]. The tool incorporates a weather database for your chosen location, and solar irradiance calculations to estimate energy falling on selected surfaces, enabling solar shading analysis. The tool is not typically used for the analysis of shade within PV systems and the present investigation adapts the application for this purpose. A geometric model incorporating 4 Sanyo HIT-250E01 PV modules beside a chimney stack has been developed, as seen in figure 3.

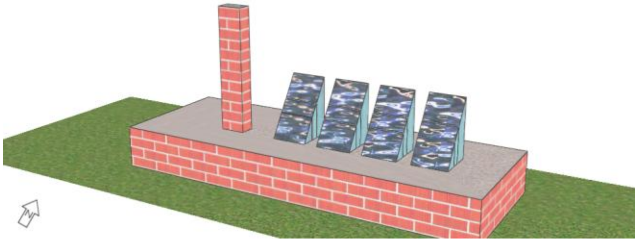

Figure 3 Geometric Model in IES

A snapshot of the shading on the PV modules is shown in figure 4, taken on March 21 at 16.30. The output data generated is a % Area calculation for each surface on the PV array. The shading information is available on an hourly basis and indicates the % of the surface area under shade over the hourly period, for every day in the year. This information is then input into the PV model in MATLAB Simulink, in order to determine Irradiance values for each section of the Modules.

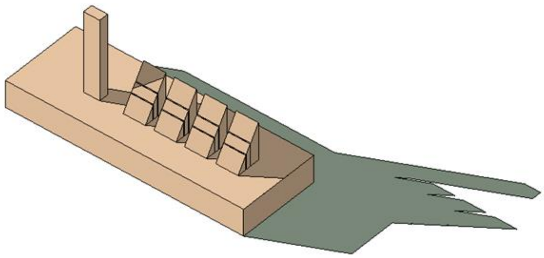

Figure 4 Shading analysis Image on March 21 16.30

B. PV Model

A model of a PV module is used to predict module power. Temperature variations are not considered in this analysis, and each module is assumed to be operated at 25°C. The model requirements are: i) to generate a power voltage curve with sufficient accuracy, ii) to be able to incorporate multiple bypass diodes and iii) to vary input environmental factors with ease. The Matlab/Simulink software has been chosen as the electrical components and environmental inputs can be modeled simultaneously. Three bypass diodes, installed at uneven intervals of 24, 12 and 24 series connected cells, are modeled in each module. This emulates the state of the art module design to be used in further experimental analysis at DIT. An image of the Matlab/Simulink model is seen in figure 6. The model is based on the 1-doide model and all governing equations can be seen in a previous publication by the author [24]. The performance of the model is compared with published experimental data from specifications of the Sanyo HIT-250E01. The comparison of simulated and measured data, as seen in Fig. 5 (a) and (b), show percentage power difference error at the maximum power points in series 1 and 2 is less than 1%; and in series 3, 4 & 5 is between 1 and 2.5%, deeming the model within acceptable levels of accuracy. In order to model the series string topology, the modules are connected in series and an image of Matlab/Simulink model of the series string is seen in figure 8.

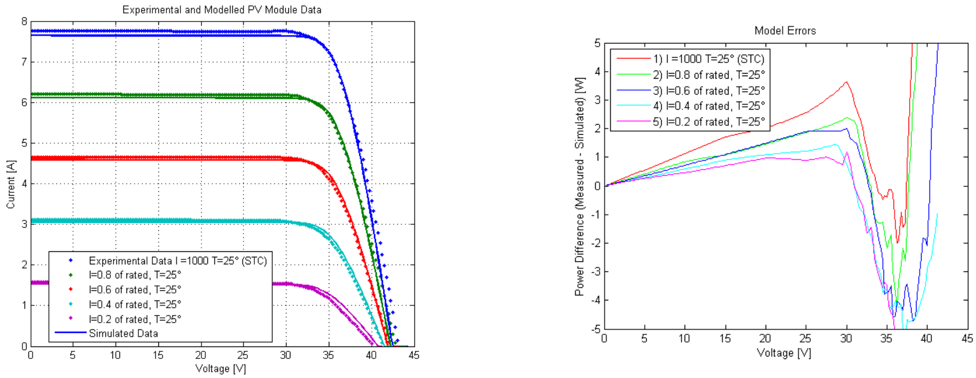

Fig. 5. (a) Experimental and modeled PV I-V curves and (b) model error .

