Studying the effect of full uniform shading on a PV module using a LabVIEW simulation model

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Abstract: Simulations designed in LabVIEW may be used in many engineering applications, including the design of stand-alone PV systems. The influence of full uniform shading, which included thin clouds and contrails, on the day to day performance of PV systems is often underestimated, and is not always accounted for in the design. The purpose of this paper is to describe the design and development of a LabVIEW simulation model that includes the influence of full uniform shading on the overall performance of a PV system. This model is used by electrical engineering students at the Central University of Technology in order to verify their designs and improve their understanding of the operation of stand-alone PV systems. The model also assists engineering students in investigating the influence of full uniform shading on the performance and sustainability of a stand-alone PV system with specific component specifications. The design of the model was based on empirical research that quantified the influence of full uniform shading on the performance of a PV system. With the use of this model, a engineering student can change the percentage of full uniform shading in conjunction with other variables, thereby visually observing the influence on the performance of a stand-alone PV system over a 24-hour period.

***Keywords*— PV design, sustainability, diffuse radiation, engineering students**

I. INTRODUCTION

"Learning by doing, peer-to-peer teaching, and computer simulation are all part of the same equation." These words, by the Greek-American architect Nicholas Negroponte, highlights the importance of computer simulations to enhance our understanding of complex concepts and systems [1]. Simulations have evolved to form an integral part of the tool set for engineers in their day to day work. It is also an invaluable tool for academics who aim to convey fundamental principles of power engineering to engineering students. In a study by Connolly et al. in 2010, researchers considered a total of 68 different simulation tools for analysing the integration of renewable energy into various energy systems [2]. The sheer number of simulation tools suggests that renewable energy systems are usually first analysed mathematically, primarily in terms of performance, before physically being installed. These simulation tools include many different variables, such as tilt and orientation angles, load profiles, solar radiation curves and environmental conditions of the installation site. It is thus essential that freshmen engineering students be exposed to simulation software packages early on in their studies, as they will progress to more advanced and complex software as the level of education increases.

One key environmental condition, which may at times be overlooked, involves full uniform shading of PV modules. Interrupting direct beam radiation lowers the output voltage of a PV module significantly, influencing the amount of output power which may lead to system downtime or even component failure over a period of time [3]. Uniform shading results in more diffused radiation, rather than direct beam radiation, being received by the PV module, resulting in the radiation intensity being approximately 20% of the direct beam component [4]. It is therefore imperative that uniform shading of PV modules be included as a variable in software simulation tools used by engineers and engineering students.

The purpose of this paper is to describe the design and development of a LabVIEW simulation model (LSM) that includes the influence of full uniform shading on the overall performance of a PV system. Empirical data, relating to the influence of full uniform shading on the output power of a PV module, was published in 2014 [5] and is used as input data to design and verify the LSM. This model can be used by engineering students to investigate the influence of various percentages of full uniform shading on the performance of a stand-alone PV system over a 24-hour period.

Firstly, the research site will be contextualized. Secondly, the LSM will be presented focusing on the user interface. Thirdly, the research methodology will be outlined followed by the results and discussions. Lastly, conclusions and recommendations will be drawn.

