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Power Optimization, Diagnostic Monitoring, and Modeling of Photovoltaic System

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POWER OPTIMIZATION, DIAGNOSTIC MONITORING, AND MODELING
OF PHOTOVOLTAIC SYSTEM

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ABSTRACT

Photovoltaic (PV) solar energy has been sustaining a major growth rate over the last decade in many parts of the world. This steep growth has been driven by concern about climate change, the adoption of renewable portfolio standards, government incentives, and reduction in PV system costs. Recently, however, such large PV penetration into the electrical grid is cause a concern that might curb such a growth; namely, the incontrollable intermittency of power generated on cloudy days. Furthermore, conventional PV system configurations often do not harness the maximum power that is available under partial shading caused by clouds or shadows of nearby structures. This thesis evaluates three issues related to this problem: (a) non-conventional PV system configurations that use distributed power electronics to harness maximum power under shaded and/or mismatch conditions, (b) system monitoring using Infra-Red (IR) imaging for operation and maintenance purposes, and (c) software tools that determine accurate current-voltage (IV) curves under partial shading. In the first issue above, a commercial software tool is used to compare the performance of conventional and non-conventional PV systems under mismatch and shaded conditions. In the second issue, an improved image processing method is proposed to better decide the status of PV modules in borderline cases. Finally, in the third issue, a MatLab based software tool is developed to accurately determine the shape of the I-V curve of a PV array under partial shade. The simulated curves compare well (i.e., within 3% error) with experimental data.
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CHAPTER 1: INTRODUCTION

Energy is the core of the modern civilization. It is obvious to realize that nations with abundance of energy resources can affect the world political arena and influence decision makers. Also, the instability of oil producing entities coupled with the depletion of fossil fuels and growing concern about the environment promise an ambiguous future. Therefore, there is an obvious shift in utilizing renewable energy resources such as wind, water and solar.

Those who live in sunny regions recognize the opportunity of harnessing what nature has given them in the form of sustainable solar radiation. For example, the sun’s thermonuclear reaction where hydrogen atoms fuse together to form helium has been producing the energy the earth receives for the past 5 billion years and it is expected to continue producing energy for the coming 5 billion years [1]. It is theoretically possible to satisfy the world’s energy demand by installing current PV technologies on only 4% of the desert surfaces [2].

Photovoltaic modules’ cheap cost and reliability made them highly desirable in areas where there is abundance of sunlight throughout the year. It is noticeable that the continuous research in the PV field has resulted in a steady advancement in the technology as well as market growth. For instance, nowadays the efficiency of commercially available modules ranges from 12% to 19%. Furthermore, although solar energy is only a small part of the US’s energy system, it has been sustaining an annual growth rate of more than 40% for the last decade.

Steep growth in the application of photovoltaic has been driven by a growing
concern over climate change, the adoption of state-level renewable portfolio standards (RPSs), incentives, and reduction in photovoltaic (PV) system costs. Many energy experts predict that solar energy will likely become a serious contender for meeting our energy needs in the coming decades.

To optimally harness the sun’s energy, many contemporary challenges have to be investigated. When mismatching of modules occurs, the output of the system decreases and the corresponding internal losses may partially or fully compromise the PV plant operation [3]. Furthermore, monitoring PV systems has provided researchers with opportunities to help improve the systems’ performance by reducing mismatch losses, providing operational displays, as well as improving theft protection and safety shutdown [4]. Moreover, sustaining a dynamic load requires monitoring of the energy production as well as solar insolation [5]. Unavoidable partial shading in crowded urban environments caused by tree branches, bird droppings, or opposite housing structures can result in significant nonlinear reduction of power generator [6]; and in extreme cases, this can degrade or permanently damages solar cells. Consequently, a conventional inverter fails to identify and operate at the global maximum power (MPP) due to the presence of multiple local power points [7]. In addition, large penetration of PV systems into the grid requires operational flexibility and forecasting strategies to evaluate the value of balancing supply, demand, and reserves over large geographic areas [8].

1.0 Literature Survey

Many contemporary and creditable resources have been reviewed to provide an adequate understanding of the topics related to mismatch, shading, monitoring, optimizing, modeling and simulating PV systems. Literature is reviewed and grouped in
the following order: mismatch and shading, optimization and monitoring, and modeling and simulation.

Reference [9] explored the mismatch-related power losses in PV arrays with non-uniform operation conditions. Performance was calculated at the cell level. Panels facing multiple directions are found to have negligible mismatch loss unless they were in the same string. The mismatch in panels characteristics was unclear but it was modeled with derate factor of 1-2%. Modeling at sub-module level gave nearly the same result as cell level modeling. The power from a partially shaded array was found to be sensitive to the amount of light available in the shade.

Reference [10] compared simulated results with real measurements from of a façade’s photovoltaic power generators. The PV system was split into two strings, each with its own designated inverter. Bypass diodes reacted to partial shading when the breakdown-voltage was reached in the shaded cells. The energy yield was nearly the same in measured and simulated data when shading losses were not taken into account.

According to reference [11], different sub-arrays with different MPP tracking methods and orientations could be connected to one inverter with a negligible loss in energy production. The study was done on 250 kWp PV system, which was distributed on the roofs of 70 homes. Some of the system sub-array’s tilt angle and orientation deviated from the optimum angle due to the spatial and design constrains of the subdivision.

Reference [12] studied five groups of arrays: Three groups consisted of crystalline silicon modules, and the remaining two consisted of thin film modules. The number of panels in each group varied as well as the arrays’ age. Raw data was collected from each
panel. Then, simulation data were compared to the measured data. The behavior of the systems under non-uniform conditions was also observed. Analysis of the measured data showed a moderate to low level of panel-level mismatch for all of the tested systems, independent of system age, technology, or operating conditions. This could be translated into minimal potential for increased energy capture of less than 1% annually. Panel level power optimizers were also used to recover mismatch related losses.

The aim of the study in reference [13] was to collect information about a PV plant status in terms of its efficiency by monitoring a one panel only as a reference panel, then, applying statistical methods to determine the plant’s status. The presence of dust and pollution were taken into account. It was possible to determine statically the cleanliness condition of the PV plant, with a given confidence interval. This allowed for optimization of the maintenance activities, which can potentially reduce the cost and increase the system’s efficiency.

Reference [14] investigated the PV modules’ electrical status in the presence of bypass diodes under mismatching conditions caused by shading. Each simulated module consisted of 36 cells that were connected in series. Each module was shunted with bypass diode. They produced $I_{sc}=2.4$ A, $V_{oc}=20.1$ V and $P_m=35$ W. Illumination and temperature were $L=1\text{kW/m}^2$ and $T=25^\circ\text{C}$. Shading rate (SR) = $N/36$. When one shaded cell in the system had SR=2.7%, shaded module’s bypass diode did not conduct with the supposed load. The output power was decreased almost to half of its original power without shading. In the case of two shaded cells, (i.e. SR=5.5%), the diode started conducting with the supposed load. In a system where two strings were connected in parallel, two fully irradiated modules had lower voltage than the other partially shaded
module in the other. Minimum shading ratio produced a less favorable scenario in which a current split between the diode and module. The diode’s current increased with the increase of SR. Short-circuited array triggered the diode into operation with minimum SR. The electrical state of shaded module is independent of the array configuration.

Reference [15] conducted a study based on the two common bypass diode configurations, which found in commercial PV panels (i.e. overlapping and non-overlapping diodes). The shadow rate, breakdown voltage and placement, and the number of diodes influenced the PV module power characteristic. Diodes were used to optimize power and prevent hot spots. A mathematical expression was derived to estimate the maximum number of solar cells that can be protected by one diode. The simulations presented in this paper could be very useful tool to enhance or create a new algorithm to calculate the MPP under the presence of shade.

Reference [16] showed that a shadow could cause a reduction in power corresponding to over 30 times its physical size, depending on the number of bypass diodes within the module. A Shade Impact Factor (SIF) formula was suggested to described the relationship between shading area and power reduction. Two case studies were conducted: The first case study employed direct incremental shading on one cell for each module; the second case study used more realistic method to create shading and employed two shading object (i.e., a PVC pipe and flat plate), which were installed nearby the PV modules to create partial shading throughout some interval of the day. SIF of the pipe was found to be higher than SIF of the plate even though the plate’s shading area was larger. Bypass diode placement was needed to accurately predict power loss due to shading.
The author in [17] used easy and accurate formulas to estimate the area of shadow on PV array by using fisheye photographs. The error of the proposed method was less than 6% for the length of the shadow and less than 3.5% for its direction.

Reference [2] aimed to compare the efficiency of a PV inverter with and without a proposed cooling system. The authors proposed a new inverter submersed in coolant (i.e. DOW CORNING 561 Silicon fluid) instead of the traditional ventilated or conditioned method. This solution provided cooling uniformity for converter’s components. In addition, this technology could reduce the cost and complexity of inverters and provide reliable solutions. The coolant proposed liquid was also a good insulating liquid and provided protection against humidity and pollution. The efficiency reduction in the liquid cooled converter was 1% compared to 3% in the air-cooled converter. The use of this technology increased the PV system’s efficiency by 2% in extreme environmental conditions (i.e., high temperature).

Reference [18] proposed multilevel PV inverters connected in series. The system used medium frequency (MF) transformers to replace bulky, low efficient, and expensive conventional transformers. Under uniform solar insolation, the voltage vectors on both sides of the converter matched, thus, power factor was unity. However, under partial shading the voltage vectors didn’t match which led to changes in phase angle. As a result, the system’s power factor dropped. The proposed controller took care of this particular issue by monitoring P and Q and adjusting the inverters’ voltage vectors individually (i.e. there is no need to have a communication system among inverters or central converter) to produce maximum power factor.

Reference [7] evaluated inverters efficiency under dynamic conditions (i.e. partial
shading) without the need of a PV solar simulator. Under uniform solar irradiance, commercial inverters with perturb and observe (P&O) algorithm could provide sufficient Maximum Power Point Tracking (MPPT) of the PV system. The PV string under test was installed in a location where it became affected by partial shading during the early morning and late afternoon hours. Hence, testing started at 10 AM and continued until 6 PM. Heavy distortion occurred during the first hour of testing (i.e., 10 Am till 11 AM on the eastern part of the string). This resulted in the formation of two Local Maximum Power Points (L-MPP), which began at 3 PM and worsened till sunset. Under partial shading, three peaks occurred at 65, 155, and 200 V. The inverter started at 80% of $V_{oc}$ and incremented its operating point until it reached a local maximum, far below the Global Maximum Power Point (G-MPP). Consequently, commercial inverters were efficient when the system operated under uniform illumination. However, under shaded conditions, commercial inverter failed to locate MPP, which resulted in loss in overall efficiency by 30%.

Reference [19] studied four 250 kWp PV systems that were installed in different locations in Europe. $V_{RMS}$ and $I_{RMS}$ on the AC side and $V_{MPP}$ and $I_{MPP}$ on the DC side were collected in SQL databases using direct-attached storage (DAS) using one-second resolution. Performance ratio (PR) was used to evaluate the overall losses in the system due to temperature, irradiance, component inefficiencies, failures, wiring, inverter inefficiencies and mismatch. Different cell materials were investigated. Polycrystalline and Monocrystalline performed well under low irradiance, but the performance dropped slightly under high irradiance due to the increase in temperature. Thin film performance under low irradiance was not satisfactory compared to crystalline modules. This could be
due to the poor ability of inverters to control thin fill devices under low irradiance. The main issue seemed to be matching of the technologies to the inverter specifications.

In reference [20], Sandia laboratory developed a new simplified procedure by using a matched cell to assist industry in understanding performance, reliability, and safety characteristics. A matched cell mimicked the array under study in terms of spectral response, optical characteristics, thermal behavior and it was oriented in the same plane as the array. Using the matched reference cell, a simplified array performance model was developed. The model investigated the sensitivity of a PV array power production to solar availability, array temperature, spectral variation, and angle of incidence effects. Performance characteristics of a PV array and its inverter were monitored in real-time in addition to the weather and solar resource information. Array performance characterization (rating) was calculated by recording its parameters throughout the day. Measured rating of the array was 2% to 10% lower than the cumulative nameplate. DC input and AC output of the inverter were used to quantify the inverter performance, which were found to have linear relationship. The array utilization for the tested inverter fell within the range between 95% to 99%. Replacing the nameplate rating with the measured array rating gave more accurate measurement metrics. The resulting uncertainty for performance ratio (PR) metric was ±5% when using the array measured rating. Performance index’s uncertainty was ±3% when using the developed system performance model.

