

CONTROL OF THE PHOTOVOLTAIC EMULATOR USING FUZZY LOGIC  
BASED RESISTANCE FEEDBACK AND BINARY SEARCH

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## **DEDICATION**

To my Family, for their patience, support, love and for enduring the ups and downs during the completion of this thesis.

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## ABSTRACT

Photovoltaic (PV) emulator is a power supply that produces similar current-voltage (I-V) characteristics as the PV module. This device simplifies the testing phase of PV systems under various conditions. The essential part of the PV emulator (PVE) is the control strategy. Its main function is to determine the operating point based on the load of the PVE. The direct referencing method (DRM) is the widely used control strategy due to its simplicity. However, the main drawback of DRM is that the output voltage and current oscillate due to the inconsistent operating point under fixed load. This thesis proposes an improved and robust control strategy named resistance feedback method (RFM) that yields consistent operating point under fixed load, irradiance and temperature. The RFM uses the measured voltage and current to determine the load of the PVE in order to identify the accurate operating point instantaneously. The conventional PV models include the I-V and voltage-current PV model. These PV models are widely used in various control strategies of PVE. Nonetheless, the RFM requires a modified PV model, the current-resistance (I-R) PV model, where the mathematical equation is not available. The implementation of the I-R PV model using the look-up table (LUT) is feasible, but it requires a lot of memory to store the data. A mathematical equation based I-R PV model computed using the binary search method is proposed to overcome the drawback of the LUT. The RFM consists of the I-R PV model and the closed-loop buck converter. In this work, the RFM is investigated with two different controllers, namely the proportional-integral (PI) and fuzzy logic controllers. The RFM using the PI controller (RFMPI) and the RFM using the fuzzy logic controller (RFMF) are tested with resistive load and maximum power point tracking (MPPT) boost converter. The perturb and observe algorithm is selected for the MPPT boost converter. In order to properly design the boost converter for the MPPT application, the sizing of the passive components is proposed, derived and confirmed through simulation. This derivation allows adjustment on the output voltage and current ripple of the PVE when connected to the MPPT boost converter. The simulation results of the proposed control strategies are benchmarked with the conventional DRM. To validate the simulation results, all controllers are implemented using dSPACE ds1104 rapid prototyping hardware platform. The RFM computes an operating point of the PVE at 20% faster than the DRM. The generated output PVE voltage and current using RFMPI and the RFMF are up to 90% more accurate compared to the DRM. The efficiency of the PVE is beyond 90% when tested under locus of maximum power point. In transient analysis, the settling time of RFMF is faster than the RFMPI. In short, the proposed RFMF is robust, accurate, quick respond and compatible with the MPPT boost converter.

## ABSTRAK

Pelagak fotovolt (PV) ialah sebuah bekalan kuasa yang menghasilkan ciri-ciri arus-voltan (I-V) yang serupa dengan modul PV. Peranti ini dapat memudahkan fasa pengujian sistem PV pada pelbagai keadaan. Bahagian penting dalam pelagak PV (PVE) ialah strategi kawalan. Fungsi utamanya adalah untuk menentukan titik pengoperasian berdasarkan beban pada PVE. Kaedah rujukan langsung (DRM) merupakan strategi kawalan yang digunakan secara meluas kerana ianya mudah. Namun, kelemahan utama DRM ialah voltan dan arus keluarannya berayun disebabkan oleh titik pengoperasian yang tidak konsisten pada beban tetap. Tesis ini mencadangkan strategi kawalan yang diperbaik dan teguh yang dinamakan kaedah suap balik perintang (RFM) yang menghasilkan titik pengoperasian yang konsisten pada beban, kesinaran dan suhu yang tetap. RFM menggunakan voltan dan arus yang diukur untuk menentukan beban pada PVE bagi menentukan titik pengoperasian yang tepat secara serta-merta. Model-model PV lazim yang digunakan ialah model PV I-V dan voltan-arus. Model-model PV ini digunakan secara meluas dalam pelbagai strategi kawalan untuk PVE. Walau bagaimanapun, RFM memerlukan model PV yang diubahsuai, iaitu model PV arus-perintang (I-R), yang persamaan matematiknya belum diterbitkan. Pelaksanaan model PV I-R menggunakan jadual carian (LUT) boleh dilaksanakan, tetapi ianya memerlukan banyak ingatan untuk menyimpan data. Satu persamaan matematik berdasarkan model PV I-R yang diselesaikan menggunakan kaedah carian gelintar perduaan, dicadangkan untuk mengatasi kelemahan LUT. RFM terdiri daripada model PV I-R dan penukar menurun gelung tertutup. Dalam tesis ini, RFM diuji dengan dua pengawal yang berbeza, iaitu pengawal kamiran-perkadaran (PI) dan pengawal logik kabur. RFM menggunakan pengawal PI (RFMPI) dan RFM menggunakan pengawal logik kabur (RFMF) diuji menggunakan beban perintang dan penukar menaik penjejakan titik kuasa maksimum (MPPT). Algoritma usik dan perhati dipilih untuk penukar menaik MPPT. Bagi mereka bentuk penukar menaik secara betul, pensaihan komponen pasif dicadangkan, diterbitkan dan disahkan melalui simulasi. Terbitan ini membolehkan pelarasan riak voltan dan riak arus keluaran PVE apabila disambung pada penukar menaik MPPT. Keputusan simulasi bagi strategi-strategi kawalan yang dicadangkan itu dibandingkan dengan DRM lazim. Bagi mengesahkan keputusan simulasi, kesemua pengawal dilaksanakan menggunakan platform perkakasan prototaip pantas dSPACE ds1104. RFM dapat mengira satu titik pengoperasian bagi PVE pada 20% lebih pantas berbanding dengan DRM. Voltan dan arus keluaran yang dihasilkan oleh PVE menggunakan RFMPI dan RFMF adalah mencecah 90% lebih tepat berbanding dengan DRM. Kecekapan PVE melebihi 90% apabila diuji pada lokus titik kuasa maksimum. Untuk analisis fana, masa enapan bagi RFMF adalah lebih pantas berbanding dengan RFMPI. Pendek kata, RFMF yang dicadangkan ialah teguh, tepat, cepat bertindak balas dan serasi dengan penukar menaik MPPT.

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## LIST OF ABBREVIATIONS

1D	-	Single Diode
1D1R	-	Single Diode Single Resistance
1D2R	-	Single Diode Double Resistance
2D2R	-	Double Diode Double Resistance
AC	-	Altenating Current
BJT	-	Bipolar Junction Transistor
CCR	-	Constant Current Region
CVR	-	Constant Voltage Region
DAC	-	Digital to Analogue Converter
DC	-	Direct Current
DRM	-	Direct Referencing Method
EMI	-	Electromagnetic Interference
ESR	-	Equivalent Series Resistance
GUI	-	Graphical User Interface
HC	-	Hill Climbing
IC	-	Integrated Circuit
I-R	-	Current-Resistance
I-V	-	Current-Voltage
LED	-	Light Emmitting Diode
LUT	-	Look-Up Table
MOSFET	-	Metal Oxide Semiconductor Field Effect Transistor
MPP	-	Maximum Power Point
MPPT	-	Maximum Power Point Tracking
P&O	-	Perturb and Observe
PI	-	Proportional-Integral
PID	-	Proportional-Integral-Derivative
PV	-	Photovoltaic
PVE	-	Photovoltaic Emulator
P-V	-	Power-Voltage
PWM	-	Pulse Width Modulation
RFM	-	Resistance Feedback Method (General)
RFMPI	-	Resistance Feedback Method using PI Controller
RFMF	-	Resistance Feedback Method using Fuzzy Controller
SMPS	-	Switched-Mode Power Supply
STC	-	Standard Test Condition
ZCS	-	Zero Current Switching
ZVS	-	Zero Voltage Switching