II. CONTEXT OF THE RESEARCH SITE

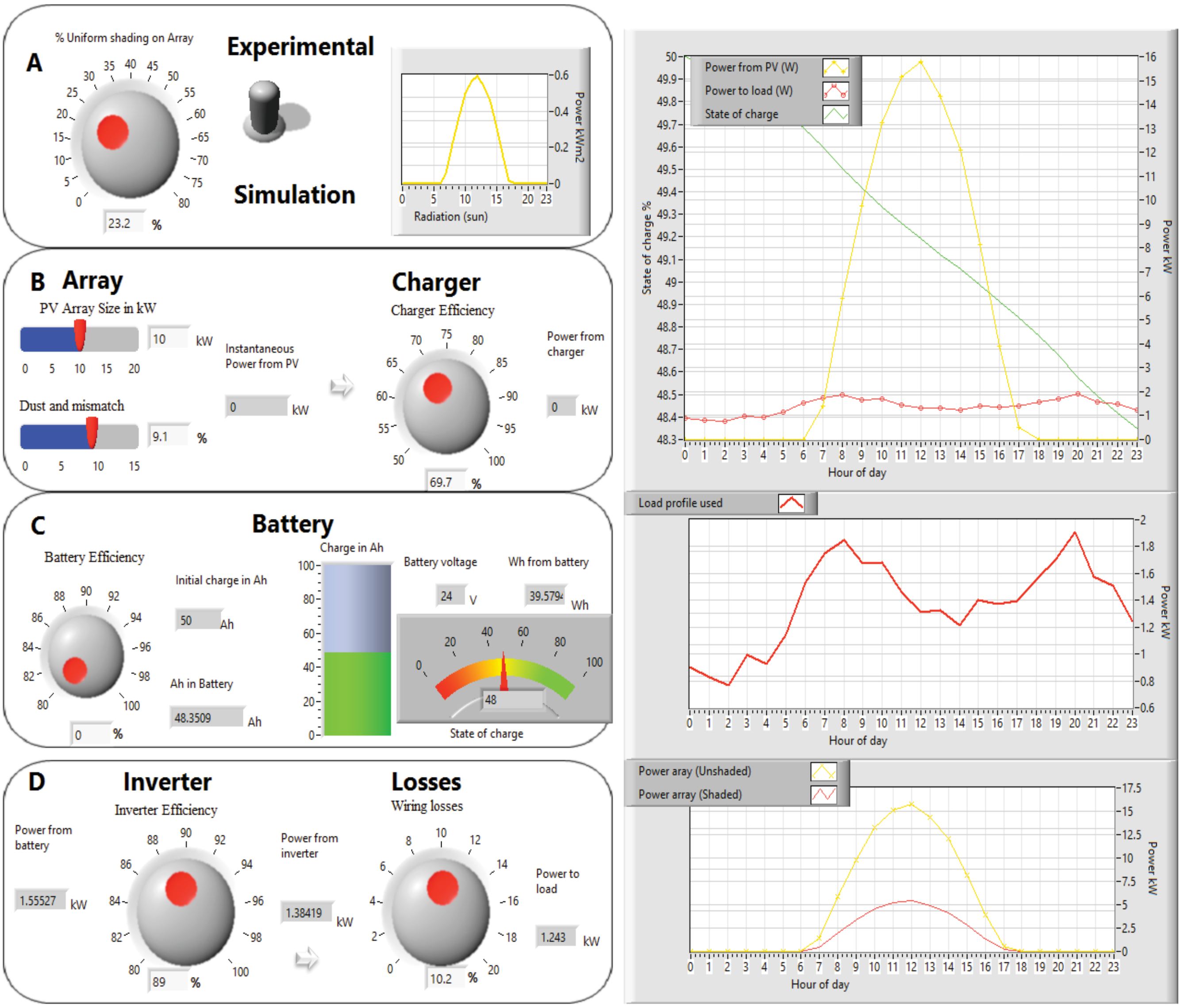
South Africa has some of the best solar radiation resources in the world, where the average daily solar radiation varies between 4.5 and 7 kWh/m^2 [6]. In the heart of South Africa lies the Free State province, where the provincial capital is Bloemfontein. The main campus of the Central University of Technology (CUT) is located in Bloemfontein, with the Faculty of Engineering and Information Technology residing on the west wing. The co-ordinates of CUT's main campus is 29°07'17.24" S (Latitude) and 26°12'56.51" E (Longitude), being at an altitude of 1304 m above sea level [7]. CUT serves as the research site for this study. Bloemfontein is a semi-arid region (82% of South Africa is classified as such a region [8]) with a daily average global horizontal radiation of 5.15 kWh/m^2/day [6]. This average daily radiation renders Bloemfontein as an ideal site for research into the performance of PV systems.

III. LABVIEW SIMULATION

Figure 1 shows the user interface of the LSM that was designed as part of this research and is presented in this paper. This user interface is used by freshmen engineering students in a module termed Solar Energy Systems 2, in order to manipulate specific variables of the model, and to visually observe its related effects. This module forms part of the Higher Certificate in Renewable Energy Technologies (HCRET) that has been offered at CUT since January 2014.

It was specifically developed in order to train technicians for the renewable energy field of the Northern Cape and Free State province.