The study in [21] attempted to find shading conditions where distributed power electronics made the greatest impact on rooftop residential PV systems. Testing was done on two side-by-side systems. One is used as reference, which was equipped with a
standard inverter, and the other was equipped with distributed power electronics (i.e., using a micro-inverter with each PV module). Three stages of shading (i.e. 7%, 15%-19%, 25% reduction in irradiance) were applied to examine the systems. Under no shading, micro-inverter produced 5% more power than the system with a central inverter. Under light shading, the micro-inverter outperformed the standard inverter by 4% and annual energy production increased. Under moderate shading condition, the micro-inverter performed better than the standard inverter by 8%-12.6%. Under heavy shading condition, the micro-inverter performed better than the standard inverter by 15%-25%. Normalized method results were as follows: Under light shading, micro-inverter showed 3.7% performance increase. Under moderate shading, micro-inverter showed 7.8% performance increase. Under heavy shading, micro-inverter showed 12.3% increase in performance. This indicated that roughly half of performance loss due to shading could be recovered through utilizing micro-inverters. One of the reasons why an inverter presented more losses in the system performance was that MPPT algorithm was not able to find the optimum operating point in some shading scenarios.

Reference [22] investigated the use of distributed power electronics (in this case, using DC-DC converters at each module and one central inverter) over several aspects. The 200W to 240W panels were tested had 2%-3% variation in $I_{mp}$ and a 2.5% variation in the current near the MPP. This current mismatch can be recovered through MPPT of each DC-DC converter. The efficiency loss, however, caused by DC-DC device (i.e. power optimizer, which bucked and boosted the panel’s output voltage) might further reduce the benefit if installed per module. In addition, these devices can only work on a limited compatible set of PV panels and inverters and DC-DC converters combined with
inverters could lead to voltage instability. In general, the system’s reliability reduced as the number of system’s components increases. There was no sufficient data in the field to draw a conclusion about the reliability of the systems with distributed DC-DC converters although warranties and lifespan expectancy provided by the manufacturers were close to traditional inverters. In short, adding more solar panels will boost the energy production in needed unless space is not available in which case the use of these technologies might be justified.

Reference [4] discussed monitoring and controlling devices based on low-cost multi sensors node Wireless Sensor Networks (WSN) technology, which were implanted at the module level. The device assessed PV module performance in terms of power efficiency by utilizing I-V characteristics as well as temperature and irradiation. The device consists of a Master node that was connected to a Graphical User Interface (GUI) and wireless sensor node, which seemed to be able to monitor current, voltage, irradiance and temperature. Theoretical I-V curve was fitted to the measured curve to determine the health and performance of the panel. To avoid the data storage problem, only ten or five parameters were stored, depending on the implemented model.

The study in [23] employed low-cost photodiodes to produce low-cost sensor array for small/medium scale PV systems. The device’s aim was to function in single-row shading conditions. The low-cost sensor lacked accuracy, so it was necessary to calibrate it based on the direct sunlight. The device was able to show that the decrease in power production correlated with the amount of shading. If the module was oriented properly, row-shading could result in as much as 38% of power reduction, but when it is oriented improperly, power loss reached as much as 92%.
Paper [24] proposed Electric Double Layer Capacitors (EDLC) to more efficiently harness the power that exists in the shaded PV modules. They also proposed a method that prevented the Hill Climbing power trackers from converging at local maximum by the use of control system and compensator circuitries.

The study in [25] derived parameters (i.e. Final System Yield, array yield, reference yield, array capture losses, system losses, performance ratio, array output energy, system output energy, nominal capacity, irradiation on plane and irradiance at STC) to evaluate and analyze the overall PV system performance during a full year period. The system’s performance relied strongly on loss factors, power condition unit (PCU) losses, and PV array temperature. Other losses, mismatch, PV array temperature and PCU losses appeared to decrease the performance ratio (PR) of the system. 75% PR indicated the system had trouble with obstructions.

Paper [26] claimed that the implemented Zegbee-enabled electronic system could monitor PV module performance with low power consumption and cost-effectiveness. A central station (i.e., a computer) via USB wireless connection was utilized to create the communication system. Faults and partial shading conditions were imposed to test the performance of this wireless technology system. The system was able to record voltage and current changes due to non-ideal conditions.

The study [27] investigated the use of IR-imaging for monitoring large-scale PV systems. It concluded that IR-imaging of PV-plants under operation conditions was a reliable and fast method to check for modules’ performance. Modules that underwent a temperature rise were defective. The types of defect that IR-imaging could detect were malfunctioning bypass sub-string, fractured cell, deficient soldering and short-circuit
cells. Operating temperature could give an indication of the defect type.

Paper [28] proposed a mathematical formula to model partially shaded PV module. It showed that diodes configuration dictated the power loss in the module. It was not feasible to use more than 6 diodes in PV modules. Extensive use of diodes would increase module’s cost and would not significantly impact power savings.

Paper [29] described the analytical formulas, parameters and algorithm in order to analytically simulate PV systems of any size. However, the paper assumed that a bypass diode was installed at the cell level, which is not feasible in practice.

This thesis investigates challenges related to mismatch, shading, power optimization, monitoring, modeling, and simulating photovoltaic systems. Chapter 2 sheds light on maximum power point tracking (MPPT) methods. It also discusses the feasibility and performance of the new commercially available power optimizers with wireless monitoring technology in comparison to the conventional inverters. It briefly touches upon and explains the different power conversion circuits.

A commercially available Pvsyst V5.74 simulation tool facilitates the evaluation of two systems’ performance that are working under full illumination condition (i.e., one contains a power optimizer and the other contains a conventional inverter). The evaluation method takes into consideration the cost analysis, the yields parameters, and systems’ losses. The study outcome suggests that the systems with power optimizers and wireless monitoring technology are unreasonably expensive even though they outperform the conventional systems.

Chapter 3 examines IR-imaging’s ability of providing accurate diagnostic information about PV systems with different sizes. The chapter briefly compares IR-
imaging monitoring method to the wireless monitoring method. The proposed Matlab-based implementation of image processing techniques provides more accurate diagnosis of the system when images are hard to interpret. The proposed method proves to give more accurate results than the other method mentioned in a previous study.

Lastly, Chapter 4 models field data test of a conventional PV system under mismatch and partial shading conditions. The proposed Matlab-based program analytically models and matches the behavior of small-scale systems under various shading and orientation mismatch conditions. The simulation tool utilizes the commonly known diode-modeling formula to represent PV modules of 6 diodes. This study also examines the behavior of the system under unclear weather and cloudy conditions. The proposed Matlab-based analytical modeling program is able to match the collected field data with decent accuracy (3%).
CHAPTER 2: MAXIMIZING AND MONITORING PHOTOVOLTAIC POWER PRODUCTION

When mismatch and shading occur, PV systems may suffer from significant power losses. For instance, a shadow could cause a reduction in power over 30 times its physical size, this is highly depend on the number of bypass diodes in the module [16]. This reduction in power can be partially compensated if harnessing power means having the ability to operate at the optimum power point of the system regardless of the P-V curve shape [21], [22].

Therefore, the chapter explains different PV systems’ architectures to harnessing power. First, it investigates maximum power point tracking strategies: perturb and observe, incremental conductance, current sweep method, and constant voltage. Next, it sheds light on the methods of harnessing PV modules’ power. The conventional method is the most popular method, which employs a central inverter to harness the maximum power in the system. The second method relies on micro-inverters and optimizers installed at module level and it briefly explains simple optimizers’ circuits and their voltage and current relationship.

2.0 Maximum Power Point Tracking Methods

Controllers usually follow one of three types of strategies to optimize the power output of an array. Maximum power point trackers may implement different algorithms and switch between them based on the operating conditions of the array [30].
2.0.1 Perturb and Observe

In this method the controller adjusts the voltage by a small amount from the array, and measures power. If the power increases, further adjustments in that direction are made until power no longer increases. This is called the perturb and observe method and is most common, although this method can result in oscillations of power output [31], [32]. It is also referred to as a hill climbing method, because it depends on the rise of the curve of power against voltage below the maximum power point and the fall above that point [33]. Perturb and observe is the most commonly used MPPT method due to its ease of implementation. -Perturb and observe method may result in top-level efficiency, provided that a proper predictive and adaptive hill climbing strategy is adopted [34], [35].

2.0.2 Incremental Conductance

In the incremental conductance method, the controller measures incremental changes in array current and voltage to predict the effect of a voltage change. This method requires more computation in the controller, but can track changing conditions more rapidly than the perturb and observe method (P&O). Like the P&O algorithm, it can produce oscillations in power output [36]. This method utilizes the incremental conductance (dI/dV) of the photovoltaic array to compute the sign of the change in power with respect to voltage (dP/dV) [37].

The incremental conductance method computes the maximum power point by comparing the incremental conductance (IΔ / VΔ) to the array conductance (I / V). When these two are the same (I / V = IΔ / VΔ), the output voltage is the MPP voltage. The controller maintains this voltage until the irradiation changes and the process is repeated.
2.0.3 Current Sweep Method

The current sweep method uses a sweep waveform for the PV array current such that the I-V characteristic of the PV array is obtained and updated at fixed time intervals. The maximum power point voltage can then be computed from the characteristic curve at the same intervals [38], [39].

2.0.4 Constant Voltage

The term "constant voltage" in MPP tracking is used to describe different techniques by different authors, one in which the output voltage is regulated to a constant value under all conditions and one in which the output voltage is regulated based on a constant ratio to the measured open circuit voltage ($V_{OC}$). If the output voltage is held constant, there is no attempt to track the maximum power point, so it is not a maximum power point tracking technique in a strict sense, though it does have some advantages in cases when the MPP tracking tends to fail, and thus it is sometimes used to supplement an MPPT method in those cases.

In the "constant voltage" MPPT method, the power delivered to the load is momentarily interrupted and the open-circuit voltage with zero current is measured. The controller then resumes operation with the voltage controlled at a fixed ratio, such as 0.76, of the open-circuit voltage $V_{OC}$. This is usually a value, which has been determined to be the maximum power point, either empirically or based on modeling, for expected operating conditions. The operating point of the PV array is thus kept near the MPP by regulating the array voltage and matching it to the fixed reference voltage $V_{ref}=kV_{OC}$. The value of $V_{ref}$ may also be chosen to give optimal performance relative to other factors as
well as the MPP, but the central idea in this technique is that $V_{\text{ref}}$ is determined as a ratio to $V_{\text{OC}}$.

One of the inherent approximations to the "constant voltage" ratio method is that the ratio of the MPP voltage to $V_{\text{OC}}$ is only approximately constant, so it leaves room for further possible optimization.

2.1 Conventional Photovoltaic Systems

Traditional solar inverters perform MPPT for an entire array as a whole. In such systems the same current, dictated by the inverter, flows through all panels in the string. Because different panels have different I-V curves and different MPPs (due to manufacturing tolerance, partial shading, etc. [41]), this architecture means some panels will be performing below their MPP, resulting in the loss of energy [42].

Because of their sequential wiring, power mismatch between PV modules within a string can lead to a drastic and disproportionate loss of power from the entire solar array. Shading of as little as 9% of the entire surface array of a PV system can, in some circumstances, lead to a system-wide power loss of as much as 54% [43]. Although this problem is most notable with "large" events like a passing shadow, even the tiniest differences in panel performance, due to dirt, differential aging or tiny differences during manufacturing, can make the array as a whole operate away from its best MPPT point. "Panel matching" is an important part of solar array design.
2.2 Photovoltaic System with Power Optimizers

The above problems have led to a number of different potential solutions that isolate panels individually or into much smaller groups (2 to 3 panels) in an effort to provide MPPT that avoids the problems of large strings.

One solution, the micro-inverter, places the entire power conversion system directly on the back of each panel. This allows the system to track the MPPT for each panel, and directly output maximum AC power to the grid. These panels are wired in parallel, so even the failure of one of the panels or micro-inverters will not lead to a loss of power from the string. However, this approach has the disadvantage of distributing the power conversion circuitry, which, in theory, is the expensive part of the system. Micro-inverters, at least as late as early 2011, had a significantly higher price per watt compared to conventional inverters.