Each section of a module that is controlled by a single bypass diode, otherwise termed bypass diode section within a module, is modelled as a block incorporating the correct number of cells in series. This approach was also taken by [15][18][19]. All modules are assumed to be mounted at the same orientation and angle. It is assumed that all modules have identical electrical characteristics, and that all mismatch is due to shade induced mismatch. Differences in performance calculated are due to shading mismatch losses and power transformation losses, as wiring losses are not considered. Using the shade area data from IES, it is assumed that if any part of the PV block is shaded, then the section is illuminated with the available diffuse level of irradiance. The diffuse irradiance values for the simulation are 300W/m^2, which is a typical value for March according to Dublin Airport weather data in IES. Shade is impacting PV blocks 1 and 2 in module 1 only as seen in Figure 4.

Data from Modular Analysis

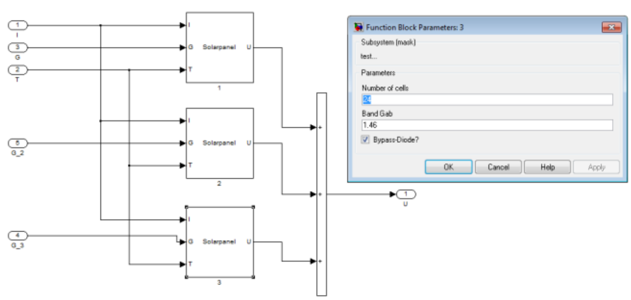

Figure 6 Matlab Simulink sub model of bypass diode blocks incorporating bypass diodes. G is irradiance factor, T is temperature, I is current and U is voltage.

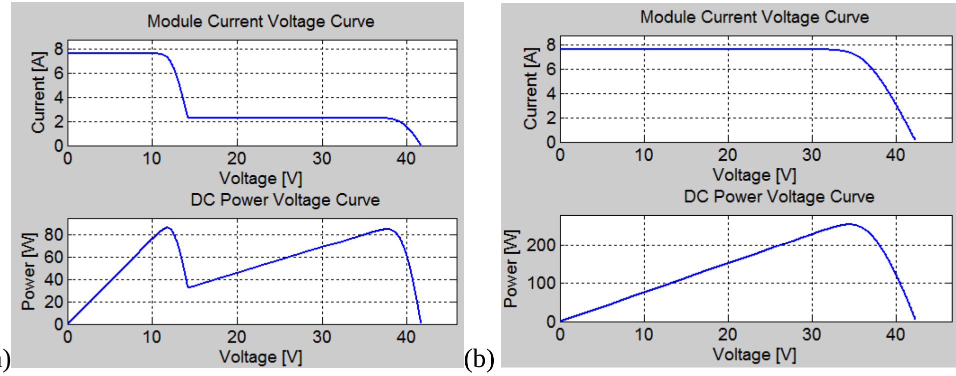

Figure 7 Module current voltage and power voltage characteristics for (a) the shaded module and (b) an unshaded module at rated conditions. (a) Max DC power = 85.95W (b) Maximum DC power 254.31 W

Data from Series string Analysis

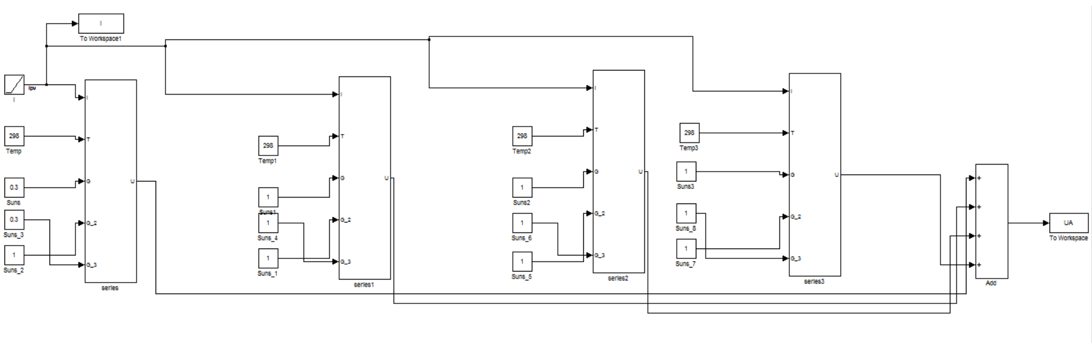

Figure 8 Matlab Simulink model for 4 PV modules in series. Each module contains 3 bypass diode blocks, as seen in figure 6