Label A in Figure 1 shows the first section of the user interface of the LSM. The first section represents the energy source, where the engineering student may manipulate the percentage of full uniform shading for the simulation. In this section the simulation can be set to simulation or experimental mode. In the simulation mode, a linear equation is used for the relationship between the full uniform shading and the available solar energy. This is due to the fact that the relationship between light intensity and power from a PV module is linear [9], which is indicated in red in Figure 2. This figure shows that 60% full inform shading will produce 75% power reduction. In order to better represent the actual simulation results, a second order polynomial function was used (see Figure 2). This is done to make the student aware that small differences between experimental and theoretical work is possible due to variations in the experimental parameters. In the experimental mode, results from other studies may be used to formulate a different equation.



% Uniform shading on Array: 23.2 %

PV Array Size in kW: 10 kW

Dust and mismatch: 9.1 %

Instantaneous Power from PV: 0 kW

Charger Efficiency: 69.7 %

Power from charger: 0 kW

Battery Efficiency: 0 %

Initial charge in Ah: 50 Ah

Ah in Battery: 48.3509 Ah

Battery voltage: 24 V

Wh from battery: 39.5794 Wh

State of charge: 48

Power from battery: 1.55527 kW

Inverter Efficiency: 89 %

Power from inverter: 1.38419 kW

Wiring losses: 10.2 %

Power to load: 1.243 kW

Figure 1: User interface of designed LabVIEW simulation module

In this section, hourly radiation data is obtained from a text file that represents a 24-hour cycle of energy from the sun. The engineering student has no control over the energy from the sun and the simulation reflects the normal daily radiation curve peaking at around 1 kW/m^2 during midday.

Since the LSM requires only one daily radiation curve, any data relating to specific days of the year can be selected as input to the simulation model. Monthly average solar radiation data may also be used, as was obtained for Bloemfontein from NASA's surface solar energy data set that provides monthly average solar radiation data for specific locations on earth [10].

Figure 3 represents one day of radiation data for summer, winter and for the average of the year. From the figure it can be derived that the average peak radiation for summer is 0.93 kWh/m^2 and for winter it is 0.6 kWh/m$^{2.}$ In the evaluation of the simulation model, only one day in July was used due to the fact that the solar radiation from the sun is at its lowest point in the year for the research site. Using the average daily radiation from July will ensure that the system will be sustainable over the full 12-month period.

The data for the monthly average solar radiation for Bloemfontein is shown in Figure 4, illustrating the difference between summer and winter seasons. The average daily radiation for December was 7.76 kWh/m^2/day, whereas in

June it was only 3.49 kWh/m^2/day. These radiation values will decrease as the percentage of full uniform shading is increased on the dial in Figure 1 A. Students, who are visual learners, will immediately be able to identify this significance.

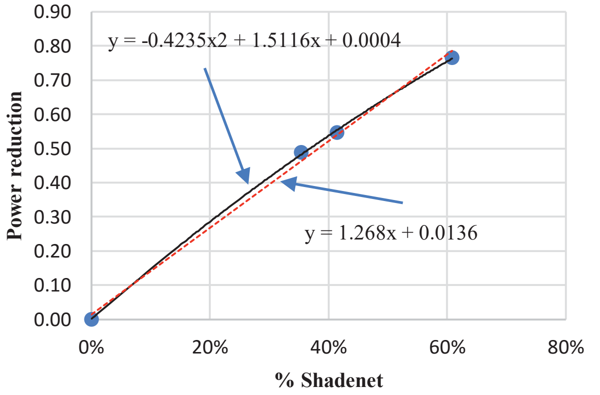


Figure 2: Relationship between the percentage of shading and the overall output power reduction.