This leads, naturally, to the power optimizer concept, where only the MPPT system is distributed to the panels. In this case the conversion from DC to AC takes place in a single inverter, one that lacks the MPPT hardware or has it disabled. According to its supporters, this "hybrid" approach produces the lowest-cost overall solution, while still maintaining the advantages of the micro-inverter approach.

Some companies are now placing peak power point converters (i.e., so-called power optimizers) into individual panels, allowing each to operate at peak efficiency despite uneven shading, soiling or electrical mismatch.

A power optimizer is a DC to DC converter technology developed to maximize the energy harvest from solar photovoltaic systems. This is achieved by individually
tuning the performance of the panel through maximum power point tracking and optionally tuning the output to match the performance of the string inverter. Power optimizers are especially useful when the performance of the power generating components in a distributed system varies extensively depending on differences in equipment, shading of light, or when they are installed facing different directions or in widely separated locations.

Power optimizers for solar applications can be similar to micro-inverters in that both systems attempt to isolate individual panels in order to improve overall system performance. A smart module is a power optimizer integrated into a solar module. A micro-inverter essentially combines a power optimizer with a small inverter in a single case that is used on every panel, while the power optimizer leaves the inverter in a separate box and uses only one inverter for the entire array. The claimed advantage to this "hybrid" approach is lower overall system cost.

Basically, power optimizers are power electronics circuits, which can be classified in three different topologies: buck, boost and buck-boost. In comparison to linear voltage regulators these optimizers have outstanding circuit efficiency. Voltage regulators dissipate the excess power as heat while power optimizers employ high frequency switching methods to reach the desirable power output.

The purpose of buck converter, as shown in Figure 2.0, is to step down the voltage and step up the current fed to the circuit. Buck converters give the best result when installed only on the modules that are subject to partial shading [22].
The relation between the input and output voltage of step down circuit in respect to the switch duty cycle (D) is shown in equation 2.0 under continuous conduction mode. Equation 2.1 illustrates the relationship between the input and the output power under ideal operation condition. Theoretically, this equation implies that the circuit has very negligible power losses due to power conversion. In equation 2.3, the output current is proportional to the input current and the switching duty cycle.

\[ V_o = D V_i \quad (2.0) \]
\[ V_i I_i = V_o I_o \quad (2.1) \]
\[ I_o = \frac{I_i}{D} \quad (2.3) \]

Boost converter (figure 2.1) is a DC-DC power electronics circuit that increases the fed voltage. This circuit sometimes is called current step down circuit due to the reverse relation between voltage and current. A boost converter works best on modules that have orientation and tilt angle mismatch and are configured in parallel [22].

Figure 2.0: Buck converter circuit

Figure 2.1: Boost converter circuit
Equation 2.4 describes the input and the output voltage relation in respect to the duty cycle (D) under the continuous conduction mode. Note that the duty cycle (D) and the input voltage can vary to achieve fixed output voltage ($V_o$). The input power of this circuit flows to the output terminal with insignificant losses in the components (equation 2.5). When input voltage is boosted current reduction relationship is shown by equation 2.6.

$$V_o = \frac{V_i}{(1-D)} \quad (2.4)$$

$$V_iI_i = V_oI_o \quad (2.5)$$

$$I_o = I_i(1-D) \quad (2.6)$$

Buck-boost power converter is a two-stage power electronics circuit that has the ability to step up or step down voltage and current. Buck-boost converter is capable of handling PV system with mismatch and shading obstacles. Figure 2.2 exhibits Simple circuit of buck-boost converter.

Equation 2.7 determines the association between input and output voltage. Note that the output voltage’s terminal receives reversed voltage polarity, since the current flows in the opposite direction. As the other circuit, equation 2.8 addresses the power
input and output relation in the circuit. The output current of this circuit is calculated in equation 2.9.

\[ V_o = \frac{V_i D}{(1-D)} \] (2.7)

\[ V_i I_i = V_o I_o \] (2.8)

\[ I_o = \frac{I_i (1-D)}{D} \] (2.9)

### 2.3 Commercially Available Power Optimizers with Monitoring Devices

There is an ongoing effort to develop cheap and reliable Zigbee wireless devices that solely monitor and diagnose PV systems and have the ability to shutdown the operation in case of emergencies [4], [26]. However, this section examines some of the commercial products that are gaining attention in today’s market. Most of these products have power optimization feature in addition to performance monitoring. In general, systems with monitoring devices need sophisticated software packages to synchronize the control and monitoring processes. In addition, some systems require data storage to collect data and provide comparison on the modules’ performance if needed. To maximize profits, the power optimizers’ vendors target residential and utility scale PV customers. Nevertheless, optimizers tend to be very expensive when installed in large-scale systems and their effects on the PV systems’ reliability are unknown due to the lack of comprehensive studies in this field [22]. Table 2.0 shows some of the commercially available power-distributed products’ characteristics.
<table>
<thead>
<tr>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Azuray</td>
<td>AP260</td>
<td>8-70</td>
<td>300 W</td>
<td>Buck</td>
<td>0-70 V</td>
<td>ACM 300</td>
</tr>
<tr>
<td>Azuray</td>
<td>AP250</td>
<td>14-80</td>
<td>250 W</td>
<td>Buck</td>
<td>0-80 V</td>
<td>ACM 300</td>
</tr>
<tr>
<td>Tigo</td>
<td>MM-ES50</td>
<td>16-48</td>
<td>350 W</td>
<td>Buck</td>
<td>0-48 V</td>
<td>Maximizer MMU</td>
</tr>
<tr>
<td>SolarEdge</td>
<td>P300</td>
<td>8-48 V</td>
<td>300 W</td>
<td>Buck-boost</td>
<td>0-60 V</td>
<td>Integrated with the inverter</td>
</tr>
</tbody>
</table>

Table 2.0: Commercial power distributed devices [22]

The Azuray’s AP260 DC-DC buck converter, an advancement of the older model AP250, came onto the market in late 2011. An AP260 device can match the MPP of each panel to the string inverter. In addition, it has the ability to shut off the power output in case of a fire emergency. The maker claims that this product has an efficiency of 99% and it can operate in harsh temperature conditions (i.e. -40°C to 80°C). Also, the maker claims that the product can function for 25 years without requiring maintenance and it comes with a limited warranty. The manufacturer recommends module level installation of AP260 to generate the optimum results. In order to remotely monitor and control the system, an Azuray ACM 300 communication gateway has to be installed. This servers up a web page that is provided by the vendor via Ethernet cable, connected directly to a computer or a network. These optimizers can work with most commercially available inverters [56].

Solar Edge P300 buck/boost DC-DC converter was introduced to the market in late 2013. This particular model can be installed in up to 60 modules at once. The manufacturer claims that the device maximum efficiency is 99.5% and the weighted efficiency is 98.8%. In addition, this system endures extreme operating temperatures.
(-40°C to 85°C). In terms of warranty, this system comes with a 20 years limited warranty. However, it requires the installation of SolarEdge inverters that come in one phase or three phase options with different power rating. The inverters communicate to the Internet via broadband or wireless Zigbee technology. The monitoring aspect of the system is available for free for 25 years. The system has to be connected to the internet as monitoring is done through the manufacturer’s website. In addition, this system has emergency shutdown protection capability. This device is a module level device. All panels have to have one in order to be integrated to the special inverter [57].

Tigo Energy’s MM-ES50 impedance matching buck converter was introduced to the market in 2012. This device can endure lower operating temperatures in comparison to the other discussed models. Its temperature range is -30°C to 70°C. It is a module level device and it can be configured with standard inverters. However, the optimizer cannot function solely. It is necessary to install the whole communication package to have a working system. To control optimizers and monitor performance, Tigo Maximizer Management Unit (MMU) coupled with Tigo Gateway are mandatory. The MMU connects to data center via CAT5-Ethernet. Like the other competitors, Tigo provides a web based monitoring interface. The manufacturer argues that the conversion efficiency of the optimizers is 99.5%. In addition, this device comes with a 20 year limited warranty. Tigo has the emergency shut off feature as well as a remote disconnectivity feature [58].

2.4 Simulation Setup and Evaluation Method

This section discusses the simulation tool, geographical location, sun path, and the specification of local system under study, which is equipped with conventional inverter and power optimizers. At this stage of the research, comparing both systems’
performance in real-settings is unfeasible, since it is financially expensive and requires an extensive period of time for data collection. Studies [44] and [45] took advantage of the simulation tool PVsyst to evaluate PV power systems, because it had the ability to make use of the real meteorological data available online [54]. Besides, it has an extensive database for the commercially available power system equipment such as inverters, optimizers, and solar panels. It also takes into account the effects of mismatch, shading, and other losses when simulating PV systems. In this study, PVsyst 5.74V performs the simulation of a system with a standard inverter that mimics the system installed on the roof of the Engineering Building (TBE) and a similar size system with optimizers added.

Both simulated systems share, location, and meteorological settings. Table 2.1 shows the shared geographical specifications for both systems. In terms of shading, the simulation intended to evaluate the systems’ performance with and without partial shading presence. The system is real (Fig. 2.5) and operates on a single-phase standard DC-AC inverter. Second system operates on a single-phase specialized inverter that is connected to DC-DC buck/boost optimizers at the module level.

<table>
<thead>
<tr>
<th>Geographical Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geographical Site</td>
</tr>
<tr>
<td>Latitude</td>
</tr>
<tr>
<td>Longitude</td>
</tr>
<tr>
<td>Altitude</td>
</tr>
<tr>
<td>Time Zone</td>
</tr>
<tr>
<td>Albedo</td>
</tr>
</tbody>
</table>

Table 2.1: Geographical parameters of both systems.

Both systems used the same module technology. They are both tilted and oriented in the same exact way to eliminate the effect of mismatch that is caused by orientation
and technology. The systems’ tilt angle is 32° and they are both facing south (i.e. azimuth 0°). The sun path diagram (Fig. 2.3) shows the position of the sun throughout the solar year for the given azimuth and tilt angle when shading is not introduced to the systems. The meteorological data used in the simulator is collected from the National Solar Radiation Data Base (i.e., 1991-2005 Typical Meteorological Year data with a one-hour resolution) [55].

![Sun path diagram at azimuth 0° and 32° tilt](image)

**Figure 2.3: Sun path diagram at azimuth 0° and 32° tilt**

When partial shading is introduced to the systems under study, the sun radiation will be blocked during certain times throughout the day. The impact of partial shading is shown in figure 2.4. It is clear that the introduced partial shading mostly affects the local system’s sun path during October, January, November, and December.
Table 2.2 exhibits the picked module specifications at irradiance=1000 W/m². Both systems consist of 10 modules that are configured in series to produce a nominal power capacity that is equal to 2.05 kWp under Standard Test Conditions (STC). The characteristics for both systems’ inverters are presented in table 2.3.

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Kyocera</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>KD205GX-LPU</td>
</tr>
<tr>
<td>P_{Max}</td>
<td>205 W</td>
</tr>
<tr>
<td>V_{Max}</td>
<td>26.6 V</td>
</tr>
<tr>
<td>I_{Max}</td>
<td>7.71 A</td>
</tr>
<tr>
<td>V_{oc}</td>
<td>33.2 V</td>
</tr>
<tr>
<td>I_{sc}</td>
<td>8.36 A</td>
</tr>
</tbody>
</table>

Table 2.2: Module’s specification under full irradiance.
<table>
<thead>
<tr>
<th></th>
<th>System 1</th>
<th>System 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Maker</strong></td>
<td>SMA</td>
<td>SolarEdge</td>
</tr>
<tr>
<td><strong>Model</strong></td>
<td>Sunny Boy SB 3000 U-240</td>
<td>SE3000A-US 240V</td>
</tr>
<tr>
<td><strong>Nominal Power</strong></td>
<td>3.0 kW AC</td>
<td>3.0 kW AC</td>
</tr>
<tr>
<td><strong>Operating Voltage (DC)</strong></td>
<td>200-400 V</td>
<td>350 V</td>
</tr>
</tbody>
</table>

Table 2.3: Inverters characteristics

Each local system’s module contains 54 Si-poly cells. The system consists of 10 modules connected in series (figure 2.5). The maximum power capacity ($P_{\text{max}}$) of the system under (STC) and full irradiance (i.e. 1000 W/m$^2$) is approximately 2.05 kW. Therefore, maximum peak current ($I_{\text{max}}$) and voltage ($V_{\text{max}}$) respectively are 7.71 A and 266 V. The system’s short circuit ($I_{\text{sc}}$) and open circuit voltage ($V_{\text{oc}}$) are 8.36 A and 332 V. However, due to aging, soiling, solar irradiance intensity, and rise in temperature when measurement is taken, maximum power capacity ($P_{\text{max}}$) of the system is found to be 1.558 kW, $V_{\text{max}} = 214.80V$ and $I_{\text{max}} = 7.260A$.