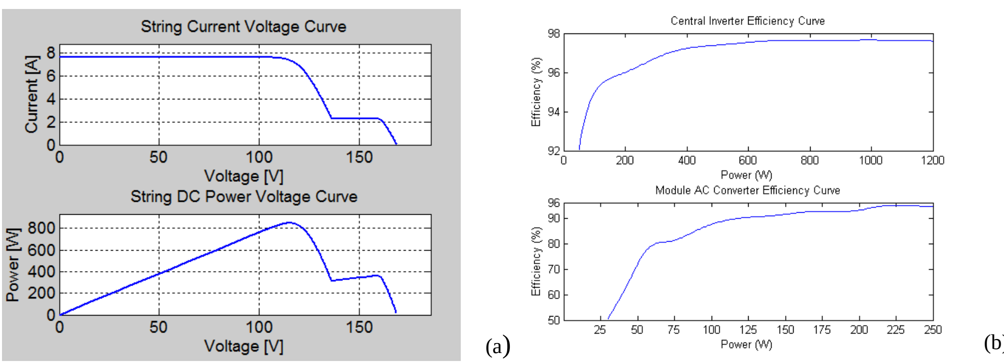

Figure 11 (a) Module current voltage and power characteristics for series string configuration for shading pattern in figure 4. Max DC power = 848.83W if global max is tracked. Local maximum at 361.22W (b) Inverter Efficiency curves

C. Power Converter Efficiency Models

The central inverter is a transformerless design, and the efficiency curve for the model is derived from experimental data from [25]. The peak efficiency of the curve is 97.65%. The modular AC converter uses a high frequency transformer in its design, and an efficiency-power curve was derived from normalised experimental efficiency curves of a push pull AC converter [26]. The efficiency of these devices is typically lower due to the high voltage gain requirements of the hardware. The overall maximum efficiency of this design did not compare with micro-inverters currently on the market. The curve was shifted to a maximum peak power to match the commercial AC converter of 94.8% [27]. In terms of selecting efficiency curves it should be noted that a great range of distributions and peak efficiency values are possible, as the inverter's efficiency is highly dependent on the dc voltage and the inverter output power [15]. This dependence, along with efficiency as a function of power, is not standard data found in manufacturers' datasheets. For these reasons the data curves are chosen as acceptable samples of high efficiency modern PV converters. The data was translated into polynomials of the order of 10 and 20 for central- and modular- converters respectively, with mean absolute differences in efficiency values, measured minus modelled, of 0.028 and 0.001. The two curves are presented in Fig. 11(b). The compiled results of simulated AC generated power are found in table 1.

TABLE 1. SIMULATION RESULTS

	AC MIC Topology			Series String Inverter Topology	
	Shaded Module	Other 3 unshaded modules	Total combined	Global Maximum	Local Maximum
Max DC power	85.95W	254.31 W	848.88W	848.84 W	361.22W
Efficiency of conversion	83.91%	94.49%	93.4% (Inferred)	97.63%	97.07%
AC Power (W)	72.12W	240.28W	793W	829W	351W

IV. DISCUSSION & CONCLUSION

If it is assumed that each PV configuration is being operated at the maximum available DC power, the string topology is the optimal selection for the shade scenario, as the topology can generate 36W in excess to the modular topology, although the margin is very small in this example. The DC power available is almost identical in both topologies, assuming the global maximum is tracked. The modular topology is operating on a lower efficiency curve due to the high gain requirements of the hardware, and this has been to its overall disadvantage in this scenario.