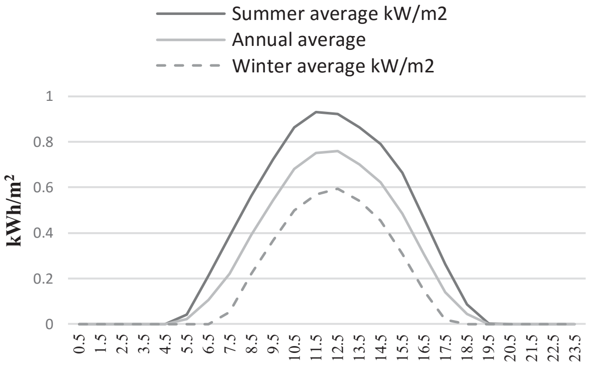


Figure 3: Average radiation per day for December and July in Bloemfontein [10]

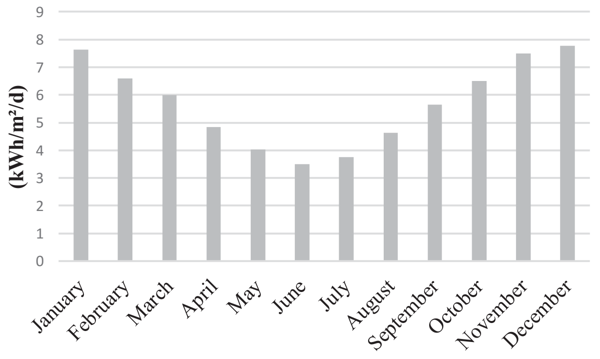


Figure 4: Average daily radiation per month for Bloemfontein [10]

Section B in Figure 1 represents the PV array. This is where the engineering student can change the array size from 0 to 20 kW. If, for example, a 5 kW array is selected and the input from the sun is set at the Standard Test Condition (STC) of 1 kW/m^2, then the output of the module will be 5 kW at 25°C. The output of each section is shown in kW to enable the student to observe the flow of energy through the system. The dust and mismatch factor of the PV array is also included where typical values are set around 15% [11]. Engineering students may manipulate this value to visually observe the adverse effects that dust and mismatches exert on the energy flow and performance of the overall system. In section B of Figure 1, the engineering student can also set the efficiency of the charge controller that serves to regulate the flow of current between the PV module, storage device and specified loads. Modern charge controllers have typical efficiencies of 97% [12]. The student may control the effectiveness of the charger by varying it between 50% and 100%, again being able to visually observe its effect on subsequent sections.

Section C of Figure 1 represents the battery bank (storage device). The efficiency of the battery may also be altered between 80 and 100%, which is in line with current technology providing battery efficiencies of around 85% [13]. It must be noted, though, that battery efficiencies rely heavily on charging and discharging periods, as well as on the depth of discharge [13]. The battery's voltage (V), amount of charge (Ah) and state of charge (SOC as a %) are also indicated in this section, playing an important role in the sustainability of the system.

Section D of Figure 1 presents the inverter where the student may set its efficiency between 80% and 100%. Current technologies allow for inverter efficiency's in the order of 97% [14]. However, it must be noted that inverter efficiency is dependent on the AC load and may vary widely over the operating range of the inverter [15]. Wiring losses are included in this section which can be manipulated between 0% and 20%. These include losses in electrical connections in the system as well as resistive losses that are affected by the length and diameter of the wires that are used [16].

The load profile may be obtained from a standard text file. The engineering student may manipulate the load profile in the LSM in order to fit specific case studies. The load is presented in one hour intervals, with the flow of energy from the battery to the load being observed in the simulation (see Figure 6). The load profile is an integral part of any renewable energy system and needs to be reliable [17] in order to ensure that the system has been designed to be sustainable. A typical load profile for a normal household was compiled and used in this research, and is shown in Figure 5. The load profile can be customised by specifying the hourly load in kW over a 24-hour period in the text file that is used as input for the load profile in the simulation.

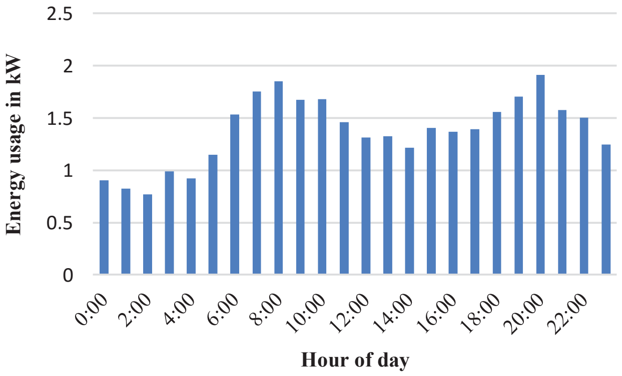


Figure 5: Load profile that was used in the evaluation of the simulation model.