## LIST OF SYMBOLS

$A$	-	System Matrix
$A_f$	-	Ideality Factor
$B$	-	Input Matrix
$C$	-	Capacitance of the Buck Converter
$C_{i\_mppt}$	-	Input Capacitance for MPPT Converter
$C_{o\_mppt}$	-	Output Capacitance for MPPT Converter
$D$	-	Duty Cycle
$D_{max}$	-	Maximum Duty Cycle for Buck Converter
$D_{min}$	-	Minimum Duty Cycle for Buck Converter
$D_{mppt(max)}$	-	Maximum Duty Cycle for MPPT Converter
$D_{mppt(min)}$	-	Minimum Duty Cycle for MPPT Converter
$D_{mppt}$	-	Duty Cycle for MPPT Converter
$D_{step}$	-	Duty Cycle Step
$E$	-	Output Matrix
$e$	-	Feedback Error
$e\%(I-R)$	-	Percentage Current Error of I-R PV Model
$e_i$	-	Absolute Current Error
$e_{pve}$	-	Photovoltaic Equation Error
$F$	-	Feedforward Matrix
$f_s$	-	Switching Frequency
$f_{mppt}$	-	Switching Frequency for MPPT Converter
$f_{pvm}$	-	Function of PV Model
$f'_{pvm}$	-	Derivative Function of PV Model against $I_{pv}$
$G$	-	Irradiance
$G_b$	-	Transfer function for Buck Converter
$G_c$	-	Transfer function for PI Controller
$G_{stc}$	-	Irradiance at Standard Test Condition
$I_D$	-	Diode Current
$I_{i\_mppt}$	-	Input Current for MPPT Converter
$I_{mp}$	-	Maximum Power Current
$I_{mp\_G(min)}$	-	Maximum Power Current at Minimum Irradiance
$I_o$	-	Output Current
$I_{ph}$	-	Photo-Generated Current
$I_{pv}$	-	Photovoltaic Current
$I_{pv(max)}$	-	Maximum Photovoltaic Current
$I_{pv(min)}$	-	Minimum Photovoltaic Current
$I_{pv\_model}$	-	PV Current obtained from PV Model
$I_{pv\_module}$	-	PV Current obtained from Manufacturer Data
$I_{sc\_G(min)}$	-	Short Circuit Current during Minimum Irradiance
$I_{ref}$	-	Reference Current
$I_s$	-	Saturation Current
$I_{s1}$	-	Saturation Current 1
$I_{s2}$	-	Saturation Current 2
$I_{sc}$	-	Short Circuit Current
$k$	-	Boltzmann Constant

$K_d$	-	Derivative Gain
$K_e$	-	Error Gain
$K_i$	-	Integral Gain
$K_{i\_mppt}$	-	Integral Gain for MPPT Converter
$K_p$	-	Proportional Gain
$K_{p\_mppt}$	-	Proportional Gain for MPPT Converter
$L$	-	Inductance of the Buck Converter
$L1$	-	Inductance in Phase One
$L2$	-	Inductance in Phase Two
$L_{mppt}$	-	Inductance for MPPT Converter
$L_{mppt(4/9)}$	-	Inductance for MPPT Converter with $R_{mp} = 4/9 R_{o\_mppt}$ Exist.
$L_{mppt(x4/9)}$	-	Inductance for MPPT Converter with $R_{mp} = 4/9 R_{o\_mppt}$ Not Exist.
$N_s$	-	Number of Cells in Series
$OS_{Io}$	-	Output Current Overshoot
$p-n$	-	Positive-Negative
$P_{max}$	-	Maximum Power
$P_{mp}$	-	Power at MPP
$P_o$	-	Output Power
$q$	-	Electron Charge
$r_C$	-	Internal Resistance of Capacitor for Buck Converter
$r_{Ci\_mppt}$	-	Internal Resistance of Input Capacitor for MPPT Converter
$r_{Co\_mppt}$	-	Internal Resistance of Output Capacitor for MPPT Converter
$R_{ds(on)}$	-	MOSFET Drain-Source On Resistance
$r_L$	-	Internal Resistance of Inductor for Buck Converter
$r_{L\_mppt}$	-	Internal Resistance of Inductor for MPPT Converter
$R_{mp(max)}$	-	Maximum Power Resistance at Low Irradiance
$R_{mp(min)}$	-	Maximum Power Resistance at High Irradiance
$R_{mp\_γIL(max)}$	-	Maximum power point resistance with the maximum inductor current ripple factor.
$R_o$	-	Output Resistance
$R_{o(max)}$	-	Maximum Output Resistance for PVE
$R_{o(min)}$	-	Minimum Output Resistance for PVE
$R_{o\_mppt}$	-	Output Resistance for MPPT Converter
$R_{o\_mppt(max\_g)}$	-	Output Resistance for MPPT Converter at Maximum Irradiance and Maximum Duty Cycle
$R_{o\_mppt(max\_g)}$	-	Output Resistance for MPPT Converter at Minimum Irradiance and Maximum Duty Cycle
$R_{o\_mppt(min\_G)}$	-	Output Resistance for MPPT Converter at Maximum Irradiance and Minimum Duty Cycle
$R_{o\_mppt(min\_g)}$	-	Output Resistance for MPPT Converter at minimum Irradiance and Minimum Duty Cycle
$R_{mp}$	-	MPP Resistance
$R_{mp(max)}$	-	Maximum MPP Resistance
$R_{mp(min)}$	-	Minimum MPP Resistance
$R_{mp\_γIL(max)}$	-	MPP Resistance with Maximum $\gamma_{IL}$
$R_p$	-	Parallel Resistance
$R_{pv}$	-	Photovoltaic Resistance

$R_s$	-	Series Resistance
$State$	-	State
$T$	-	Temperature
$T_{mppt}$	-	Switching Period of MPPT Boost Converter
$t_{pert}$	-	Perturbation Period
$t_s$	-	Settling Time
$T_{stc}$	-	Temperature at Standard Test Condition
$u$	-	Input Matrix
$V_f$	-	Forward Voltage
$V_i$	-	Input Voltage
$V_{i\_mppt}$	-	Input Voltage for MPPT Converter
$V_{mp}$	-	Maximum Power Voltage
$V_{mp\_G(min)}$	-	Maximum Power Voltage at Minimum Irradiance
$V_o$	-	Output Voltage
$V_{oc}$	-	Open Circuit Voltage
$V_{pv}$	-	Photovoltaic Voltage
$V_{pv\_ref}$	-	Reference Photovoltaic Voltage
$V_{pv\_start}$	-	PV Starting Voltage
$V_{pv\_step}$	-	PV Step Voltage
$V_{mp\_G(min)}$	-	Maximum Power Point Voltage at Minimum Irradiance
$V_{oc\_G(min)}$	-	Open Circuit Voltage at Minimum Irradiance
$V_T$	-	Thermal Voltage
$x$	-	State-Space Vector
$y$	-	Output Vector
$\alpha$	-	Temperature Coefficient of $I_{sc}$
$\beta$	-	Temperature Coefficient of $V_{oc}$
$\gamma_{IL\_mppt}$	-	Inductor Current Ripple Factor for MPPT Converter
$\gamma_{Vmp}$	-	Maximum Power Point Voltage Ripple Factor for MPPT Converter
$\gamma_{Vo}$	-	Output Voltage Ripple Factor for Buck Converter
$\gamma_{Vo\_mppt}$	-	Output Voltage Ripple Factor for MPPT Converter
$\rho_{e\_PVE}$	-	Accuracy Improvement of PVE
$\rho_{ts}$	-	Settling Time Improvement
$\Delta i_{L\_mppt}$	-	Change of MPPT Inductor Current
$\Delta Q_i$	-	Change of Charge in $C_{i\_mppt}$
$\Delta Q_o$	-	Change of Charge in $C_{o\_mppt}$
$\eta$	-	Efficiency
$\rho_{ts}$	-	Settling Time Improvement

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# CHAPTER 1

## INTRODUCTION

### 1.1 Background of the Study

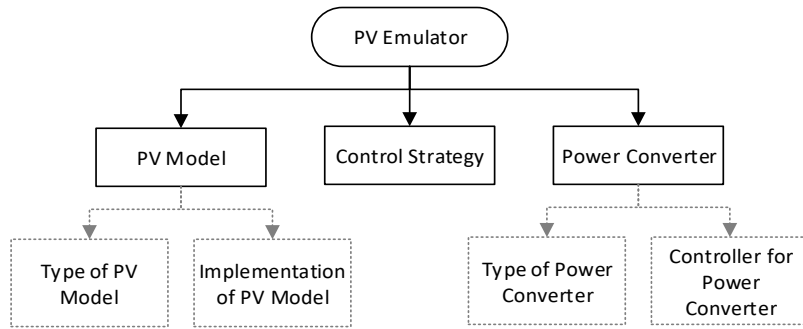
A recent study shows the potential of the solar based energy generation using the photovoltaic (PV) panel to fulfil the world's energy demand. Solar energy is one of the renewable energies that requires little maintenance, which has low operation cost and pollution free. Up to 2015, there was a 50 GW<sub>p</sub> increase annually in the global PV energy production, which totalled up to 227 GW<sub>p</sub> of the estimated global capacity of the PV energy [1]. This shows a 22% increase in the global energy production from the PV generation based system. Malaysia has the potential for solar-based energy generation due to its high and steady irradiance throughout the year [2]. There was a 27.1% increase in the PV energy production in Malaysia from 2016 to 2017 [3]. The rise in PV's popularity is due to an increase in awareness of the PV's potential, government programs to promote the use of the renewable energy and the increase in the market competition of the PV.