Respectively, the general schematics of the System 1 with standard inverter and the System 2 with power optimizers are presented in figure 2.6 and 2.7. Generation of power in PV systems goes through three main stages. Stage one consists of PV modules that are configured in series in this case to convert the sun irradiance into DC power. Second stage takes the DC power and converts it to AC power through inverters. The last
stage utilizes the produced power and directly injects it to either the local load or the grid. In System 2, the system contains the power optimizers at each individual module, which is different from System 1 conventional inverter. At this stage, power optimizers adjust the power produced by the PV modules to reach specific voltage, which the inverter in second stage dictates.

![Diagram of PV System 1 with conventional inverter](image1)

**Figure 2.6: General schematic of PV System 1 with conventional inverter**

![Diagram of System 2 with power optimizers](image2)

**Figure 2.7: General schematic for System 2 with power optimizers**

Many variables that are associated with the systems' losses, input, output, efficiency, and performance have to be taken in consideration when evaluating PV systems [5], [19]. Normalized System Production ($Y_F$) or Final System Yield gives
indication of the PV system AC useful energy production. Its measurement unit is (kWh/kWp/day) and is shown in equation 2.10. $E_P$ is the system output energy and the $P_o$ is the nominal power rating the system.

$$Y_F = \frac{E_P}{P_o} \quad (2.10)$$

To determine the actual system performance against theoretical performance ($Y_R$), Ratio (PR) relationship in equation (2.11) is used, which has unity measurement for maximum value. ($Y_R$) is the ideal array yield according to the nominal power rating provided by the manufacturer without any loss.

$$PR = \frac{Y_F}{Y_R} \quad (2.11)$$

System Loss ($L_S$) of the system, which is measured in (kWh/kWp/day), accounts for the losses occur in the system’s electronics and inverter. Equation 2.12 shows the losses in the system, which is defined as the array ideal DC energy ($Y_A$) subtracted from useful AC energy of the system ($Y_F$).

$$L_S = Y_A - Y_F \quad (2.12)$$

2.6 Simulation Results and Discussion

The parameters discussed in the previous section are put to use and are going to be computed in the two case studies. The case study will consist of two small-scale systems operating under normal condition. The second case study investigates two small-scale systems under full partial shading cause by a tree. Throughout the discussion System 1 indicates the system with standard inverters and System 2 is referred to the system with distributed power optimizers and monitoring capability. In the following graphs, System 1 is represented in blue color bars while the System 2’s color is red.
2.6.1 Small-Scale Systems without Partial Shading

Both systems’ equipment characteristics and orientation are mentioned in the previous sections. For both systems, the installed array power capacity is 2kWp (i.e. 10 modules in series). System 1’s and System 2’s normalized useful AC energy production (Final Yield) is illustrated in figure 2.8. System 1’s Final Yield is 4.79 kWh/kWp/day while System 2’s is 4.89 kWh/kWp/day. The average percentage increase of Final Yield in respect to System 1 is 2.1%. This increase in production is due to the optimizers’ higher efficiency, and their ability in operating at the MPP for each module.

![Final Yield Graph](image)

*Figure 2.8: Small-scale with systems’ final yield without partial shading.*

The average monthly losses due to energy conversion from DC to AC are illustrated in figure 2.9. It is clear that the system with a standard inverter suffers from higher system losses due to inverter stand-by mode (i.e., the period required by the inverter to detect the MPP) and its components’ inefficiency [25]. In addition, there is a ±3% power variation among the system panels that leads to module array mismatch loss. The mismatch forces the standard inverter to operate on the average MPP. Therefore, System 1 has additional 0.06 kWh/kWp/day System Losses compared to System 2. The average percentage increase in System Losses between System1 and System2 is approximated to be 33% in respect to System 2, which seems to be significant.
Figure 2.9: Small-scale systems’ system losses without partial shading.

Performance Ratio measures the quality of the power plant. This parameter shows the overall losses in the system due to module temperature, incomplete utilization of irradiance, system component inefficiency, and mismatch [19]. Figure 2.10 shows that System 2 has an improved performance ratio that is equal to 1.6% when compared to System 1. When Performance Ratio falls below 75%, it indicates serious issues associated obstructions [25]. Both systems have exceeded the 75% threshold. Subsequently, they are expected to perform stably without faults [25]. Note that PR’s magnitude is slightly lower during summer months due to the negative impact of ambient temperature.

Figure 2.10: Small-scale systems’ performance ratio without partial shading
To further visualize the conversion process from power irradiance to AC injected power to the grid, a loss diagram (figure 2.11) is shown. System 1’s parameters are to the left of the diagram while the right of the diagram represents System 2’s parameters. The diagram illustrates that System 1 undergoes higher and more influential losses such as module mismatch loss (2.1%), wiring loss (1.3%) and inverter loss (4.8%). However, System 2 has higher inverter threshold loss (which is only 0.1%), since it needs to step the voltage up and down to a certain threshold operate at fixed voltage.

Figure 2.11: Small-Scale Systems’ loss diagram

The distribution of the output power injected into the grid is exhibited in figure 2.12. It is clear that there is a slight shift in power as well as a slight increase in magnitude for System 2 over System 1. This is due to the optimizers’ power conversion
efficiency and its fast tracking algorithm. For System 1, the maximum peak of effective power occurs at 1.4 kW with energy magnitude value that is equal to 133 kWh. On the other hand, System 2’s maximum peak occurs at 1.42 kW with a solar insolation magnitude value of 141 kWh.

Figure 2.12: Small-scale systems’ array power distribution

Figure 2.13a describes System 1’s operating voltage behavior while figure 2.13b shows System 2’s operating voltage distribution. System 1’s conventional inverter has a wider voltage distribution range (i.e. between 200 V to 262 V), since it is constantly looking for the average MPP of the overall system. It appears that variation in weather conditions forces system to operate at 1.4 kWp MPP, which occurs at 200 V. System 1 approximately spends 392 hours operating at 200 V. On the other hand, System 2 operates at a fixed voltage of 350 V all the time, since the optimizers (DC-DC converters) boost the output voltage in each module to match it with the specialized inverter’s operating voltage. Therefore, System 2 has a more efficient power conversion than System 1.
Overall, System 2 produces only 76 kWh (i.e., 2.12% more energy than System 1) more per year than System 1 under no partial shading conditions. Assuming that both systems are well maintained over their lifespan, which are expected to be 25 years, System 2 will produce 1900 kWh more energy than System 1. If the local utility company does not adopt the Time-Of-Use Pricing and continues selling energy at the same rate (i.e., $0.11 per kWh), System 2 can approximately save the user about $8.36 per year and $209 for 25 years. Accordingly, System 2 slightly outperformed System 1 in terms of efficiency under no partial shading conditions. However, the dollar savings associated with System 2 are negligible compared to the equipment cost. For example, power optimizer costs $70 per module and the special inverter costs $1,305. Moreover, the
mandatory communication accessories cost approximately $425. Excluding the price of labor, wires, modules and the monitoring software (which comes for free, but it has to be renewed for money after a period of time), the approximate total cost of System 2 is $2430. On the other hand, the standard inverter costs $1535 and there are no special devices that have to be installed at the module level.

2.6.2 Small-Scale Systems under Partial Shading

This section investigates the same exact systems in the previous section, but under partial shading condition that is imposed by a nearby structure such as a tree. Figure 2.14 shows the system under study and the shading object position. The tree is located 6.5 m away from the system and it has a height that is equal to 5 m. The tree’s diameter is 2 m. The overall loss in the system’s energy due to partial shading is only 1.3%, which is due to the shading structure’s large distance and short height.

![Figure 2.14: PV system (2 kWp) with partial shading due to nearby structure](image)

The final yield ($Y_F$) of both systems is shown in figure 2.15. By examining the graph, it appears that the system with the power optimizing and wireless technology has an insignificant increase in the net useful AC generated energy at this particular partial shading condition. System 1’s final yield is 4.73 kWh/kWp/day. On the contrary, System 2’s final yield is 4.83 kWh/kWp/day. Since the systems’ equipment efficiencies are fixed,
it is clear that the gap between the two systems’ final yield is still the same (0.1 kWh/kWp/day), even when partial shading is imposed on the systems.

![Graph showing final yield][1]

**Figure 2.15: Small-scale systems' final yield under partial shading.**

When it comes to systems’ losses (figure 2.16), it is clear that System 2 continues to have less loss in the equipment than System 1. System 2 has a better DC energy to AC energy conversion performance. System 1’s average system loss is 0.24 kWh/kWp/day. On the other hand, System 2’s average system loss is 0.18 kWh/kWp/day, due to its better inversion method and equipment efficiencies.

![Graph showing system losses][2]

**Figure 2.16: Small-scale systems' system losses under partial shading.**

Performance ratio is an explicit indication to examine the power quality of the power plants. Figure 2.17 displays the PR of both systems for the purpose of comparing the two different architectures under partial shading condition. It is obvious that System 2

![Graph showing performance ratio][3]
has noticeable increase of PR in respect to System 1. System 1’s average PR is 0.743, which falls below the acceptable threshold (i.e., 0.75). On the other hand, System 2’s power optimizers boosts the system performance just enough to meet the industry’s acceptable standard. System 2 has a PR that is equal to 0.75 even under nearby shading.

Figure 2.17: Small-scale systems’ performance ratio under partial shading.

Figure 2.18 shows the overall losses diagram that occurs in both systems under examination. System 1’s parameters are to the left of the diagram while the right of the diagram represents System 2’s parameters. The diagram exhibits that System 1 undergoes higher module mismatch loss (2.1%), wiring loss (1.3%), and inverter loss (4.8%). However, System 2 has higher inverter threshold loss (which is only 0.1%) since it needs to step up the voltage to a certain threshold to operate at fixed voltage. System 2 produces 2.14% more energy than System 1, which is a negligible difference. Therefore, the cost of System 2 equipment cannot be justified under partial shading that is created by a distant and small shading structure.
Figure 2.18: Losses diagram for systems under partial shading
CHAPTER 3: PHOTOVOLTAIC SYSTEM DIAGNOSIS AND MONITORING VIA IR-IMAGING

To maximize a PV system’s efficiency and performance over its lifetime, monitoring means are required to highlight fault occurrences and reduction of power. Without wasting too much time and manpower, it is crucial to have this process quickly react to the reduction in power and accurately pinpoint the source of trouble to avoid the economical damage and sharp reduction in power associated with the system’s downtime [46].

Therefore, Infrared (IR) thermography technique has been employed for over a decade and it is becoming increasingly important to perform failure analysis on large-scale PV systems due to its fast performance and affordable cost in comparison to other techniques such as wireless monitoring technology and I-V tracker devices [46]. Furthermore, the market for wireless and power optimizer technology is not well established yet. Therefore, maintenance and customer support for these devices will be difficult in case of a provider’s bankruptcy [47], [48]. Under suitable weather conditions, IR cameras can recognize a number of defects such as cell fracture, faulty soldering shunted cell, bypassed substring as well as pollution based on the thermal behavior of PV modules without physical contact and during the operating time, which can be a very daunting task with conventional diagnosing tools [27]. Further, IR imaging technique can reliably perform on small-scale and large-scale (i.e. system larger than 1MW) PV plants [27].

However, sometimes pictures taken by IR camera can be difficult to interpret. Thus, it is beneficial to use software tool to facilitate the diagnostic process. The result of
taking a picture of a PV module with an IR camera leads to three possible scenarios. In the first scenario, the picture is clear and no abnormality is observed. In the second scenario, defects can be clearly identified in the module. In the third scenario, the IR image is not clear and processing is highly beneficial to draw conclusion about the status of the module under examination.

In [49], a simple algorithm was proposed to diagnose the image in the third scenario and draw a conclusion about the module status, but the used method did not provide robust results and sometimes highlighted regions prove not to be a threat to the system. This study proposes a more accurate Matlab-based method to pinpoint the area of abnormality in the module, which is an extension of the strategy proposed in [49].