The power to the load, power extracted from the PV array and the battery's SOC is presented graphically in Figure 6 for a 24-hour period. It may be observed that the SOC was 50%

at the start of the cycle and gradually decreased to 48.8% at the end of the cycle (diagonal solid line). This provides the engineering student with an indication of the decline in SOC due to the load requiring more power than what is available from the sun (yellow line illustrating the daily solar radiation curve).

Figure 7 represents the power extracted from the PV array for a non-shaded and shaded condition with a difference of 2.6 kW at 12:00 in this specific simulation. In this sketch, the student can visually observe the influence of shading on the output performance of the PV array. The next section covers the research methodology that was followed in this study.

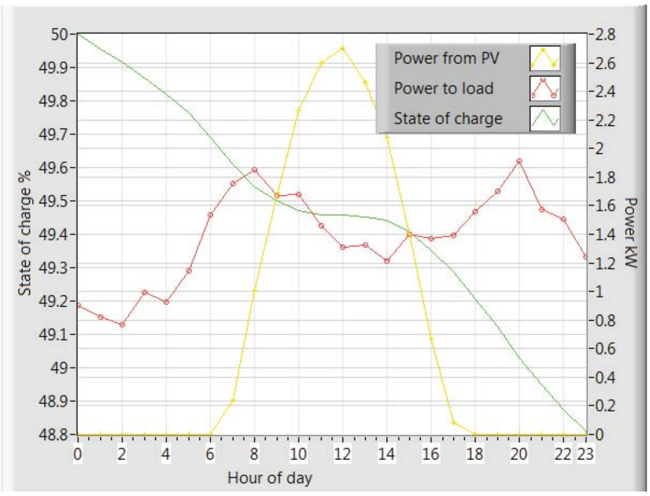


Figure 6: Graphical display in simulation of power from PV array, power to the load and the state of charge in the batteries

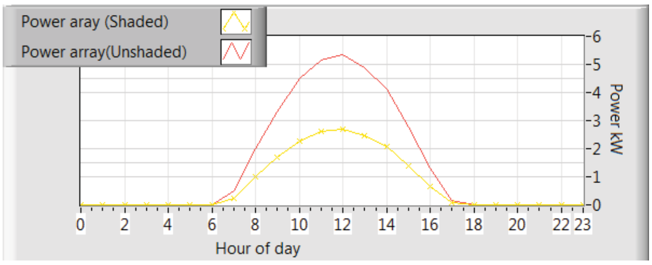


Figure 7: Graphical display of power extracted from the PV array over a 24 hour day due to un-shaded and shaded conditions

IV. RESEARCH METHODOLOGY

The purpose of this paper is to describe the design and development of a LSM that includes the influence of full uniform shading on the overall performance of a PV system. In a previous study, reported on in 2014 [5], the influence of various percentages of full uniform shading on the output power of a PV module was investigated and quantified. Firstly, the percentage of light intensity that passed through three different shade nets was determined. The shade nets were then used separately to apply 10 minutes of full uniform shading to one specific PV module (called the experimental system), while an identical one remained un-shaded (called the control system). The amount of output power from each system was then recorded, and the amount of power reduction calculated for each separate shade net.

The results of this 2014 study were used as the input data to the LSM. The simulated data results where then compared to the empirical data results in order to verify the validity of the simulation model. The components of the stand-alone PV system that are used in the evaluation of this LSM include a PV array size of 15 kW, a charge controller rating, a battery size of 100 Ah, an inverter rating and losses. The charge controller and inverter efficiencies were selected as 95%. The in-out efficiencies of the batteries (100 Ah 24 V) were set to 85%. Dust and mismatch losses were taken as 10% while wiring losses were set to 15%.

V. RESULTS AND DISCUSSION

Firstly, the results concerning the empirical data of the full uniform shading of the 2014 study are presented as a review (Figure 8); after that, the results of the LSM are given. Using both direct beam radiation from the Sun and two different LEDs (3 W and 4 W) as the light source enabled similar shade net percentages to be calculated. A 35% shade net allows 65% of light to pass while a 61% shade net allows 39% of light to pass.