One of the components in the PV energy generation system is the maximum power point tracking (MPPT). Since the PV module is a nonlinear source, the MPPT ensures the maximum power is extracted from the PV module at any prevailing environmental condition. In the development stage of the MPPT, the PV module is emitted with irradiance from the controllable halogen lamp or the light emitting diode (LED) to test the effectiveness of the MPPT [4]. However, the setup for this test bed is complex and temperature manipulation is not flexible. This method also requires a large area for the actual PV module, the light source and a controllable direct current (DC) or alternating current (AC) source to control the light source. Besides, this method is inefficient since a high power is required by the light source to produce the irradiance for the PV module. These drawbacks can be overcome using an alternative test bed for MPPT testing, which is known as the PV emulator (PVE).

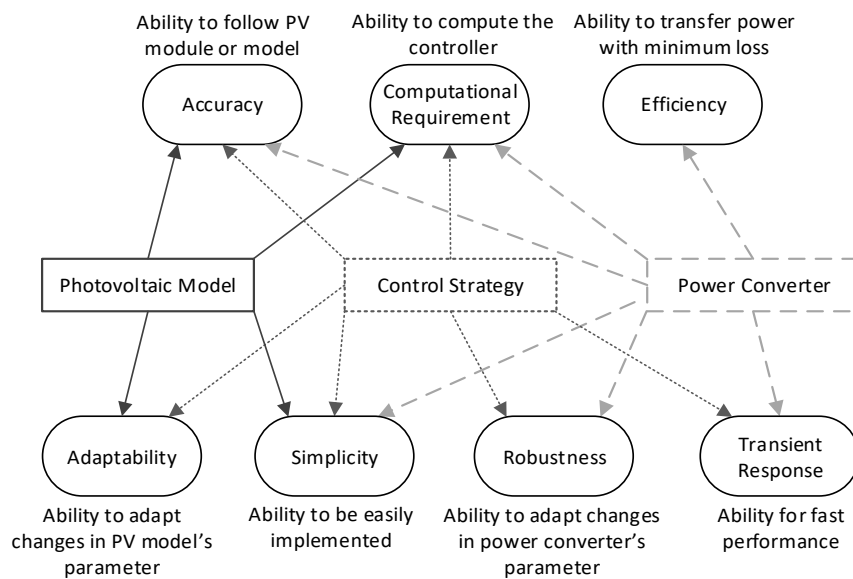


The PVE is a nonlinear power supply which is capable of producing the current-voltage (I-V) characteristic curve of a PV module. The PVE functions as a power source in the experimental stage of the solar energy generating system to allow repeatable testing conditions without sunlight. The PVE offers a convenient control of ambient conditions rather than complex irradiance and temperature control to allow fast and efficient solar energy generation system testing. The PVE available in the market varies from a single panel emulation (approximately 300 W) to a PV array emulation (larger than 300 W). However, this type of PVE is expensive, ranging from (US)\$ 6,385 (Elgar ETS60X14C-PVF) to (US)\$ 21,000 (Magna Power TSD50050240) [5, 6]. Therefore, much research related to the PVE has been conducted to reduce the overall cost and improve the transient response of the PVE.

In general, there are three components in a PVE system, namely the PV model, the power converter and the control strategy, as shown in Figure 1.1. The PV model is highly responsible for the accuracy, the computational requirement and the adaptability of the PVE, as shown in Figure 1.2. The PVE require real-time calculation of the PV model to operate properly. The delays in the computation of the PV model results in incorrect output for the PVE. Therefore, the PV model used in the PVE application needs to be simple enough without compromising the accuracy of the I-V characteristic produced [7]. This accuracy and simplicity depend on the type and implementation method of the PV model. The types of PV models include the Interpolation Model and the Electrical Circuit Model. While the implementation methods of the PV model includes the PV model simplification [8-12], Look-Up Table (LUT) [13-18], Piecewise Linear Method [19-22], and Neural Network [9, 23]. The PV model implementation method affects the adaptability of the PVE since some of the methods require offline adjustment of the PV model parameters.



**Figure 1.1:** The three components of the PVE system.



**Figure 1.2:** The influence of the three components in the PVE system toward the performance of the PVE.

The power converter is also a part of the PVE system. It affects the robustness, transient response, the efficiency and the computational requirement of the PVE. The actual PV panel response approximately tenth of microseconds [24]. Therefore, the PVE is aimed to have a fast response time similar to an actual PV panel. The performance depends on the type and controller of the power converter. The switched-mode power supply (SMPS) is commonly used in the PVE and is highly efficient [18, 25-28]. The linear regulator is useful if the output ripple for the PVE needs to be removed [29-32]. The design of the PVE using the programmable power supply is simple since the closed-loop system for the power converter is already included in the

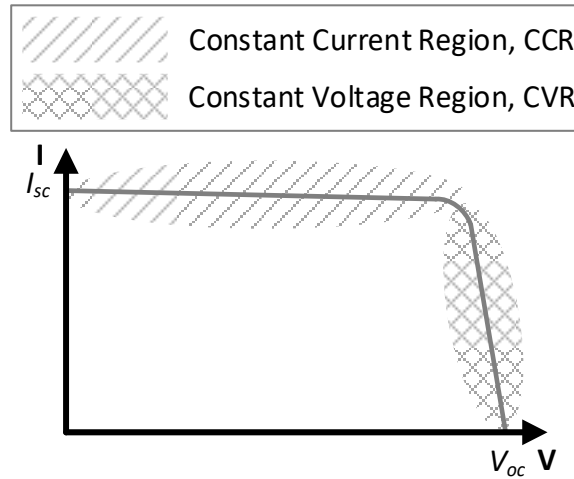
system [33-35]. While the commonly used controller for the power converter is the proportional-integral (PI) or proportional-integral-derivative (PID) controllers [24, 28, 36, 37]. There is also the fuzzy PI or PID controllers [38, 39] and the sliding mode controller [40, 41].

The control strategy of the PVE is the method used to obtain the operating point based on the given load, irradiance and temperature. It combines the PV model and power converter to become PVE. The control strategy affects the various performance of the PVE. A good control strategy features accurate output voltage and output current similar to the PV model, easily implemented, robustness, fast transient response, high adaptability in emulating various PV model and low processing burden. There are several control strategies used in PVE implementation. The direct referencing method (DRM) is commonly used in the PVE due to its simplicity [9, 11, 39, 42-44]. The hybrid-mode control method [29, 33, 45] and the resistance comparison method [26, 28, 46] produce a stable output for the PVE at any load condition. The hill climbing (HC) method for the PVE is easily designed since a compensator is not required [47, 48]. The analogue based method does not have a computational delay and the partial shading condition is easily emulated [44, 49-52].

## **1.2 Problem Statement**

The commonly used control strategy in PVE is the DRM due to its simplicity in implementation. The PVE is formed by connecting the PV model directly to the input reference of the closed-loop controller in the power converter. The operating point of the PVE using the DRM is determined by the PI controller and the buck converter. This is not a robust control strategy because any changes in the PI controller gains and the buck converter output may result in oscillation or instability in the PVE output voltage and current. Besides, the design of the PI controller is affected by the DRM and the process of tuning the PI controller gains becomes complicated. To avoid these problems, the hybrid-mode control method and the resistance comparison method is introduced. The hybrid-mode control method combines two types of DRMs, namely

the voltage-mode and current-mode control. The voltage-mode control DRM produces a non-oscillate and stable PVE output in I-V characteristic curve over the constant voltage region (CVR); yet the PVE output oscillates or becomes unstable when it moves over the constant current region (CCR), shown in Figure 1.3. Contrary, the current-mode control DRM produces a non-oscillate and stable PVE output in the CCR, but oscillates or becomes unstable in the CVR. Therefore, hybridise the operation of the PVE in the voltage-mode control DRM over the CVR and the current-mode control DRM over the CCR, non-oscillate and stable output of PVE can be achieved. Besides, the dependency of the hybrid-mode control method on the power converter and its controller is minimized, which ease the tuning of the PI controller. Nevertheless, the implementation becomes complicated since two different PV models and PI controllers are needed. An additional algorithm to switch between two DRMs is also needed in the control strategy. On the other hand, the resistance comparison method is robust since it computes the PVE operating point using the iterative method instead of relies on the power converter and its controller. This control strategy computes various data points in the I-V characteristic curve of the PV model and compares it with the output resistance before reaching the true operating point. Therefore, a high computational power is needed to avoid delays in producing the PVE operating points. Delay in computational results in inaccurate output voltage and current of the PVE. Acknowledged the benefits and drawbacks of the control strategies, an improved control strategy features a robust characteristic, simple implementation and low computational power has been proposed.