The proposed method performs Gaussian and median filtering, Canny edge detection, Hough line detection, and connected component operation to extract information from each cell separately. Figure 3.0 shows the stages of the proposed algorithm.

![Figure 3.0: Proposed algorithm for IR-imaging](image)
3.0 Experiment Settings

The experiment is performed on a 2 kWp grid tied PV system where the system is facing south and its planes are tilted 32° to optimize the system power production throughout the year. Each individual module has characteristics is shown in table 2.2. To observe the module performance at peak power production period pictures are collected at noon when the sun’s irradiance is perpendicular on the modules’ surface. A hand-held camera Flir ThermaCam E45 is fixed on a tripod to collect pictures of the entire system’s modules. The camera has a 600X800 resolution and the temperature is approximately set within the following range: (84.5 ° F to 146.8° F).

3.1 Algorithm Description

This section elaborates on the techniques the algorithm used to generate the resultant images. Basically, it consists of filtering, detection, thresholding and segmentation, and temperature mapping stages.

3.1.1 Gaussian Filter

Filtering images is a typical pre-processing step in the image processing field. Therefore, the purpose of this step is to smooth the image and remove noise and unnecessary details. Gaussian filter is a low pass linear filter that attenuates high frequency components. It is used to smooth images by reducing noise and details, and it is also called a blur filter. After testing the Gaussian filter on several images, it is found that 3x3 Gaussian kernel with standard deviation, σ=3 gives the optimum result for the set of collected images. The low pass smoothing filter kernel is created by equation (3.0). Subsequently, the unfiltered image is convoluted with the generated kernel.
\[ h_g(x, y) = e^{-(x^2 + y^2)/2\sigma^2} \quad (3.0) \]

### 3.1.2 Median Filter

This non-linear filter is used to smooth the image and filter noise that a linear filter is unable to remove (i.e. Gaussian filter). A 5x5 window is used in this stage. This filter replaces the center pixel value for a region in an image with median value of all pixels within the region of 5x5 window size. For instance, suppose that there is a given 3x3 region of an unfiltered image, which is illustrated in figure 3.1a. The algorithm for the median filter finds the median value of the entire pixels values in the unfiltered region of the image and then replaces the center pixel with the median value found by the algorithm as shown in figure 3.1b.

![Figure 3.1: Median filter: a) Unfiltered image region. b) Filtered image region](image)

### 3.1.3 Canny Edge Detection

In this study, Canny Edge Detection is not used to highlight regions of interests as in [49]. On the contrary, Canny is used here to highlight module’s fine edges. This algorithm utilizes the vertical and horizontal gradient to the find the absolute gradient magnitude for each point in the image, which represent the edge strength in equation 3.2. Large intensity gradients are more likely to correspond to edges. Then, the direction is calculated for each pixel by equation 3.3. All directions are rounded to only present horizontal, vertical and diagonal angles. From the computed direction and gradient magnitude, non-maximal suppression, which is an edge thinning process, can be easily
computed. Lastly, hysteresis is used to eliminate the streaking of edges contour. Canny edge detection facilitates the process for Hough line detection to provide higher line detection accuracy. The low threshold of Canny is set to 0.0067 and the high threshold is 0.0069. Low threshold is for gradient high edge sensitivity. High threshold is for low threshold sensitivity.

\[
G = \sqrt{G_x + G_y} \quad (3.2)
\]

\[
\theta = \tan^{-1}(G_y/G_x) \quad (3.3)
\]

### 3.1.4 Hough Line Detection

At first, the parameters of lines are estimated, and then presented by the Hough transform matrix \( H \), angle \( \theta \), and distance \( r_i \). Thresholding the Hough transform matrix will result in desired peak lines. The automated threshold is set to 26 \% of the maximum peak value in the matrix. Hough line detection uses unconventional line representation to avoid the infinite line slope values when vertical lines exist in the image, which is shown in equation 3.4. Figure 3.2 depicts hough line representation in the x-y plane.

\[
r_i = x \cos(\theta_i) + y \sin(\theta_i), \text{where} -90 < \theta_i < 90 \quad (3.4)
\]
3.1.5 Thresholding

This stage distinguishes the image’s regions above certain intensity value to highlight abnormal behavior in the module’s image. The image’s global intensity threshold is calculated according to the maximum intensity value of the gray image under examination, which is assigned to be 82.3% of the highest intensity value in the gray image. This threshold value is selected manually to highlight the region of interest in an image.

3.1.6 Segmentation

After performing Hough line detection, a new binary image is created. The binary image only contains the cells’ edges, which are assigned high values (i.e., 1). The rest of the binary image’s values are set to low value (i.e., 0). The new binary image assists in a precise connected component extraction. The connected components of the binary image are found by utilizing 8-connected neighborhood flood-fill algorithm. Based on bounding box dimension of each cell, composition algorithm is developed to fill in gray level values from the actual image to the binary created image.

3.1.7 Mapping Temperature to Pixel Intensity Values

Mapping the pixels intensity values of the actual image to the panel’s temperature is important for diagnosing the system status. Comparison of the actual image’s histogram pattern to the panel’s temperature histogram is shown in figure 3.3a and figure 3.3b respectively. This gives a straightforward indication that image intensity and the temperature recorded by the IR-camera of the panel under test are directly correlated. Except, the image has higher resolution than temperature profile. A new temperature
vector with higher resolution is created after mapping highest pixel intensity value to highest temperature given and lowest pixel intensity value to lowest temperature value.

![Image](image_url)

**Figure 3.3:** Histogram of the temperature and the pixel intensity. a) Normalized module’s temperature. b) Normalized gray level image intensity histogram.

### 3.2 Results and Discussion

#### 3.2.1 Old Method

Figure 3.4a shows an image taken under normal operation conditions with no shading impact. The image does not indicate any sign of defects or abnormalities. The old method presented in [49] was implemented and tested on figure 3.4b after imposing partial shading. Even with the presence of bypass diodes in the module, partial shading can cause hot-spots in the group of cells that are connected to the same bypass diode due to shaded cell’s reverse current [50], [51]. In case of outstanding partial shading, it is obvious that IR camera can detect the partial shading effect on the module without the use of any software tool as demonstrated in figure 3.4b.
Figure 3.4: IR image of PV module. a) IR image under no shading conditions b) IR image of a partially shaded module

Figure 3.5 demonstrates the results of the algorithm in [49]. It is clear that the two middle columns accumulate more heat than the rest of the panel, due to hot-spot formation. The old method was unable to precisely highlight the region of interest. On the other hand, this method highlighted the bottom left corner of the panel even though it is cooler than the rest of the panel; an effect caused by camera angle. The highlighted region does not carry significant information in this scenario.

Figure 3.5: Old technique failed to accurately highlight the area of interest

3.2.2 Proposed Method

Figure 3.6b shows the image under processing after applying Gaussian and Median filters. There is a minimal difference between the images in figure 3.6, since the original image does not have high noise ratio. Under close examination, the image in
figure 3.6b contains higher color contrast and its details are sharper. This step paved the road for the second step of the algorithm.

![Figure 26](image)

**Figure 3.6: IR-Image before and after filtering.** a) IR image before filtering. b) IR image of unshaded panel after applying Gaussian and Median filters

After performing Canny edge detection on the image in figure 3.6b, figure 3.7 is generated. At this stage of the process, the figure conveys rich edges details information. These edges details can be very challenging to interpret. Especially, if the module was working under normal operating conditions without it being modified in any way to create artificial or manual faults for the purpose of analysis. Canny detection establishes cells borders, which serves as a Hough line detection step. It is obvious that this image needs more processing steps to produce meaningful results.
Applying Hough line detection to figure 3.7 results in very accurately detected lines that run along the cells’ edges. From the lines detected by this method, a new binary image (figure 3.8) was created to only convey the cells’ edges information. At this stage, the cells intensity values are set to low to create a high contrast between the area of the actual cells and the borders. This aids the program to easily fill in the real cells intensity values later on.

![Binary image shows cells borders after Hough line detection](image)

Performing Hough line detection paved the way to run the composition algorithm on figure 3.8, which uses 8-neighborhood connected components to extract cells properties. Based on the obtained regions’ properties, each cell is filled with the actual pixels values from the module’s filtered gray image. For illustration purpose, figure 3.9 is generated. In this figure a single cell’s area is filled with high pixel values to demonstrate the accuracy of the algorithm in relation to each cell.
After filling the binary image with the real intensity gray value of the actual image, threshold operation is executed. The results from both operations are exhibited in figure 3.10a. Anything above the value of the threshold is padded with 1 to visualize the regions of abnormal temperature.

The large white spot visible in both images is due to poor heat dissipation caused by the junction box installed on the back of the panel. The small white dot in the third row and first column to the left indicates an unwelcome object on the surface of the panel. The heat at the small white dot is caused by pollution. Specifically, it occurs because of a bird dropping on the cell’s surface, which may create partial shading effect [46], [52]. Figure 3.10b is a 2-D surface intensity image that visualizes the heat distribution in the module.
To achieve more accurate diagnosis, segmentation and pixel level temperature mapping are performed on each cell. To draw a conclusion about the status of each cell a diagnostic algorithm is executed to calculate each cell’s average temperature. Figure 3.11 shows a normal cell and abnormal cell temperatures. Figure 3.11a shows a cell that has a normal operating temperature in respect to the threshold set by the user. Figure 3.11b and 3.11c exhibit the top two cells that have the junction box installed behind them. Lastly, figure 3.11d has the highest temperature of all due to the foreign object on the cell.

The study conducted in [27] suggests that normal cells operate at an absolute temperature of up to 145.4 °F. Therefore, all the cells diagnosed in figure 3.11 are in fact normal. This can be easily fixed by adjusting the thresholding parameter in the program. The threshold is set lower than the normal operating temperature to test the program’s ability of detecting regions of interest that fall below any given temperature.
CHAPTER 4: MODELING AND FIELD TEST OF A CONVENTIONAL PV SYSTEM UNDER PARTIAL SHADING AND MISMATCH

In spite of the recent developments in simulation tools to model PV systems behavior under partial shading, mismatch and disruptive environmental factors, few software tools address the nonlinear behavior of P-V and I-V curves under these extreme conditions [41]. For instance, when exposing conventional PV systems to severe partial shading, multiple MPP peaks take place at the DC output power curve. This greatly impacts the efficiency of most conventional maximum power point tracking (MPPT) resulting in significant power loss. It is crucial to employ software tools and programs to study the behavior of the IV and PV curves to assist in designing efficient and effective maximum power point trackers (MPPT).

Moreover, When Perturbation and Observation (P&O) algorithm is used, the inverter will not operate at the optimal MPP. As an illustration, the inverter starts operating at the reference voltage ($V_{ref}$) point indicated by the red region in figure 4.0. $V_{ref}$ is 80 percent of the open circuit voltage ($V_{oc}$). Thereafter, the inverter slowly converges to MPP it encounters, which happens to be the local maxima (L-MPP) located in the green region of figure 4.0. In this particular example, the optimal global maximum power point (G-MPP) falls within the blue region [7].
The study proposes a Matlab-based program to analytically investigate PV system’s nonlinear behavior under partial shading, mismatch and unclear weather. The program utilizes the diode modeling equation to represent the solar cell electrical behavior.

4.0 Analytical Model and Simulation Algorithm

To best model an n-p junction of a solar cell, a diode circuit should consist of a parallel resistor ($R_P$) that is connected to a diode (D) and a series resistor ($R_S$). Figure 4.1 illustrates an equivalent diode circuit of the n-p solar cell. Equation 4.0 explains the simple KCL relationship of currents in the equivalent circuit. The detailed parameters of the modeling equations are explained below in table 4.0:
Table 4.0: Detailed equation parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I$: cell current</td>
<td>(A)</td>
</tr>
<tr>
<td>$I_{ph}$: photon-generated current</td>
<td>(A)</td>
</tr>
<tr>
<td>$I_o$: diode current</td>
<td>(A)</td>
</tr>
<tr>
<td>$I_{sc}$: short circuit current</td>
<td>(A)</td>
</tr>
<tr>
<td>$K_i$: short circuit current coefficient</td>
<td>(A/C°)</td>
</tr>
<tr>
<td>$K_v$: open circuit voltage coefficient</td>
<td>(V/C°)</td>
</tr>
<tr>
<td>$T_R$: reference temperature</td>
<td>(300 K°)</td>
</tr>
<tr>
<td>$T_K$: operating temperature</td>
<td>(K°)</td>
</tr>
<tr>
<td>$G_R$: reference irradiance</td>
<td>(1000 W/m²)</td>
</tr>
<tr>
<td>$G_K$: actual irradiance</td>
<td>(W/m²)</td>
</tr>
<tr>
<td>$k_b$: boltzmann coefficient</td>
<td>(1.38e⁻²³ J/K)</td>
</tr>
<tr>
<td>$q$: electron charge</td>
<td>(1.602e⁻¹⁹ C)</td>
</tr>
</tbody>
</table>

It is essential for manufacturer to reduce the power consumed by the parallel and series resistors and the diode to have a highly efficient solar cell.