However, if the local maxima is tracked, as is often the case in PV inverters, the string configuration can generate only 351W of AC power, but the modular inverter maintains its power levels as the two power points are almost equal, as seen in figure 7(a). There exists a trade-off between array capture losses, seen here in the difference between the global and local maximum in the string topology; and the transformation efficiency curves over the power range. The string topology is highly dependent on having a MPPT algorithm that can recognise the existence of several operating points for partially shaded strings, namely to be able to distinguish the local maximum from the global maximum. The modular topology is not as dependent on this function, as it is recouping losses by removing current and voltage mismatch losses down at the modular level. All unshaded modules are operating at their maximum; however the topology suffers due to its lower overall efficiency values, when compared to the string configuration.

The model is to be extended to include time, and the course of shadows over the PV array, to determine what length of time the shadow is impacting the system. This will enable a more accurate calculation of annual energy yield. The results presented are simulation results, and the following validation procedures are in progress: i) the validation of shaded power-voltage curves, which incorporate bypass diodes, using a bespoke PV measurement test bed under development in Bolton St, controlled by LabVIEW software and DAQ hardware, and ii) the incorporation of measured experimental efficiency curves into the model, using off-the-shelf microinverter [27] benchmarking data being monitored at the solar research facility in Kevin St. DIT.

This validated model can be used for further investigation of topology selection, incorporating variables such as the proportion of the shaded PV modules in relation to the total generator and the impact of the length of the string, within a variety of common shading scenarios. The purpose of the investigations is to clarify some of the grey areas that occur when deciding on the most efficient control topology when designing a PV system which will incorporates shade to some degree; and to investigate the scope of application of the particular topologies.

REFERENCES

[1] Krauter, S (2006). *Solar electric Power Generation Photovoltaic Energy Systems*. The Netherlands: Springer . p19.

[2] DIRECTIVE 2010/31/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL (19 May 2010) The energy performance of buildings (recast). Official Journal of the European Union 18.6.2010 L 153/13 Available online: http://www.epbd-ca.eu/

[3] SEAI Best Practice guide for PV [Online] Available : http://www.seai.ie/Publications/Renewables_Publications_/Solar_Power/Best_Practice_Guide_for_PV.pdf (December 2013)

[4] (SEAI 2012) Sustanable energy authority of Ireland. Dwelling energy assessment procedure v 3.2.1. (June 2012) [Online] Available: http://www.seai.ie/Your_Building/BER/BER_Assessors/Technical/DEAP/DEAP_2009/DEAP_Manual.pdf (December 2013)

[5] Solar Power Europe (SPE), formerly known as EPIA – European Photovoltaic Industry Association. "Global Market Outlook for Solar Power 2015-2019"(PDF). [Online] Available : http://www.solarpowereurope.org/. Archivedfrom the original on 9 June 2015. Retrieved 9 June2015

[6] Bloomberg New Energy Finance (2012). Reconsidering the economics of PV power – a co-authored white paper on PV economics Bazilian M Onyeji I Leibreich M MacGill I Chase J Shah J Gielen D Arent D Landfear D Zhengrong S [Online] Available: www.**bnef**.com/InsightDownload/7178/pdf (December 2013)

[7] Wang, X Kurdgelashvili, L. Byrne, J. Barnett, A., 2011. The value of module efficiency in lowering the levelised cost of energy of photovoltaic systems. Renewable and Sustainable Energy reviews 15, 4248-4254.

[8] Farrell, J., 2011. Grid Parity for Solar PV with Balance of System Cost Reductions. Renewable Energy World.

[9] Bony, L. Doing, S., Hart, C>, Maurer, E., Newman, S., 2010. Achieving Low cost Solar PV: Industry workshop recommendations for near-term balance of system cost reductions. [Online] Available: www.rmi.org/content/Files/BOSReport.pdf (2016)

[10] E. Román, R. Alonso, P. Ibanez, S. Elorduizapatarietxe, D. Goitia, 2006. Intelligent PV module for grid-connected PV systems**,** IEEE Trans on Industrial Electronics, 53 (2006), pp. 1066–1073.

[11] T. Sugiura, T. Yamada, H. Nakamura, M. Umeya, K. Sakuta, K. Kurokawa, 2003. Measurements, analyses and evaluation of residential PV systems by Japanese monitoring program, Solar Energy Materials and Solar Cells, 75 (), pp. 767–779/

[12] Baltus, C.W.A, Eikelboom, J.A., van Zolingen, R.J.C., 1997. Analytical monitoring of losses in PV systems. In: 14th European Photovoltaic Solar Energy Conference, July, Barcelona, Spain, pp. 1547–1550.