**Figure 1.3:** The area of the constant current and voltage regions in the PV I-V characteristic curve.

The PI controller for the closed-loop buck converter is designed specifically for a load condition. Even though this PI controller is able to operate under other load conditions, the performance of the buck converter decreases significantly. As the load increases, the settling time for the output voltage and current of the closed-loop buck converter increases. Conversely, the PI controller used in the PVE with the DRM produces a low settling time for the PVE output voltage and current when the output resistance is high. The fast performance of the DRM at high output resistance is due to the high input reference during the transient response that causing the duty cycle to change quickly. Still, the PVE with the DRM performs slowly when output resistance is low. Consequently, the characteristics of the conventional PI controller for the closed-loop buck converter during low output resistance and the DRM during high output resistance are desired. Hence, this combination produces fast output voltage and current response for the buck converter at various load condition. These characteristics can be applied to the fuzzy controller in order to improve the performance of the PVE.

### **1.3 Research Objectives**

The objectives of the research are:

1. To design a control strategy for the PVE features robust characteristic, simple implementation and low computational power.
2. To improve the transient performance of the PVE at various load conditions using the fuzzy controller.
3. To validate the proposed PVE system experimentally and benchmarked with the DRM.

### **1.4 Research Methodology**

Firstly, the literature review on the PVE is conducted. In the review, the control strategy, PV model and power converter used in the PVE is analysed. The advantages and disadvantages of the various components in the PVE are investigated based on the simulations and experiments conducted on the PVE. The problems faced by the conventional PVE is studied and the new controller for the PVE is suggested to overcome these problems.

The new controller for the PVE is simulated using MATLAB/Simulink. A PV module is chosen during the emulation process. The performances of the PVE are analysed using the resistive load and the maximum power point tracking (MPPT) boost converter. The results from the new controller is compared with the conventional controller.

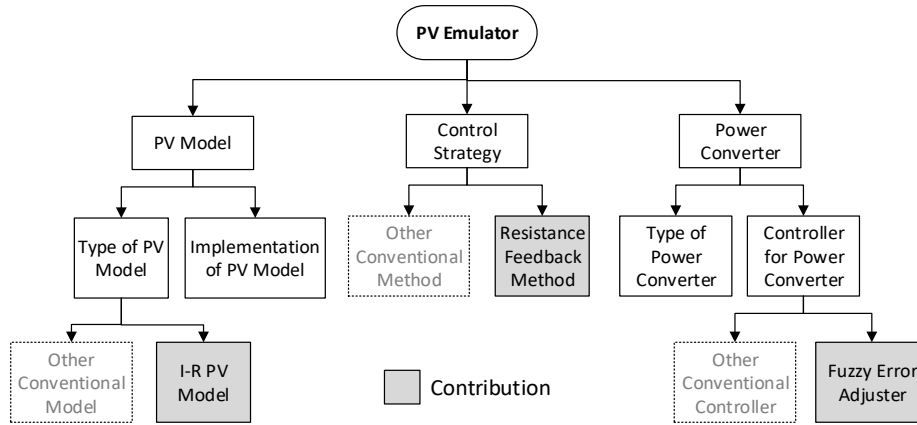
Lastly, the simulation results are experimentally validated, which the controllers for the PVEs are implemented in dSPACE ds1104 rapid prototyping. The experimental results is observed using an oscilloscope and dSPACE ControlDesk software package.

## 1.5 Research Contribution

The thesis presents the proposed work on PVE research with contributions as follow:

1. To proposes a control strategy called the resistance feedback method (RFM), which requires only a single iteration of the PV model to produce an operating point. It is highly accurate, easily implemented, robust against various changes in the parameters of the power converter and its controller, adapts to various PV module, and produces fast output voltage and current response.
2. To proposes a modified current-resistance (I-R) PV model which the input to the PV model is the resistance. It is computed using the binary search method. This model allows the change of irradiance and temperature during operation, which is highly accurate and easily implemented. This PV model is suitable for the RFM.
3. To proposes a fuzzy controller for the buck converter called the fuzzy error compensator, which is capable of maintaining fast response at various load conditions. The fuzzy error compensator is integrated into the RFM to further improve the performance of the PVE.
4. To develops a procedure to design the boost converter specifically for the MPPT application. This allows simple calculations of the passive components in the MPPT boost converter.

The first three contributions improve all three components of the PVE system as shown in Figure 1.4. While the last contribution improves the results obtained when the PVE is connected to the MPPT converter.



**Figure 1.4:** The contribution categories based on the components of the PVE system.

## 1.6 Scope of the Study

The simulation of the PVE is done using the MATLAB/Simulink software package. The improvement of the PVE focused on the control strategy, PV model and the controller for the power converter. There is no modification on the type of power converter used in the PVE. The PVE is able to emulate the PV module with the open circuit voltage of 44.4 V, the short circuit current of 2.32 A and the maximum power of 75.7 W<sub>p</sub>. The single diode model is used as the PV model. The PVE requires real-time calculation of the PV model. Therefore, the PV model used for PVE application needs to compromise between the complexity and the accuracy.

The buck converter is chosen as the power converter for the PVE since it is efficient, able to operate at various condition and easily controlled. The load for the PVE is a resistive load and the MPPT boost converter with the perturb and observe (P&O) method. The performance of the proposed controller is benchmarked with the



conventional DRM. The controller for the PVE is implemented using the dSPACE ds1104 rapid prototyping board and it is monitored using the dSPACE ControlDesk software package.

In this thesis, the partial shading is not considered in the PVE since the real-time calculation of the PV model burdens the digital hardware platform. The load of the PVE ranges from  $5 \Omega$  to  $90 \Omega$ . The short and open circuit tests are not conducted due to the limitation of the buck converter. The PVE and MPPT boost converter is designed to operate with the irradiance between  $200 \text{ W/m}^2$  to  $1000 \text{ W/m}^2$  and temperature between  $0^\circ\text{C}$  to  $75^\circ\text{C}$ . During this condition, the PVE and MPPT boost converter operates in the continuous current-mode. The operation outside the irradiance and temperature ranges may result in a large voltage ripple, inaccurate emulation and damages to the components. The standard test condition (STC), which is  $1000 \text{ W/m}^2$  and  $25^\circ\text{C}$ , is used to analyse the performance of the PVEs. Nonetheless, the designed PVE and MPPT boost converter capable of operating within the real-world irradiance and temperature condition.

## **1.7 Thesis Organization**

The thesis is organised as follows:

Chapter 2 reviews the various types and implementation of the PV model, the types of power converter and its controller, and several types of the control strategy. The benefits and drawbacks of each component are also discussed.

Chapter 3 discusses the methodology of the conventional single diode PV model used in the PVE. The design of the buck converter and the derivation of the transfer function are reported in this chapter. There are two controllers for the buck converter, namely the conventional PI controller and the proposed fuzzy error compensator. The

procedure for developing the conventional DRM, the proposed RFM with PI controller (RFMPI) and the proposed RFM with the fuzzy controller (RFMF) are elaborated in this chapter. The proposed design procedure of the MPPT boost converter is also derived.

Chapter 4 discusses the simulation results of the conventional DRM, the proposed RFMPI and the proposed RFMF. This chapter covers the convergence of one data point in the I-V characteristic curve using the conventional and the proposed PV model. In addition, the robustness, accuracy and transient response of the control strategy are detailed. The performance of the PVE when it is connected to the MPPT converter is also analysed. The derived equations of the MPPT boost converter are validated using simulations.

Chapter 5 discusses the experimental results of the conventional DRM, the proposed RFMPI and the proposed RFMF. The procedure for developing the experimental set-up is discussed in this chapter. The experimental results are compared with the simulation results in order to validate the proposed method.

Chapter 6 draws the conclusion of the thesis and provides possible directions for further research.