![Diode solar cell's equivalent circuit](image)

$\text{Figure 4.1: A diode solar cell's equivalent circuit.}$

\[ I = I_{ph} - I_o - I_p \quad (4.0) \]

Solar-generated current ($I_{ph}$) depends on the amount of the solar irradiance received by the solar cell. Also, the operating temperature of the cell influences the photon-generated current. Equation 4.1 and 4.2 exhibit the relationship between all the previously mentioned parameters. Equation 4.1 accounts for the change of a generated current due to the change in temperature by including the current coefficient that is provided by the manufacturer.

\[ I_{ph}(G_K) = (I_{sc} + K_i \Delta T) \left( \frac{G_K}{G_R} \right) \quad (4.1) \]

\[ \Delta T = T_K - T_R \quad (4.2) \]
Equation 4.3 shows the contribution of diode current \( I_o \) and the current flows in the parallel resistor to the equivalent cell current. Mainly, the operating temperature influences the diode current \( I_o \).

\[
I = I_{ph} - I_o \left( \frac{qV_d}{e^{k_b T_K} - 1} \right) \frac{V_d}{R_p} \quad (4.3)
\]

Once the cell’s current is calculated it is important to take a look at the voltage across the cell’s terminal. Equation 4.4 calculates the voltage across the cell’s terminals, which is basically the difference between the voltage across the diode and the series resistor. From equation 4.4, it is easy to calculate the total voltage generated by the module by multiplying the number of cells in the module by the voltage across the cell.

\[
V_{cell} = V_d - IR_s \quad (4.4)
\]

However, in this simulation the module’s open circuit voltage is calculated by equation 4.5, which takes in consideration the operating temperature effect on the open circuit voltage of the module. Equation 4.6 accounts for the open circuit voltage of the module at the operating temperature. On the other hand, equation 4.7 determines the open circuit voltage of the module under standard test conditions (STC).

\[
V_{oc} = V_{oc1} + V_{oc2}K_v \Delta T \quad (4.5)
\]

\[
V_{oc1} = \frac{k_b T_K}{q} \ln \left( \frac{I_{sc}}{I_o} + 1 \right) \quad (4.6)
\]

\[
V_{oc2} = 0.0257 \ln \left( \frac{I_{sc}}{I_o} + 1 \right), \text{where } T_K = 25^\circ \quad (4.7)
\]

The numbers of bypass diodes in modules are often not supplied by manufacturers. Therefore, they are determined through the simulation results. In this study, each module is simulated to contain six substrings of cells. Each group of substrings consists of nine
cells connected in series with one bypass diode. This brings the simulated system’s substrings total to 60. When one cell of a substring is completely shaded the diode starts to conduct, forcing the substring to shut down. Otherwise, a hot-spot will be formed in the shaded cell due to reverse current, which may lead to the permanent damage of the cell [15].

To count of the bypass diodes’ function in the program, the current of each substring is generated separately and then all currents are concatenated at the end to produce the system’ net current. A high-level flowchart (figure 4.2) shows the algorithm steps to calculate the array I-V curve.

![Flowchart](image)

**Figure 4.2: I-V curve simulator algorithm**

4.1 Experiment Settings

The panels’ electrical characteristics were presented previously in table 2.2. Each module contained 54 Si-poly cells. The system consisted of 10 modules connected in series (figure 2.5). The maximum power capacity ($P_{\text{max}}$) of the system under (STC) and full irradiance (i.e. 1000 W/m$^2$) was approximately 2.05 kW. Therefore, maximum peak
current ($I_{\text{max}}$) and voltage ($V_{\text{max}}$) respectively were 7.71 A and 266 V. The system’s short circuit ($I_{\text{sc}}$) and open circuit voltage ($V_{\text{oc}}$) were 8.36 A and 332 V. However, since the measurements were not taken under (STC), maximum power capacity ($P_{\text{max}}$) of the system was found to be 1.558 kW, $V_{\text{max}}= 214.80\text{V}$ and $I_{\text{max}}=7.260\text{A}$. The equivalent values of the system’s resistors and operating temperature were determined through a trial and error method in the simulation ($R_p= 4\ \Omega$, $R_S= 0.052\ \Omega$, and $I_o=10^{9.82}\ \text{A}$).

The experiment took place on the roof of the Engineering Building (TBE) at the University of Nevada, Las Vegas. Measurement was collected on May-27-2014 around 11:00 am, which happened to be a sunny and very hot day. Temperature is approximated to be 311 K° (100 F°) when measurement is taken. To collect the system’s I-V and P-V data, an I-V curve tracer was utilized (i.e. Daystar DS-100C I-V). Also, a Fluke 179 multi-meter was used to detect the inverter’s operating DC voltage when tied to the grid.

### 4.2 Results and Discussion

The experiment was composed of six scenarios. First, measurement of the system was taken under full illumination to use the curve as a reference in all scenarios. Second, one of the modules was heavily shaded to create multiple peaks in I-V curve. Third, mismatching in orientation was created in the system by orienting half of the modules to face east and the other half to face south. Fourth, partial shading was created on one of the panels that faced east. Then, partial shading was created on one of the panels that faced south. Lastly, partial shading was creating on two panels each facing a different direction.
4.2.1 Fully Illuminated System (Base Case)

The first scenario of the system under full irradiance is estimated to have high solar irradiance magnitude that is equal to $G_K=955$ W/m$^2$. Figure 4.3 shows the schematic of the system under full solar irradiance. It is noticeable that the simulated result matched real data curve except at the knee of the I-V curve. The percentage error between the two peaks of the field data and simulated curves shows the accuracy of the simulation program. The percentage error between the two P-V peaks is calculated to be 3.0 %, which falls within the accepted range (i.e. ± 5%). The green region (i.e., 223V to 227 V) in figure 4.4 shows the inverter’s voltage point of operation. It is very close to the peak power when the system is fully illuminated. The power peak of real data was $P_{\text{max}}=1.55$ kWp while the simulated curve has power peak that was equal to $P_{\text{max}}=1.51$ kWp.

![Figure 4.3: PV system under full solar irradiance.](image)

![Figure 4.4: PV system I-V and PV curves under full solar irradiance. a) I-V curve. b) P-V curve.](image)
4.2.2 Partially Shaded System

In this scenario, the system faced south and one panel was heavily shaded by an obstruction. The irradiance distribution on the shaded panel was determined to be 10 W/m² and 645 W/m², where low irradiance dominated most of the panel and higher irradiance only reflected one group of sub-array (figure 4.5). The open circuit voltage of the system was dropped by approximately 28 V, which indicated all the bypass diodes in the shaded module were conducting. This resulted in reduction of power (i.e., the real \( P_{\text{max}} = 1.38 \text{ kW} \) and the simulated \( P_{\text{max}} = 1.33 \text{ kW} \) as shown in figure 4.6). The error percentage between the two peaks was 4.57 %.

The green area indicates the inverter’s voltage operating range (i.e., 178V -185V). It is obvious that the standard inverter has the ability to operate at the MPP when heavy shading was presented on one module. The result indicated that the central inverter did not exhibit any difficulty operating at the MPP of the system when one panel was heavily shaded.
4.2.3 Disoriented System

In this scenario, half of the system was oriented toward east and the other half south with no shading imposed as shown in figure 4.7. The effect of mismatch in orientation forced each string to generate different currents, since the solar irradiance received by each sub-array was different. This mismatch in orientation has very little effect on the overall power production of the conventional small system around noon. Half of the system received irradiance that was equal to 988 W/m² and the other half received 920 W/m².
The inverter MPP was recorded to be the optimal, as indicated by the green region (i.e., between 203V and 211V) that is shown in figure 4.8. The power peak of real data was $P_{\text{max}}=1.49 \text{ kWp}$ while the simulated curve has power peak that was equal to $P_{\text{max}}=1.44 \text{ kWp}$. The error percentage between the simulated and real MPP peak was found to be 3.18 %. Even though the mismatch in direction was significant the central inverter was able to function at the MPP of the entire system at peak production time. This proved that slight mismatch in orientation would not result in massive loss due to central inverter inefficiency [53].

![Figure 4.8: PV system's I-V and P-V curves with mismatch in orientation a) I-V curve. b) P-V curve.](image)

### 4.2.4 East Partial Shading on Disoriented System

The system in this scenario was oriented to face east and south while creating artificial partial shading on one of the modules that was facing east. According the simulation program, solar irradiance received on the shaded panel were 10 and 965 W/m² where the lower irradiance dominated the shaded panel. Figure 4.9 shows a schematic of the system orientation and shading position.
Figure 4.9: Disoriented PV system with partially shaded east panel

The general form of the system’s curve in figure 4.10 matches the previous scenario’s curve. Whereas, the heavy partial shading caused a significant drop in DC generated power magnitude and open circuit voltage compared to the previous scenario. The power peak of field data was $P_{\text{max}} = 1.34$ kWp while the simulated curve has power peak that was equal to $P_{\text{max}} = 1.32$ kWp. The conventional inverter was still able to operate at the MPP. The MPP of the system falls within the green region (i.e., between 184V and 192V) reflected in figure 4.11. The percentage error between the real and simulated MPP is determined to be 1.91%, the lowest in the entire study.

Figure 4.10: Disoriented PV system’s I-V and P-V curves with partially shaded east panel a) I-V curve. b) P-V curve.
4.2.5 South Partial Shading on Disoriented System

When the south half of the system was introduced to partial shading while it is disoriented, the curve at the knee underwent very little changes. Based on the simulation tool, the distributions of the solar irradiances on the panel are 10, 860, and 960 W/m². The schematic of the system is in figure 4.11.

![Figure 4.11: PV system with mismatch in orientation with south panel partially shaded](image)

Figure 4.12 indicates the overall system’s I-V and P-V curves. Again in this scenario, the standard inverter was able to detect the MPP of the system even though the peak of the power curve is slightly distorted. The green region in the figure 4.12 illustrates where the conventional inverter is operating (i.e., between 201V and 205V). The maximum power point of the field data was $P_{max}=1.4$ kWp while the simulated curve has power peak that was equal to $P_{max}=1.36$ kWp. The error percentage continues to be negligible (i.e., 2.53%).
4.2.6 South and East Partial Shading on Disoriented System

In this scenario two modules were partially shaded in disoriented system. Each module faced different directions (i.e. one faces east the other is oriented south). Shaded panels in both sides obtained solar irradiances equal to 10, 240, and 850 W/m². The schematic of the system panels is shown in figure 4.13.

Mismatch in orientation coupled with partial shading produced a noticeably distorted I-V curve compared to previous scenarios, illustrated in figure 4.14. Although the I-V curve is distorted, the inverter was successfully able to find the MPP. The green
region in the figure highlights the inverter’s voltage operating point (i.e., between 177V and 183V). The maximum power point of the field data was $P_{\text{max}} = 1.16 \text{ kWp}$ while the simulated curve has power peak that was equal to $P_{\text{max}} = 1.12 \text{ kWp}$. The error percentage between the simulated and real data was 3.08%.

![Graphs showing I-V and P-V curves with mismatch in orientation and partial shading on panels facing east and south.]