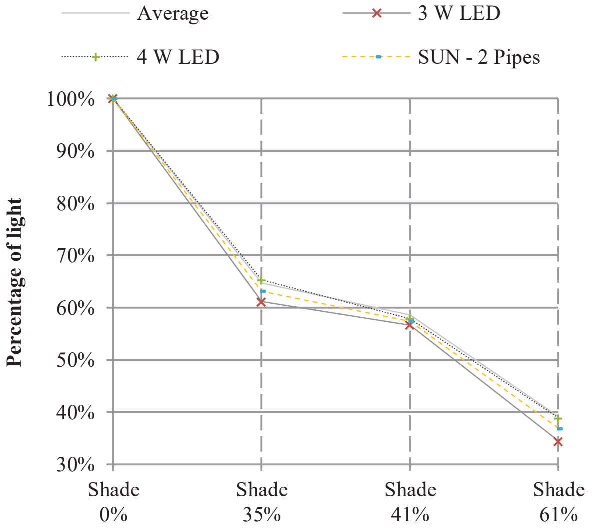


Figure 8: Full uniform shading results using LED's and the SUN [18]

Figure 9 reveals the correlation of output power to the percentage of full uniform shading of a given PV module within a controlled environment. The percentage of full uniform shading equates to the percentage of light intensity of the direct beam component which is not proportional to the output power of the PV module (e.g. 35% shading allows 65% of light to pass which results in a 50% reduction of the output power) [18].

Figure 10 presents the empirical results of the influence of three different shade nets on the output power of the PV module, as well as the results of the simulation model. A similarity of 99.7% exists between the empirical and simulation data. This is an indication that the simulation values are valid and can be used by an engineering student to study the influence of full uniform shading on a stand-alone PV system.

One of the main considerations for the sustainability of any stand-alone PV system is the SOC in the battery bank. As an example, Figure 11 represents the influence that the different percentages of shading will have on the SOC over a 24-hour period. This is valuable information for an engineering student to enable him or her to determine if the current PV system design will be sustainable. In this regard, results from the simulation model for a specific system is shown in Figure 11, where the initial SOC is 50%. The engineering student can now observe that no shading will cause the SOC of the system to also be 50% at the end of the 24-hour day. For uniform shading of 61%, the SOC will drop with more than 1% to 48.75% which must be considered in the design of the physical system.

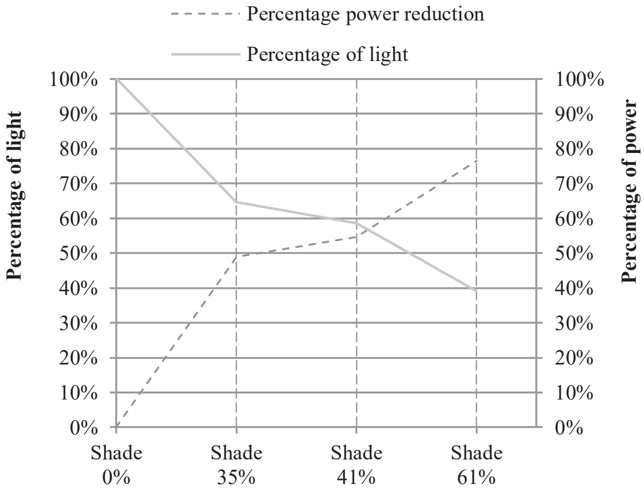


Figure 9: Power reduction to full uniform shading percentages [18]