## REFERENCES

- [1] REN21, "Renewables 2016 Global Status Report (GSR)," 2016.
- [2] A. Belhamadia, M. Mansor, and M. A. Younis, "Assessment of wind and solar energy potentials in Malaysia," in *Clean Energy and Technology (CEAT), 2013 IEEE Conference on*, 2013, pp. 152-157.
- [3] S. Malaysia. (2018). *Sustainable Energy Development Authority (SEDA) Malaysia: Renewable Energy Generation*. Available: <http://www.seda.gov.my/>
- [4] S. Armstrong, C. K. Lee, and W. G. Hurley, "Investigation of the harmonic response of a photovoltaic system with a solar emulator," in *Power Electronics and Applications, 2005 European Conference on*, 2005, pp. 8 pp.-P.8.
- [5] *Ametek Programmable Power*. Available: <http://www.programmablepower.com/>
- [6] *Magma Power*. Available: <http://www.magna-power.com/>
- [7] E. Lattanzi, M. Dromedari, V. Freschi, and A. Bogliolo, "Tuning the complexity of photovoltaic array models to meet real-time constraints of embedded energy emulators," *Energies*, vol. 10, 2017.
- [8] M. C. Di Piazza, M. Pucci, A. Ragusa, and G. Vitale, "A grid-connected system based on a real time PV emulator: Design and experimental set-up," in *IECON 2010 - 36th Annual Conference on IEEE Industrial Electronics Society*, 2010, pp. 3237-3243.
- [9] M. C. Di Piazza, M. Pucci, A. Ragusa, and G. Vitale, "Analytical Versus Neural Real-Time Simulation of a Photovoltaic Generator Based on a DC-DC Converter," *IEEE Transactions on Industry Applications*, vol. 46, pp. 2501-2510, 2010.
- [10] D. Ickilli, H. Can, and K. S. Parlak, "Development of a FPGA-based photovoltaic panel emulator based on a DC/DC converter," in *Photovoltaic Specialists Conference (PVSC), 2012 38th IEEE*, 2012, pp. 001417-001421.
- [11] D. Abbes, A. Martinez, G. Champenois, and B. Robyns, "Real time supervision for a hybrid renewable power system emulator," *Simulation Modelling Practice and Theory*, vol. 42, pp. 53-72, 3// 2014.
- [12] Y. Erkaya, P. Moses, I. Flory, and S. Marsillac, "Steady-state performance optimization of a 500 kHz photovoltaic module emulator," in *2016 IEEE 43rd Photovoltaic Specialists Conference (PVSC)*, 2016, pp. 3205-3208.
- [13] M. T. Iqbal, M. Tariq, M. K. Ahmad, and M. S. B. Arit, "Modeling, analysis and control of buck converter and Z-source converter for photo voltaic emulator," in *2016 IEEE 1st International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES)*, 2016, pp. 1-6.
- [14] Z. Weichao and J. W. Kimball, "DC-DC converter based photovoltaic simulator with a double current mode controller," in *2016 IEEE Power and Energy Conference at Illinois (PECI)*, 2016, pp. 1-6.
- [15] S. Gadelovits, M. Sitbon, and A. Kuperman, "Rapid Prototyping of a Low-Cost Solar Array Simulator Using an Off-the-Shelf DC Power Supply," *IEEE Transactions on Power Electronics*, vol. 29, pp. 5278-5284, 2014.

- [16] E. Koutroulis, K. Kalaitzakis, and V. Tzitzilioni, "Development of an FPGA-based system for real-time simulation of photovoltaic modules," *Microelectronics Journal*, vol. 40, pp. 1094-1102, 2009.
- [17] L. M. Barrera, R. A. Osorio, and C. L. Trujillo, "Design and implementation of electronic equipment that emulates photovoltaic panels," in *Photovoltaic Specialist Conference (PVSC), 2015 IEEE 42nd*, 2015, pp. 1-5.
- [18] González-Medina, Raúl Patrao, Iván Garcerá, Gabriel Figueres, and Emilio, "A low-cost photovoltaic emulator for static and dynamic evaluation of photovoltaic power converters and facilities," *Progress in Photovoltaics: Research and Applications*, vol. 22, pp. 227-241, 2012.
- [19] G. Martin-Segura, J. Lopez-Mestre, M. Teixido-Casas, and A. Sudria-Andreu, "Development of a photovoltaic array emulator system based on a full-bridge structure," in *Electrical Power Quality and Utilisation, 2007. EPQU 2007. 9th International Conference on*, 2007, pp. 1-6.
- [20] H. Abidi, A. B. Ben Abdelghani, and D. Montesinos-Miracle, "MPPT algorithm and photovoltaic array emulator using DC/DC converters," in *Electrotechnical Conference (MELECON), 2012 16th IEEE Mediterranean*, 2012, pp. 567-572.
- [21] Z. Ziming, Z. Jianwen, S. Haimeng, W. Gang, H. Xiwen, and Z. Shi, "Research on Photovolta Array Emulator System Based on A Novel Zero-Voltage Zero-Current Switching Converter," in *Power and Energy Engineering Conference (APPEEC), 2010 Asia-Pacific*, 2010, pp. 1-4.
- [22] D. D. C. Lu and Q. N. Nguyen, "A photovoltaic panel emulator using a buck-boost DC/DC converter and a low cost micro-controller," *Solar Energy*, vol. 86, pp. 1477-1484, 5// 2012.
- [23] F. Gomez-Castaneda, G. M. Tornez-Xavier, L. M. Flores-Nava, O. Arellano-Cardenas, J. A. Moreno-Cadenas, and Ieee, "Photovoltaic panel emulator in FPGA technology using ANFIS approach," in *2014 11th International Conference on Electrical Engineering, Computing Science and Automatic Control (Cce)*, 2014, p. 6.
- [24] K. Nguyen-Duy, A. Knott, and M. A. E. Andersen, "High Dynamic Performance Nonlinear Source Emulator," *IEEE Transactions on Power Electronics*, vol. 31, pp. 2562-2574, Mar 2016.
- [25] A. Vijayakumari, A. T. Devarajan, and N. Devarajan, "Design and development of a model-based hardware simulator for photovoltaic array," *International Journal of Electrical Power & Energy Systems*, vol. 43, pp. 40-46, 12// 2012.
- [26] A. V. Rana and H. H. Patel, "Current controlled buck converter based photovoltaic emulator," *Journal of Industrial and Intelligent Information*, vol. 1, 2013.
- [27] C.-C. Chen, H.-C. Chang, C.-C. Kuo, and C.-C. Lin, "Programmable energy source emulator for photovoltaic panels considering partial shadow effect," *Energy*, vol. 54, pp. 174-183, 6/1/ 2013.
- [28] C. H. Balakishan and N. Sandeep, "Development of a Microcontroller Based PV Emulator with Current Controlled DC-DC Buck Converter " *International Journal of Renewable Energy Research*, vol. 4, p. 1, 22 November 2014.
- [29] Y. Kim, W. Lee, M. Pedram, and N. Chang, "Dual-mode power regulator for photovoltaic module emulation," *Applied energy*, vol. 101, pp. 730-739, 2013.