**4.3 Partial Shading Caused by Patchy Clouds**

A theoretical study was conducted to show the consequences of having patchy clouds that obstructed the solar irradiance from being uniformly distributed on the system’s plane with no mismatch in orientation and under the ideal operating temperature (i.e., 300 K°). The study utilized the proposed Matlab-based program to mimic various situations where the patchy clouds’ intensity varied. Eight scenarios were studied to investigate the behavior of the system’s I-V curve. When the behavior of the system is well known under extreme conditions, it may encourage inverter designers to further the advancement of the maximum power point tracking (MPPT) algorithm for conventional inverters to harness the maximum power.
The proposed simulation software was used to generate the small-scale system’s I-V and P-V curves starting from the best-case scenario and ending with the worst-case scenario. The patchy clouds’ intensities were represented in the program by generating matrices with random numbers of uniform distribution. Each module’s substring was allowed to receive different solar irradiance when clouds were present. In figure 4.15 the generated matrices filled with the maximum value that the module could receive (1000 W/m²) to mimic the system under full illumination. In this case, notice that the maximum power point (MPP) was equal to 2 kW as shown in figure 4.15b.

![Figure 4.15: Illustration of the system’s I-V and P-V curves under full solar irradiance (1000 W/m²). a) I-V curve. b) P-V curve.](image)

In the second case, the system randomly absorbed radiations that were ranging from 900 to 1000 W/m², which is indicated in figure 4.16. The resultant I-V curve (Fig. 4.16a) is slightly distorted due to the variation of solar irradiance. There was no significant reduction in power production (Fig. 4.16b).
The third scenario shows the system when patchy clouds blocked more solar irradiances. The irradiances of the system, shown in figure 4.17, were ranging from 800 to 1000 W/m². Patchy clouds caused the system’s MPP to drop to approximately 1.7 kWp and the I-V curve to have a deeper slope than the previous cases.
In the fourth case, the system received solar irradiances that were ranging from 700 to 1000 W/m$^2$, as shown in figure 4.18. It is clear in figure 4.18a, that the slope of the I-V curve increased as more clouds blocked solar radiations. Then, the intensity of the patchy clouds was further increased to block 400 W/m$^2$ of the solar irradiance. In this scenario, the MPP dropped slightly more than that of the previous case (1.68 kWp). However, the effects of the bypass diodes were clearer in this scenario, since the I-V curve shows sharper knees in I-V curve.

![Graph](image)

**Figure 4.18**: Illustration of the system’s I-V and P-V curves under solar irradiance range (700-1000 W/m$^2$). a) I-V curve. b) P-V curve.

Figure 4.19 shows the system when the solar insulations were between 600 and 1000 W/m$^2$. It was clear that the curves started to show sharper local maximum power points than in previous cases. The P-V curve had a G-MPP that was equal to 1.55 kWp and L-MPP that was equal to 1.53 kWp. In this particular case, the conventional inverter’s inefficient MPPT algorithm would not result in huge power loss.
Figure 4.19: Illustration of the system’s I-V and P-V curves under solar irradiance range (600-1000 W/m²). a) I-V curve. b) P-V curve.

When the system received solar insolation between 500 to 1000 W/m², as illustrated in figure 4.20, the formation of local peak (L-MPP=1.39 kWp) is approximately as high in magnitude as the global peak (G-MPP=1.4kWp). This might lead the inverter to operate at either maximum. This would not result in significant power loss in the system due to inverter’s lack of detection ability of global maximum peak. For the inverter the problem was presented when the system irradiance further decreased and varied between 400 to 1000 W/m².
Figure 4.20: Illustration of the system’s I-V and P-V curves under solar irradiance range (500-1000 W/m²). a) I-V curve. b) P-V curve.

Figure 4.21 exhibits formation of local peak right after the inverter’s reference voltage ($V_{ref} = 265V$). The conventional inverter in this scenario might lock its operating point at the L-MPP, causing notable power loss in the system. The global peak (G-MPP) is equal to 1.19 kWp and the local peak (L-MPP) is equal to 1.13 kWp.

Figure 4.21: Illustration of the system’s I-V and P-V curves under solar irradiance range (400-1000 W/m²). a) I-V curve. b) P-V curve.
The final and worst case scenario was when solar irradiances fluctuated between 300 to 1000 W/m². Figure 4.22 presents a case where the global maximum of the system occurred before the inverter’s reference voltage ($V_{\text{ref}}$). Thus, the standard inverter surely missed the global peak (i.e., $G\text{-MPP}= 1.22$ kWp) and operated at one of the local maxima (i.e., $L\text{-MPP1}= 1.01$ kWp or $L\text{-MPP2}= 0.9$ kWp). In either case, the system would suffer a considerable amount of power loss.

![Figure 4.22: Illustration of the system’s I-V and P-V curves under solar irradiance range (300-1000 W/m²). a) I-V curve. b) P-V curve.](image)
CHAPTER 5: CONCLUSION

This study explores the current research in the leading journals and articles to conduct a thorough analysis related to contemporary issues such as mismatch, partial shading, power optimization, monitoring, modeling and simulation. Second, it discusses the various MPPT strategies. The functionality of conventional and non-conventional power harnessing are addressed. Brief circuitry explanations are provided for the non-conventional power optimizing solution as well as some of the common commercially available optimizers with monitoring properties.

Subsequently, it uses simulation software (PVSyst) to evaluate conventional inverters and optimizers installed in small-scale PV systems based on different yields and power losses. Cost analysis illustrates that standard inverters are more feasible than optimizers even though they improved performance on a small scale. Large-scale system with power optimizers undergoes voltage in stability that the simulator fails to exhibits.

Additionally, IR imaging process based on the Matlab program is employed to facilitate the decision process regarding the status of the PV module under operation. The study extends the method presented in [49] to reach more satisfactory result. The proposed method has the following stages: Gaussian and median filtering, canny edge detection, Hough line detection, composition, thresholding and temperature mapping. The new method is able to pinpoint abnormal regions with higher accuracy in respect to a given threshold. The proposed method can be improved by accommodating multiple thresholds to highlight regions with different temperature profiles.
Finally, field measurement is collected to examine the effects of mismatch in orientation and partial shading on small-scale conventional PV system. Proposed Matlab-based program utilizes the diode model of PV cells to match the field-collected data. The simulation program is able to simulate the small-scale system under study with good accuracy (i.e. ±5%). The proposed program regenerates the results of the actual system when the system is partially shaded and disoriented. In addition, the proposed program is used to investigate the effects of patchy clouds with different intensities on the system. It successfully simulates the behavior of the system when solar irradiances vary from 1000 to 300 W/m².
APPENDICES

1.0 IR-Image Processing Matlab Program

cd(’/Volumes/Other Things HD/MATLAB/ECG 782/project/all pic/’);
%% import image
currentFolder=pwd;
filePattern=fullfile(currentFolder,’*.jpg’);
imagesNames=dir(filePattern);
images=cell(1,length(imagesNames));
image1medgray=cell(1,length(imagesNames));
image1bw=cell(1,length(imagesNames));
image1canny=cell(1,length(imagesNames));
image1sobel=cell(1,length(imagesNames));
image1prewitt=cell(1,length(imagesNames));
thres=cell(1,length(imagesNames));
for i=1:length(imagesNames)
   images{i}=imread(imagesNames(i).name);
   images{i}=im2double(images{i});
end
%% convert images to grayscale and black and white
for i=1:length(imagesNames)
   image1medgray{i}=rgb2gray(images{i});
end
%% Gaussian filter
h1 = fspecial(’gaussian’, [3 3],3);
for i=1:length(imagesNames)
   image1medgray{i}=imfilter(image1medgray{i},h1,’replicate’);
end
%% medain filter
for i=1:length(imagesNames)
   image1medgray{i}=medfilt2(image1medgray{i},[5 5]);
end
%% edge detection
for i=1:length(imagesNames)
   [image1canny(i)]=edge(image1medgray{i},’canny’,[0.0067,0.0069],4);
   image1sobel{i}=edge(image1medgray{i},’sobel’,0.001,’both’);
   image1prewitt{i}=edge(image1medgray{i},’prewitt’,0.004);
end
%% hough transform
close all;
[H,T,R]=hough(image1canny{25});
P=houghpeaks(H,30,’threshold’,ceil(0.26*max(H(:))));
x = T(P(:,2)); y = R(P(:,1));
%plot(x,y,’s’,’color’,’r’);
lines = houghlines(image1canny{25},T,R,P,’FillGap’,400,’MinLength’,400);
testlm=false([600 800]);
figure,imshow(testIm);hold on
for k = 1:length(lines)
    if(((lines(k).theta>-88)&&(lines(k).theta<45))||(lines(k).theta>45)&&(lines(k).theta<90))
        xy = [lines(k).point1; lines(k).point2];
        plot(xy(:,1),xy(:,2),'LineWidth',1.5,'Color','w');
    end
end
cd('/Volumes/Other Things HD/MATLAB/ECG 782/project/all pic/modified/');
export_fig('lines '-'jpg','-native');
hold off;
ImLines=imread('lines.jpg');
figure;
imshow(ImLines);
hold on;
ImLines=im2double(ImLines);
ImLines=im2bw(ImLines);
ImLinesCopy=ImLines;
for i=1:r
    for j =1:c
        if(ImLines(i,j)==0)
            ImLinesCopy(i,j)= image1medgray{25}(i,j);
        else
            ImLinesCopy(i,j)=0;
        end
    end
end
%% image cropping and
ImLines= imcrop(ImLines,[64.5 40.5 555 555]);
ImLinesCorners= imcrop(ImLinesCorners,[64.5 40.5 555 555]);
ImLinesCopy= imcrop(ImLinesCopy,[64.5 40.5 555 555]);
ImLineCopy1=ImLinesCopy;
real= imcrop(images{25},[64.5 40.5 555 555]);
realeges= imcrop(image1canny{25},[64.5 40.5 555 555]);
%% thresholding and surface graphing
[sr sc]=size(ImLinesCopy);
s_auto_thre=max(max(ImLinesCopy))*0.8232;
for i=1:sr
for j=1:sc
    if(s_auto_thre<=ImLinesCopy(i, j) )
        ImLinesCopy(i,j)=1;
    end
end
figure;
imshow(ImLinesCopy);
tempImName=[imagesNames(25).name(1:length(imagesNames(25).name)-
4),'_temp','.csv'];
temp=csvread(tempImName);
direction = [1 0 0];
figure;
h=surf(temp/max(max(temp)))
set(h, 'edgecolor','none');
rotate3d on;
figure;
a=surf(ImLinesCopy);
set(a, 'edgecolor','none');
rotate3d on;
figure;
imshow(real);
figure;
imshow(realedges);
figure;
imshow(ImLines);
figure;
imshow(ImLinesCopy);

%% cells dimensions
CCLines = bwconncomp(ImLines,8);
stats = [regionprops(ImLines); regionprops(not(ImLines))];
% centroids = cat(1, S.Centroid);
figure;
imshow(ImLines); hold on
for i=1:numel(stats)
    if((stats(i).Area>=2400)&&(stats(i).Area<=8500)&&(i~=12))
        rectangle('Position', stats(i).BoundingBox, 'Linewidth', 3, 'EdgeColor', 'r', 'LineStyle', '-');
    end
end
hold off;

%% cells extraction
PVcells=cell(1,54);
PVcells1=cell(1,54);
counter=1;
for i=1:numel(stats)
    resetPVIm=ImLinesCopy;
    resetPVIm1=ImLineCopy1;
    if((stats(i).Area>=2400)&&(stats(i).Area<=8500)&&(i~=12))

dimension=stats(i).BoundingBox;
testimage=ImLines;

testimage((dimension(2)):(dimension(2)+dimension(4)),(dimension(1)):(dimension(1)+dimension(3)))=1;
PVcells{counter}=imcrop(resetPVIm,dimension);
PVcells1{counter}=imcrop(resetPVIm1,dimension);
counter=counter+1;
end
end

%% importing temperature historam for image and temp

temp = csvread('IR_0353_temp.csv');
figure;
subplot(1,2,1),hist(temp/max(max(temp)));
title('Normalized Temperature ');
subplot(1,2,2),hist(image1medgray{25}/max(max(image1medgray{25})));
title('Normalized Image Intinsity ');

%% temp and image mapping
maxTemp=max(max(temp));
minTemp=min(min(temp));
imageVector=reshape(image1medgray{25},1,[]);
ImVectorSize=size(imageVector,2);
SortedImVector=sort(imageVector);
CorespodingTemp=linspace(minTemp,maxTemp,ImVectorSize);

%% giving cell temp
tempvalue=cell(1,54);
for i=1:54
    [m,n]=size(PVcells1{i});
    tempvalue{i}=zeros(m,n);
    for r=1:m
        for c=1:n
            pixValue=PVcells1{i}(r,c);
            index=find(SortedImVector==pixValue);
            tempvalue{i}(r,c)=CorespodingTemp(round(median(index)));
        end
    end
end