[13] Becker, H., Kiefer, K., Hoffman, V.U., Rindelhardt, U., Heilscher, G., 1997. Five years of operational experience in the German 1000-roofs-PV programme results of monitoring and system inspection. In: 14th European Photovoltaic Solar Energy Conference, July, Spain, pp. 1677–1680.

[14] Chouder, A, 2009. Analysis model of mismatch losses in PV systems. Journal of Solar Energy Engineering 131(May) 024504.

[15] Celik, B., Karatepe, E., Gokmen, N., Silvestre, S., 2013. A virtual reality study of surrounding obstacles on BIPV systems for estimaton of long-term performance of partially shaded PV Arrays. Renewable energy 60 (2013) 402-414.

[16] Argul, FJ., Castro, M., Delgado, A., Carpio, J., Peire, J., 2003. Software modelling of grid connectedphotovoltaic buildings.Prog. Photovoltaics 2003;11:255-73.
[17] G. Bettenwort, J. Laschinski: "Schattenmanagement – Der richtige Umgang mit teilverschatteten PVGeneratoren" (Shadow management – The correct handling of partially shaded PV generators); 23. Symposium Photovoltaische Solarenergie, 2008, Bad Staffelstein, Germany (only available in german) English summary http://www.sma-italia.com/fileadmin/content/global/Solutions/Documents/Medium_Power_Solutions/GlobalPeak-UEN101210.pdf
[18] Ishaque, K., Salam, Z., Syafaruddin, 2011. A comprehensive MATLAB Simulink PV system simulator with partial shading capability based on two-diode model, Solar Energy 85 (2011) 2217-2227
[19] Karatepe, E., Boztepe, M., Colak, M., 2007. Development of suitable model for characterizing photovoltaic arrays with shaded cells. Sol Energy. 81: 977-92.
[20] Mäki, A., Valkealahti, S. and Leppäaho, J, 2011. Operation of series-connected silicon-based photovoltaic modules under partial shading conditions. Progress in Photovoltaics: Research and Applications.
[21] Enslin, J.H.R.; Wolf, M.S.; Snyman, D.B.; Swiegers, W., 1997, "Integrated photovoltaic maximum power point tracking converter," *Industrial Electronics, IEEE Transactions on* , vol.44, no.6, pp.769-773, Dec.
[22] W. Xiao, N. Ozog, W.G. Dunford, 2007. Topology study of photovoltaic interface for maximum power point tracking, *IEEE Trans. Ind Electron*., vol 54, no. 3, pp 1696-1704, June.
[23] (SEAI 2013) Sustanable energy authority of Ireland . Legislation and background (2013) [online] Available: http://www.seai.ie/Your_Building/EPBD/ (December 2013)
[24] O'Callaghan, L., McKeever, M., Norton, B., 2012. A simulation analysis of photovoltaic AC Module Integrated Converters in parallel, under controlled edge shading conditions. Environment and Electrical Engineering (EEEIC), 2012 11th International Conference on. 2012 699 - 705, Available on IEEE Conference Publications
[25] Valentini, M.; Raducu, A.; Sera, D.; Teodorescu, R, 2008. "PV inverter test setup for European efficiency, static and dynamic MPPT efficiency evaluation," Optimization of Electrical and Electronic Equipment, 2008. OPTIM 2008. 11th International Conference, 22-24 May.
[26] Herrmann, U.; Langer, H.G.; van der Broeck, H.,1993. "Low cost DC to AC converter for photovoltaic power conversion in residential applications," *Power Electronics Specialists Conference, 1993. PESC '93 Record., 24th Annual IEEE* , vol., no., pp.588-594, 20-24 Jun
[27] Enecsys Micro Inverters, (2012) 'datasheets Smi-S240W-60 [online] http://www.enecsys.com/products/datasheets.php [02/02/12].
[28] Patel, H.; Agarwal, V, 2008. "MATLAB-Based Modeling to Study the Effects of Partial Shading on PV Array Characteristics," *Energy Conversion, IEEE Transactions on* , vol.23, no.1, pp.302-310, March.