- [30] D. M. K. Schofield, M. P. Foster, and D. A. Stone, "Low-cost solar emulator for evaluation of maximum power point tracking methods," *Electronics Letters*, vol. 47, pp. 208-209, 2011.
- [31] K.-H. Tang, K.-H. Chao, Y.-W. Chao, and J.-P. Chen, "Design and implementation of a simulator for photovoltaic modules," *International Journal of Photoenergy*, vol. 2012, 2012.
- [32] S. Jin and D. Zhang, "A simple control method of open-circuit voltage for the FPGA-based solar array simulator," in *Power and Renewable Energy (ICPRE), IEEE International Conference on Power and*, 2016, pp. 209-216.
- [33] T. D. Mai, S. De Breucker, K. Baert, and J. Driesen, "Reconfigurable emulator for photovoltaic modules under static partial shading conditions," *Solar Energy*, vol. 141, pp. 256-265, 1 January 2017.
- [34] V. Rajguru, K. Gadge, S. Karyakarte, S. Kawathekar, and V. Menon, "Design and implementation of a prototype DC photovoltaic power system simulator with Maximum Power Point Tracking system," in *2016 IEEE 1st International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES)*, 2016, pp. 1-5.
- [35] A. Xenophontos, J. Rarey, A. Trombetta, and A. M. Bazzi, "A flexible low-cost photovoltaic solar panel emulation platform," in *Power and Energy Conference at Illinois (PECI)*, 2014, pp. 1-6.
- [36] L. P. Sampaio and S. A. O. d. Silva, "Graphic computational platform integrated with an electronic emulator dedicated to photovoltaic systems teaching," *IET Power Electronics*, vol. 10, pp. 1982-1992, 2017.
- [37] U. K. Shinde, S. G. Kadwane, R. K. Keshri, and S. Gawande, "Dual Mode Controller-Based Solar Photovoltaic Simulator for True PV Characteristics," *Canadian Journal of Electrical and Computer Engineering*, vol. 40, pp. 237-245, 2017.
- [38] W. Shao, Z. Q. Meng, H. A. Zhou, and K. Zhang, "A photovoltaic array simulator based on current feedback fuzzy PID control," *Journal of Intelligent and Fuzzy Systems*, vol. 29, pp. 2555-2564, 2015.
- [39] J. Zhang, S. Wang, Z. Wang, and L. Tian, "Design and realization of a digital PV simulator with a push-pull forward circuit," *Journal of Power Electronics*, vol. 14, pp. 444-457, 2014.
- [40] U. K. Shinde, S. G. Kadwane, S. P. Gawande, and R. Keshri, "Solar PV emulator for realizing PV characteristics under rapidly varying environmental conditions," in *2016 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES)*, 2016, pp. 1-5.
- [41] A. Cordeiro, D. Foito, V. Fern, and P. o, "A PV panel simulator based on a two quadrant DC/DC power converter with a sliding mode controller," in *2015 International Conference on Renewable Energy Research and Applications (ICRERA)*, 2015, pp. 928-932.
- [42] C. Roncero-Clemente, E. Romero-Cadaval, V. Minambres, M. Guerrero-Martinez, and J. Gallardo-Lozano, "PV Array Emulator for Testing Commercial PV Inverters," *Elektronika ir Elektrotechnika*, vol. 19, pp. 71-75, 2013.
- [43] A. Koran, T. LaBella, and J. S. Lai, "High Efficiency Photovoltaic Source Simulator with Fast Response Time for Solar Power Conditioning Systems Evaluation," *IEEE Transactions on Power Electronics*, vol. 29, pp. 1285-1297, 2014.

- [44] A. Koran, K. Sano, K. Rae-Young, and L. Jih-Sheng, "Design of a Photovoltaic Simulator With a Novel Reference Signal Generator and Two-Stage LC Output Filter," *IEEE Transactions on Power Electronics*, vol. 25, pp. 1331-1338, 2010.
- [45] L. Yuan, L. Taewon, F. Z. Peng, and L. Dichen, "A Hybrid Control Strategy for Photovoltaic Simulator," in *Applied Power Electronics Conference and Exposition, 2009. APEC 2009. Twenty-Fourth Annual IEEE*, 2009, pp. 899-903.
- [46] Z. Qingrong, S. Pinggang, and C. Liuchen, "A photovoltaic simulator based on DC chopper," in *Electrical and Computer Engineering, 2002. IEEE CCECE 2002. Canadian Conference on*, 2002, pp. 257-261 vol.1.
- [47] Y. Erkaya, P. Moses, I. Flory, S. Marsillac, and Ieee, "Development of a Solar Photovoltaic Module Emulator," in *2015 Ieee 42nd Photovoltaic Specialist Conference*, New York, 2015.
- [48] J. Gonzalez-Llorente, A. Rambal-Vecino, L. A. Garcia-Rodriguez, J. C. Balda, and E. I. Ortiz-Rivera, "Simple and efficient low power photovoltaic emulator for evaluation of power conditioning systems," in *2016 IEEE Applied Power Electronics Conference and Exposition (APEC)*, 2016, pp. 3712-3716.
- [49] O. M. Midtgard, "A simple photovoltaic simulator for testing of power electronics," in *Power Electronics and Applications, 2007 European Conference on*, 2007, pp. 1-10.
- [50] H. Nagayoshi, "I-V curve simulation by multi-module simulator using I-V magnifier circuit," *Solar Energy Materials and Solar Cells*, vol. 82, pp. 159-167, 5/1/ 2004.
- [51] A. Zegaoui, M. Aillerie, P. Petit, and J.-P. Charles, "Universal Transistor-based hardware SIMulator for real time simulation of photovoltaic generators," *Solar Energy*, vol. 134, pp. 193-201, 9// 2016.
- [52] Z. Zhou, P. M. Holland, and P. Igic, "MPPT algorithm test on a photovoltaic emulating system constructed by a DC power supply and an indoor solar panel," *Energy Conversion and Management*, vol. 85, pp. 460-469, 9// 2014.
- [53] S. K. Garai, "A Photovoltaic Cell Emulator," Master of Technology in Instrumentation & Electronics Engineering Department of Instrumentation and Electronics Engineering, Jadavpur University, Kolkata, West Bengal, India, 2013.
- [54] K. Khouzam and K. Hoffman, "Real-time simulation of photovoltaic modules," *Solar Energy*, vol. 56, pp. 521-526, 1996.
- [55] J.-P. Lee, B.-D. Min, T.-J. Kim, J.-H. Kim, M.-H. Ryu, J.-W. Baek, *et al.*, "Development of a photovoltaic simulator with novel simulation method of photovoltaic characteristics," in *Telecommunications Energy Conference, 2009. INTELEC 2009. 31st International*, 2009, pp. 1-5.
- [56] M. C. D. Piazza and G. Vitale, "Photovoltaic Sources: Modelling and Emulation," ed: Springer Science & Business Media, 2012.
- [57] J. Agrawal and M. Aware, "Photovoltaic system emulator," in *Power Electronics, Drives and Energy Systems (PEDES), 2012 IEEE International Conference on*, 2012, pp. 1-6.
- [58] A. M. Koran, "Photovoltaic Source Simulators for Solar Power Conditioning Systems: Design Optimization, Modeling, and Control " Doctor of Philosophy Virginia Polytechnic Institute and State University, Blacksburg, Virginia 2013.

- [59] J. Cubas, S. Pindado, and M. Victoria, "On the analytical approach for modeling photovoltaic systems behavior," *Journal of Power Sources*, vol. 247, pp. 467-474, 2014.
- [60] M. De Blas, J. Torres, E. Prieto, and A. Garcia, "Selecting a suitable model for characterizing photovoltaic devices," *Renewable energy*, vol. 25, pp. 371-380, 2002.
- [61] P. Hyeonah and K. Hyosung, "PV cell modeling on single-diode equivalent circuit," in *Industrial Electronics Society, IECON 2013 - 39th Annual Conference of the IEEE*, 2013, pp. 1845-1849.
- [62] X. Lingyun, S. Lefei, H. Wei, and J. Cong, "Solar cells parameter extraction using a hybrid genetic algorithm," in *Measuring Technology and Mechatronics Automation (ICMTMA), 2011 Third International Conference on*, 2011, pp. 306-309.
- [63] J. H. Agrawal and M. V. Aware, "Photovoltaic simulator developed in LabVIEW for evaluation of MPPT techniques," in *2016 International Conference on Electrical, Electronics, and Optimization Techniques (ICEEOT)*, 2016, pp. 1142-1147.
- [64] W. De Soto, S. Klein, and W. Beckman, "Improvement and validation of a model for photovoltaic array performance," *Solar energy*, vol. 80, pp. 78-88, 2006.
- [65] K. Ishaque, Z. Salam, and Syafaruddin, "A comprehensive MATLAB Simulink PV system simulator with partial shading capability based on two-diode model," *Solar Energy*, vol. 85, pp. 2217-2227, 9// 2011.
- [66] A. C. Atoche, J. V. Castillo, J. Ortégón-Aguilar, R. Carrasco-Alvarez, J. S. Gío, and A. Colli-Menchi, "A high-accuracy photovoltaic emulator system using ARM processors," *Solar Energy*, vol. 120, pp. 389-398, 2015.
- [67] F. Attivissimo, A. D. Nisio, M. Savino, and M. Spadavecchia, "Uncertainty analysis in photovoltaic cell parameter estimation," *Instrumentation and Measurement, IEEE Transactions on*, vol. 61, pp. 1334-1342, 2012.
- [68] N. Belhaouas, M. A. Cheikh, A. Malek, and C. Larbes, "Matlab-Simulink of photovoltaic system based on a two-diode model simulator with shaded solar cells," *Revue RER*, vol. 16, pp. 65-73, 2013.
- [69] S. Chowdhury, S. Chowdhury, G. Taylor, and Y. Song, "Mathematical modelling and performance evaluation of a stand-alone polycrystalline PV plant with MPPT facility," in *Power and Energy Society General Meeting- Conversion and Delivery of Electrical Energy in the 21st Century, 2008 IEEE*, 2008, pp. 1-7.
- [70] M. C. Di Piazza, M. Luna, A. Ragusa, and G. Vitale, "A dynamic model of a photovoltaic generator based on experimental data," in *Renew Energy Power Qual J. ISSN*, 2010.
- [71] J. Gow and C. Manning, "Development of a photovoltaic array model for use in power-electronics simulation studies," in *Electric Power Applications, IEE Proceedings-*, 1999, pp. 193-200.
- [72] J. A. Jervase, H. Bourdoucen, and A. Al-Lawati, "Solar cell parameter extraction using genetic algorithms," *Measurement Science and Technology*, vol. 12, p. 1922, 2001.
- [73] L. Sandrolini, M. Artioli, and U. Reggiani, "Numerical method for the extraction of photovoltaic module double-diode model parameters through cluster analysis," *Applied Energy*, vol. 87, pp. 442-451, 2010.