%% cell status
cellStatus=zeros(1,54);
for i=1:54
    [m,n]=size(PVcells{i});
    for r=1:m
        for c=1:n
            if(PVcells{i}(r,c)==1)
                cellStatus(i)=1;
            end
        end
    end
end
for i=1:53
    if (cellStatus(i)==1)
        diagnosis='unnormal condition, ';
    else
        diagnosis='normal condition, ';
    end
    titlecell=['Status: ',diagnosis, num2str(mean(mean(tempvalue{i}))) ];
    figure
    imshow(PVcells{i});
    title(titlecell);
end
2.0 PV Modeling Matlab Program

Rp=4;
Rs=0.052;
exp =-9.82;
g=955;
% irradiance
temp=311;
irr1=[g,g,g, g,g,g];
irr2=[g,g,g, g,g,g];
irr3=[g,g,g, g,g,g];
irr4=[g,g,g, g,g,g];
irr5=[g,g,g, g,g,g];
irr6=[g,g,g, g,g,g];
irr7=[g,g,g, g,g,g];
irr8=[g,g,g, g,g,g];
irr9=[g,g,g, g,g,g];
irr10=[g,g,g, g,g,g];
% ten panels that have 6 diodes each
[I,V]=SimulationDiodeEquation4(temp,irr1,Rs,Rp,exp);
[I2,V2]=SimulationDiodeEquation4(temp,irr2, Rs,Rp,exp);
[I3,V3]=SimulationDiodeEquation4(temp,irr3,Rs,Rp,exp);
[I4,V4]=SimulationDiodeEquation4(temp,irr4,Rs,Rp,exp);
[I5,V5]=SimulationDiodeEquation4(temp,irr5,Rs,Rp,exp);
[I6,V6]=SimulationDiodeEquation4(temp,irr6,Rs,Rp,exp);
[I7,V7]=SimulationDiodeEquation4(temp,irr7,Rs,Rp,exp);
[I8,V8]=SimulationDiodeEquation4(temp,irr8, Rs,Rp,exp);
[I9,V9]=SimulationDiodeEquation4(temp,irr9,Rs,Rp,exp);
[I10,V10]=SimulationDiodeEquation4(temp,irr10,Rs,Rp,exp);
% import real data
filename='No_shading.csv';
NoShading = csvread(filename,22,1);
NoShadeVolt=NoShading(:,1);
NoShadeAmper=NoShading(:,2);
NoShadeWatt=NoShading(:,3);
totalCurrent=[I,I2,I3,I4,I5,I6,I7,I8,I9,I10];
max(totalCurrent)
c=size(totalCurrent,2);
totalCurrent=sort(totalCurrent,'descend');
totalVoltage=V+V2+V3+V4+V5+V6+V7+V8+V9+V10;
powerRealdata=NoShadeWatt;
xaxisGraph2=linspace(0,totalVoltage,size(totalCurrent,2));
powerSimulated=totalCurrent.*xaxisGraph2;
real_data_power=max(powerRealdata)
real_data_current=max(NoShadeAmper)
real_data_voltage=max(NoShadeVolt)
sim_data_power=max(powerSimulated)
Error_percentage=((real_data_power-sim_data_power)/real_data_power)*100
%% ploting
figure
plot(NoShadeVolt, NoShadeAmper, '-r', 'LineWidth', 3); grid on, hold on;
plot(xaxisGraph2, totalCurrent, '-b', 'LineWidth', 3);
regionHighlight=area([223 227], [8 8]); hold on;
alpha(.5);
fig1leg=legend('Real data', 'Simulated data');
set( fig1leg, 'Location', 'SouthWest');
set(regionHighlight, 'FaceColor', [0, 0.95, 0.35]);
xlabel('Voltage [ V ]', 'FontSize', 12, 'FontWeight', 'bold')
ylabel('Current [ I ]', 'FontSize', 12, 'FontWeight', 'bold')
hold off
export_fig( 'noShading_IV', '.jpg', '-native');
figure
plot(NoShadeVolt, powerRealdata, '-r', 'LineWidth', 3); grid on, hold on;
plot(xaxisGraph2, powerSimulated, '-b', 'LineWidth', 3);
regionHighlight2=area([223 227], [1600 1600]); hold on;
alpha(.5);
fig2leg=legend('Real data', 'Simulated data');
xlabel('Voltage [ V ]', 'FontSize', 12, 'FontWeight', 'bold')
ylabel('Power [ W ]', 'FontSize', 12, 'FontWeight', 'bold')
set( fig2leg, 'Location', 'NorthWest')
set(regionHighlight2, 'FaceColor', [0, 0.95, 0.35]);
hold off
export_fig( 'noShading_PV', '.jpg', '-native');

function [Im, Vm]=SimulationDiodeEquation4(temp, irr, Rs, Rp, power)
Vd= linspace(0, 1, 10^5);
Isc=8.36;
Io= 10^(power);
Ki=0.00505;% Short circuit current coefficient (A/C degree celcius)
Kv=-0.120;% Opern circuit voltage coefficient (V/C)
Tr=300; % Kelvin reference
Tk=temp;
Tdif=Tk-Tr;
Gr=1000; % W/m^2 (reference)
kb=1.38e-23;
q=1.602e-19;
const= q/(kb*Tk);
lph1=(Isc+Ki*(Tdif))*irr(1)/Gr;
lph2=(Isc+Ki*(Tdif))*irr(2)/Gr;
lph3=(Isc+Ki*(Tdif))*irr(3)/Gr;
lph4=(Isc+Ki*(Tdif))*irr(4)/Gr;
lph5=(Isc+Ki*(Tdif))*irr(5)/Gr;
lph6=(Isc+Ki*(Tdif))*irr(6)/Gr;

%%% creating the system current and voltage
l1=lph1-Io*(exp(const*Vd)-1)-Vd/Rp;
l2=lph2-Io*(exp(const*Vd)-1)-Vd/Rp;
I_3 = I_{ph3} - I_o \cdot (\exp(const \cdot V_d) - 1) - V_d/R_p;
I_4 = I_{ph4} - I_o \cdot (\exp(const \cdot V_d) - 1) - V_d/R_p;
I_5 = I_{ph5} - I_o \cdot (\exp(const \cdot V_d) - 1) - V_d/R_p;
I_6 = I_{ph6} - I_o \cdot (\exp(const \cdot V_d) - 1) - V_d/R_p;
V_{cell1} = V_d - I_1 \cdot R_s;
V_{cell2} = V_d - I_2 \cdot R_s;
V_{cell3} = V_d - I_3 \cdot R_s;
V_{cell4} = V_d - I_4 \cdot R_s;
V_{cell5} = V_d - I_5 \cdot R_s;
V_{cell6} = V_d - I_6 \cdot R_s;
V_g1 = 9 \cdot V_{cell1};
V_g2 = 9 \cdot V_{cell2};
V_g3 = 9 \cdot V_{cell3};
V_g4 = 9 \cdot V_{cell4};
V_g5 = 9 \cdot V_{cell5};
V_g6 = 9 \cdot V_{cell6};
I_1 = [I_1, I_2, I_3, I_4, I_5, I_6];
V_p = [V_g1, V_g2 + V_g1, V_g1 + V_g2 + V_g3, V_g1 + V_g2 + V_g3 + V_g4, V_g1 + V_g2 + V_g3 + V_g4 + V_g5, V_g1 + V_g2 + V_g3 + V_g4 + V_g5 + V_g6];
deletthese = (I < 0);
I = I(\neg deletthese);
V_p = V_p(\neg deletthese);
deletthese = (V_p < 0);
I = I(\neg deletthese);
V_p = V_p(\neg deletthese);
I = sort(I, 'descend');
c = size(I, 2);
% V_p = linspace(0, max(V_p), c);
V_p = sort(V_p, 'ascend');
Voc_1 = (((k_b * T_k) / q) * log(I_{sc} / I_o + 1)) * 9;
Voc_2 = (((k_b * T_k) / q) * log(I_{sc} / I_o + 1)) * 9;
Voc_3 = (((k_b * T_k) / q) * log(I_{sc} / I_o + 1)) * 9;
Voc_4 = (((k_b * T_k) / q) * log(I_{sc} / I_o + 1)) * 9;
Voc_5 = (((k_b * T_k) / q) * log(I_{sc} / I_o + 1)) * 9;
Voc_25 = (0.0257 * log(I_{sc} / I_o + 1)) * 9;
Voc = Voc_1 + Voc_2 + Voc_3 + Voc_4 + Voc_5 + Voc_6;
Voc = Voc + Voc_25 * (K_v) * (T_{dif});
V_m = Voc;
I_m = I;
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# Curriculum Vita

**Khalid Hurayb**

**KhalidHurayb@gmail.com**

<table>
<thead>
<tr>
<th>Education</th>
<th>University of Nevada, Las Vegas, Nevada. M.S. in Electrical Engineering</th>
<th>Aug, 2014</th>
</tr>
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<table>
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<tr>
<th>Work Experience</th>
<th>Volunteer, Saudi Electricity Company, Taif City, Saudi Arabia</th>
<th>Summer 2012</th>
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<td></td>
<td>• Solved voltage drop due to overload, distance and cable size</td>
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<tr>
<th>Work Experience</th>
<th>Intern, Al Hada Armed Forces Military Hospital, Taif City, Saudi Arabia</th>
<th>Summer 2007</th>
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<tr>
<td></td>
<td>• Configured the hospital’s Local Area Network (LAN) and Wide Area Network (WAN)</td>
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<tr>
<td></td>
<td>• Installed and configured Voice Over IP (VOIP) Cisco units</td>
<td></td>
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<tr>
<td></td>
<td>• Wired both straight and crossover cables</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Installed and Configured Dell servers</td>
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<tr>
<th>Teaching &amp; Research Experience</th>
<th>Research Assistant, Research Transportation Center, University of Nevada Las Vegas</th>
<th>Fall 2013-Summer 2014</th>
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<tbody>
<tr>
<td></td>
<td>• Developed Python code to collect real-time data from Las Vegas’s Highways</td>
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<tr>
<td></td>
<td>• Designed MySQL tables to efficiently store collected data</td>
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<table>
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<th>Teaching Assistant, Electrical and Computer Engineering Department, University of Nevada Las Vegas</th>
<th>Spring 2013</th>
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<td></td>
<td>• Taught Introduction to Engineering Experience Lab</td>
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<tr>
<td></td>
<td>• Graded assignments and exams for Introduction to Engineering Experience and Computer Architecture Classes</td>
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<th>Presenter, 4th Annual Diversity Conference, University of Cincinnati</th>
<th>Spring 2012</th>
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<tr>
<td></td>
<td>• Explained the use of names in the Arabic culture</td>
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<tr>
<td></td>
<td>• Taught the structure of the Arabic names</td>
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<tr>
<td></td>
<td>• Provided tips on how to pronounce Arabic names to English speakers</td>
<td></td>
</tr>
<tr>
<td>Undergraduate Associate, Department of English, Miami University</td>
<td>Fall 2010</td>
<td></td>
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<tr>
<td>• Taught students how to design and create multi-modal movie project</td>
<td></td>
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<tr>
<td>• Composed midterm and final exams</td>
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<td>• Facilitated students in group discussion</td>
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<td>• Full tuition scholarship, <em>King Abdulla Scholarship Program (KASP)</em></td>
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<td>• Dean’s list, <em>Miami University</em></td>
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<tr>
<td>• Fastest wire skimmer award, <em>EAS 102 problem solving and design</em></td>
<td></td>
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<tr>
<td>• Undergraduate Associate, <em>Miami University, Department of English</em></td>
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<tr>
<td>• Institution of Electrical and Electronics Engineers (IEEE)</td>
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<tr>
<td>• Engineering Without Borders (EWB)</td>
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<tr>
<th>Publications</th>
<th>2013</th>
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<table>
<thead>
<tr>
<th>Computer skills</th>
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<tbody>
<tr>
<td>C/C++, Java, MatLab, Assembly Language, Pspice, Multisim, LTSpice, I-V Curve Tracer, EasyPower, Microsoft Office, Python, PVsyst, MySQL, UNIX, Windows, Macintosh</td>
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<table>
<thead>
<tr>
<th>Language skills</th>
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<tbody>
<tr>
<td>Fluent in Arabic and English</td>
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