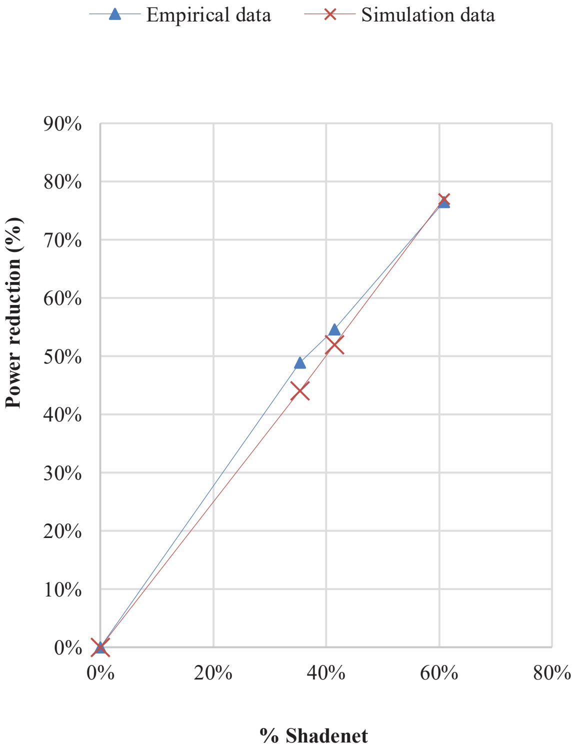


Figure 10: Empirical data from the 2014 study for power reduction compared with simulation data for 3 different shade nets

The output of the PV array is affected by the percentage of full uniform shading. As an example, the simulation results available to the engineering student for different percentages of full uniform shading can be observed in Figure 12. A 35% full uniform shading will have a power reduction of 44% and a 61% shading will have a reduction of 77% (see Figure 12).

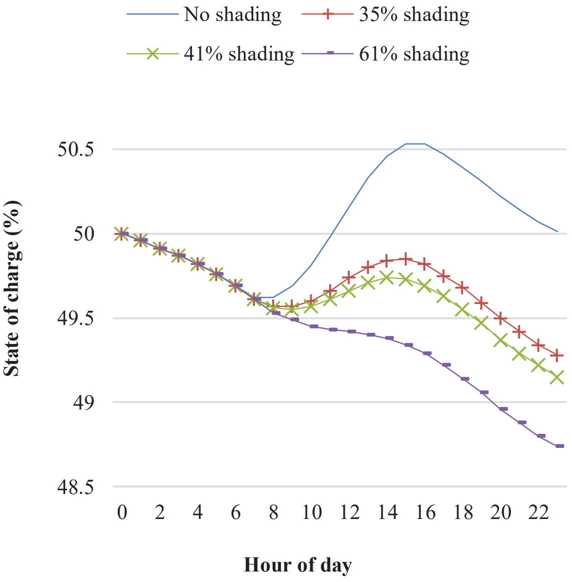


Figure 11: Simulated influence of 3 different percentages of shading on the SOC of the battery bank over a 24 hour period.

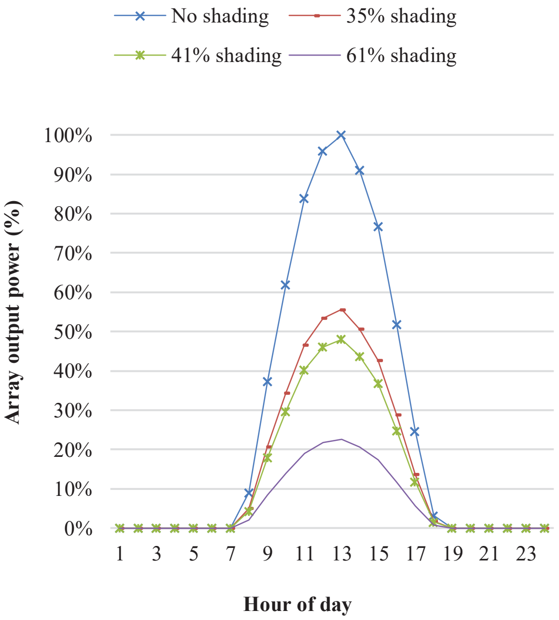


Figure 12: Simulated influence of the various percentages of shading on the output of the PV array

VI. CONCLUSIONS

The purpose of this paper was to describe the design and development of a LSM that includes the influence of full uniform shading on the overall performance of a PV system. This system includes sections for adjusting the percentage of full uniform shading, array size and efficiencies (charger, battery and inverter). Losses, in terms of dust, mismatch and wiring, may also be set in the LSM.

The results of the LSM were compared with the empirical results of a previous study done in 2014, where a correlation of 99.7% was obtained. This indicates that the LSM can be used by engineering student to accurately investigate the effects of uniform full shading on the output power of a specified PV system. This PV system may be customized within the LSM to fit an exact real life application.

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