- [74] S. M. Azharuddin, M. Vysakh, H. V. Thakur, B. Nishant, T. S. Babu, K. Muralidhar, *et al.*, "A Near Accurate Solar PV Emulator Using dSPACE Controller for Real-time Control," in *Energy Procedia*, 2014, pp. 2640-2648.
- [75] M. Balato, L. Costanzo, D. Gallo, C. Landi, M. Luiso, and M. Vitelli, "Design and implementation of a dynamic FPAA based photovoltaic emulator," *Solar Energy*, vol. 123, pp. 102-115, 1// 2016.
- [76] F. Barra, M. Balato, L. Costanzo, D. Gallo, C. Landi, M. Luiso, *et al.*, "Dynamic and Reconfigurable Photovoltaic Emulator Based on FPAA," 2014.
- [77] D. Dolan, J. Durago, J. Crowfoot, and Taufik, "Simulation of a photovoltaic emulator," in *North American Power Symposium (NAPS), 2010*, 2010, pp. 1-7.
- [78] J. G. Durago, "Photovoltaic Emulator Adaptable To Irradiance, Temperature and Panel-Specific I-V Curves," Master of Science in Electrical Engineering, Electrical Engineering, California Polytechnic State University, San Luis Obispo, California, United States, 2011.
- [79] W. Lee, Y. Kim, Y. Wang, N. Chang, M. Pedram, and S. Han, "Versatile high-fidelity photovoltaic module emulation system," in *Proceedings of the 17th IEEE/ACM international symposium on Low-power electronics and design*, 2011, pp. 91-96.
- [80] P. G. Bernal, "Study and Development of a Photovoltaic Panel Simulator," Master in Electrical and Computers Engineering University of Porto, 2012.
- [81] A. F. Ebrahim, S. M. W. Ahmed, S. E. Elmasry, and O. A. Mohammed, "Implementation of a PV emulator using programmable DC power supply," in *SoutheastCon 2015*, 2015, pp. 1-7.
- [82] J. Ollila, "A medium power PV-array simulator with a robust control strategy," in *Control Applications, 1995., Proceedings of the 4th IEEE Conference on*, 1995, pp. 40-45.
- [83] T. P. V. Preethishri, K. S. Kumar, and P. Sivakumar, "Embedded emulator of photovoltaic array and wind driven induction generator by using digital signal controller (tms320f28335)," in *Power Electronics (IICPE), 2010 India International Conference on*, 2011, p. 1.
- [84] R. G. Wandhare and V. Agarwal, "A low cost, light weight and accurate photovoltaic emulator," in *Photovoltaic Specialists Conference (PVSC), 2011 37th IEEE*, 2011, pp. 001887-001892.
- [85] K. Ding, X. Bian, H. Liu, and T. Peng, "A MATLAB-simulink-based PV module model and its application under conditions of nonuniform irradiance," *Energy Conversion, IEEE Transactions on*, vol. 27, pp. 864-872, 2012.
- [86] K. Leban and E. Ritchie, "Selecting the accurate solar panel simulation model," in *Nordic Workshop on Power and Industrial Electronics (NORPIE/2008), June 9-11, 2008, Espoo, Finland*, 2008.
- [87] G. Walker, "Evaluating MPPT converter topologies using a MATLAB PV model," *Journal of Electrical & Electronics Engineering, Australia*, vol. 21, pp. 49-56, 2001.
- [88] Y. Yusof, S. H. Sayuti, M. Abdul Latif, and M. Z. C. Wanik, "Modeling and simulation of maximum power point tracker for photovoltaic system," in *Power and Energy Conference, 2004. PECon 2004. Proceedings. National*, 2004, pp. 88-93.
- [89] B. D. Patel and A. Rana, "A pole-placement approach for buck converter based PV array Emulator," in *2016 IEEE 1st International Conference on Power*



- Electronics, Intelligent Control and Energy Systems (ICPEICES)*, 2016, pp. 1-5.
- [90] P. J. Binduhewa and M. Barnes, "Photovoltaic emulator," in *Industrial and Information Systems (ICIIS), 2013 8th IEEE International Conference on*, 2013, pp. 519-524.
- [91] N. A. Kamarzaman and C. W. Tan, "A comprehensive review of maximum power point tracking algorithms for photovoltaic systems," *Renewable and Sustainable Energy Reviews*, vol. 37, pp. 585-598, September 2014.
- [92] V. J. Chin, Z. Salam, and K. Ishaque, "Cell modelling and model parameters estimation techniques for photovoltaic simulator application: A review," *Applied Energy*, vol. 154, pp. 500-519, 15 September 2015.
- [93] Y. T. Seo, J. Y. Park, and S. J. Choi, "A rapid I-V curve generation for PV model-based solar array simulators," in *ECCE 2016 - IEEE Energy Conversion Congress and Exposition, Proceedings*, 2016.
- [94] J. Yuncong, J. A. A. Qahouq, and I. Batarseh, "Improved solar PV cell Matlab simulation model and comparison," in *Circuits and Systems (ISCAS), Proceedings of 2010 IEEE International Symposium on*, 2010, pp. 2770-2773.
- [95] H. Bellia, R. Youcef, and M. Fatima, "A detailed modeling of photovoltaic module using MATLAB," *NRIAG Journal of Astronomy and Geophysics*, vol. 3, pp. 53-61, 6// 2014.
- [96] H. Can, D. Ickilli, K. S. Parlak, and Ieee, "A New Numerical Solution Approach for the Real-Time Modeling of Photovoltaic Panels," in *2012 Asia-Pacific Power and Energy Engineering Conference*, New York, 2012.
- [97] D. S. L. Dolan, J. Durago, and Taufik, "Development of a photovoltaic panel emulator using Labview," in *Photovoltaic Specialists Conference (PVSC), 2011 37th IEEE*, 2011, pp. 001795-001800.
- [98] J. Zhao and J. W. Kimball, "A digitally implemented photovoltaic simulator with a double current mode controller," in *2012 Twenty-Seventh Annual IEEE Applied Power Electronics Conference and Exposition (APEC)*, 2012, pp. 53-58.
- [99] A. M. Koran, "Photovoltaic Source Simulators for Solar Power Conditioning Systems: Design Optimization, Modeling, and Control " Doctor of Philosophy, Faculty of the Virginia Polytechnic Institute and State University, Virginia Polytechnic Institute and State University, 2013.
- [100] D. S. H. Chan and J. C. H. Phang, "Analytical methods for the extraction of solar-cell single- and double-diode model parameters from I-V characteristics," *Electron Devices, IEEE Transactions on*, vol. 34, pp. 286-293, 1987.
- [101] J. Chavarría, D. Biel, F. Guinjoan, A. Poveda, F. Masana, and E. Alarcón, "FPGA-based design of a step-up photovoltaic array emulator for the test of PV grid-connected inverters," in *Industrial Electronics (ISIE), 2014 IEEE 23rd International Symposium on*, 2014, pp. 485-490.
- [102] A. F. Cupertino, H. A. Pereira, and V. F. Mendes, "Modeling, Design and Control of a Solar Array Simulator Based on Two-Stage Converters," *Journal of Control, Automation and Electrical Systems*, July 31 2017.
- [103] S. Raizada and V. Verma, "Sizing sampling rate of the integrated PV simulator," in *Industrial Electronics and Applications Conference (IEACon), 2016 IEEE*, 2016, pp. 97-103.
- [104] J. Chavarría, D. Biel, F. Guinjoan, A. Poveda, F. Masana, and E. Alarcon, "Low cost photovoltaic array emulator design for the test of PV grid-connected

- inverters," in *Multi-Conference on Systems, Signals & Devices (SSD), 2014 11th International*, 2014, pp. 1-6.
- [105] S. Masashi, Y. Naoki, and I. Muneaki, "Development of Photovoltaic cell emulator using the small scale wind turbine," in *Electrical Machines and Systems (ICEMS), 2012 15th International Conference on*, 2012, pp. 1-4.
- [106] A. Algaddafi, N. Brown, R. Gammon, and S. A. Altuwayjiri, "Effect of PV array emulator on power quality of PV inverter compared to a real PV array," in *2015 3rd International Renewable and Sustainable Energy Conference (IRSEC)*, 2015, pp. 1-6.
- [107] A. Rachid, F. Kerrou, R. Chenni, and H. Djeghloud, "PV emulator based buck converter using dSPACE controller," in *2016 IEEE 16th International Conference on Environment and Electrical Engineering (EEEIC)*, 2016, pp. 1-6.
- [108] Ö. Ö, Y. Duru, S. Zengin, and M. Boztepe, "Design and implementation of programmable PV simulator," in *2016 International Symposium on Fundamentals of Electrical Engineering (ISFEE)*, 2016, pp. 1-5.
- [109] S. Thale, R. Wandhare, and V. Agarwal, "A novel low cost portable integrated solar PV, fuel cell and battery emulator with fast tracking algorithm," in *Photovoltaic Specialist Conference (PVSC), 2014 IEEE 40th*, 2014, pp. 3138-3143.
- [110] D. W. Hart, *Power Electronics*. Valparaiso University, Indiana: Tata McGraw-Hill Education, 2011.
- [111] A. Pressman, *Switching Power Supply Design* vol. 3: McGraw-Hill, Inc., 1997.
- [112] M. Ilic and D. Maksimovic, "Interleaved zero-current-transition buck converter," *Industry Applications, IEEE Transactions on*, vol. 43, pp. 1619-1627, 2007.
- [113] J. Garcia, A. J. Calleja, D. Gacio Vaquero, and L. Campa, "Interleaved buck converter for fast PWM dimming of high-brightness LEDs," *Power Electronics, IEEE Transactions on*, vol. 26, pp. 2627-2636, 2011.
- [114] M. Bendali, C. Larouci, T. Azib, C. Marchand, and G. Coquery, "Design methodology with optimization of an interleaved buck converter for automotive application," in *EUROCON, 2013 IEEE*, 2013, pp. 1066-1072.
- [115] Y. Qiu, M. Xu, K. Yao, J. Sun, and F. C. Lee, "Multifrequency Small-Signal Model for Buck and Multiphase Buck Converters," *IEEE Transactions on Power Electronics*, vol. 21, pp. 1185-1192, 2006.
- [116] O. García, P. Zumel, A. De Castro, and J. A. Cobos, "Automotive DC-DC bidirectional converter made with many interleaved buck stages," *Power Electronics, IEEE Transactions on*, vol. 21, pp. 578-586, 2006.
- [117] Y. Jang, M. M. Jovanovic, and Y. Panov, "Multiphase buck converters with extended duty cycle," in *Proc. IEEE Applied Power Electronics Conf.(APEC'06)*, 2006, pp. 38-44.
- [118] M. Esteki, B. Poorali, E. Adib, and H. Farzanehfard, "Interleaved Buck Converter With Continuous Input Current, Extremely Low Output Current Ripple, Low Switching Losses, and Improved Step-Down Conversion Ratio," *Industrial Electronics, IEEE Transactions on*, vol. 62, pp. 4769-4776, 2015.
- [119] I.-O. Lee, S.-Y. Cho, and G.-W. Moon, "Interleaved buck converter having low switching losses and improved step-down conversion ratio," *Power Electronics, IEEE Transactions on*, vol. 27, pp. 3664-3675, 2012.

- [120] M. Cacciato, A. Consoli, G. Scarcella, and A. Testa, "A Multhi-Phase DC/DC Converter for Automotive Dual-voltage Power Systems," *IEEE Industry Applications Magazine*, vol. 40, pp. 2-9, 2004.
- [121] M. Esteki, B. Poorali, E. Adib, and H. Farzanehfard, "High step-down interleaved buck converter with low voltage stress," *Power Electronics, IET*, vol. 8, pp. 2352-2360, 2015.
- [122] M. K. Kazimierczuk, *Pulse-width Modulated DC-DC Power Converters*. Chichester, West Sussex, PO19 8SQ, United Kingdom: John Wiley and Son, Ltd, 2008.
- [123] C.-H. Chang, E.-C. Chang, and H.-L. Cheng, "A high-efficiency solar array simulator implemented by an LLC resonant DC-DC converter," *IEEE Transactions on Power Electronics*, vol. 28, pp. 3039-3046, 2013.
- [124] R. D. Cruz and M. Rajesh, "Half bridge LLC resonant DC-DC converter for solar array simulator application," in *2015 International Conference on Technological Advancements in Power and Energy (TAP Energy)*, 2015, pp. 138-143.
- [125] R. W. Erickson and D. Maksimovic, *Fundamentals of Power Electronics*, 2 ed. New York, Boston, Dordrecht, London, Moscow: Kluwer Academic Publishers, 2004.
- [126] A. Soetedjo, Y. I. Nakhoda, A. Lomi, and G. E. Hendroyono, "Development of PV simulator by integrating software and hardware for laboratory testing," in *2015 International Conference on Automation, Cognitive Science, Optics, Micro Electro-Mechanical System, and Information Technology (ICACOMIT)*, 2015, pp. 96-100.
- [127] S. Jin, D. Zhang, C. Wang, and Y. Gu, "Optimized Design of Space Solar Array Simulator with Novel Three-port Linear Power Composite Transistor Based on Multiple Cascaded SiC-JFETs," *IEEE Transactions on Industrial Electronics*, vol. PP, pp. 1-1, 2017.
- [128] A. Belaout, F. Krim, B. Talbi, H. Feroura, A. Laib, S. Bouyahia, *et al.*, "Development of real time emulator for control and diagnosis purpose of Photovoltaic Generator," in *2017 6th International Conference on Systems and Control (ICSC)*, 2017, pp. 139-144.
- [129] O. López-Santos, M. C. M. Riveros, M. C. S. Castaño, W. A. Londoño, and G. Garcia, "Emulation of a Photovoltaic Module Using a Wiener-Type Nonlinear Impedance Controller for Tracking of the Operation Point," in *Workshop on Engineering Applications*, 2017, pp. 482-494.
- [130] S. Bacha, I. Munteanu, and A. I. Bratcu, *Power Electronic Converters Modeling and Control: with Case Studies* Springer, 2014.
- [131] P. Chetty, "Current injected equivalent circuit approach to modeling of switching DC-DC converters in discontinuous inductor conduction mode," *IEEE Transactions on Industrial Electronics*, vol. 3, pp. 230-234, 1982.
- [132] V. Vorperian, "Simplified analysis of PWM converters using model of PWM switch. II. Discontinuous conduction mode," *Aerospace and Electronic Systems, IEEE Transactions on*, vol. 26, pp. 497-505, 1990.
- [133] G. W. Wester and R. D. Middlebrook, "Low-Frequency Characterization of Switched dc-dc Converters," *Aerospace and Electronic Systems, IEEE Transactions on*, vol. AES-9, pp. 376-385, 1973.
- [134] G. Suman, B. V. S. P. Kumar, M. S. Kumar, B. C. Babu, and K. R. Subhashini, "Modeling, Analysis and Design of Synchronous Buck Converter Using State

- Space Averaging Technique for PV Energy System," in *Electronic System Design (ISED), 2012 International Symposium on*, 2012, pp. 281-285.
- [135] C. Jingquan, R. Erickson, and D. Maksimovic, "Averaged switch modeling of boundary conduction mode DC-to-DC converters," in *Industrial Electronics Society, 2001. IECON '01. The 27th Annual Conference of the IEEE*, 2001, pp. 844-849 vol.2.
- [136] S. Cuk and R. D. Middlebrook, "A general unified approach to modelling switching DC-to-DC converters in discontinuous conduction mode," in *Power Electronics Specialists Conference, 1977 IEEE*, 1977, pp. 36-57.
- [137] S. Kasat, "Analysis, Design and Modeling of DC-DC Converter using Simulink," Master of Science, Institute of Engineering and Technology Oklahoma State University 2004.
- [138] M. A. Abdullah, C. W. Tan, A. H. Yatim, M. Al-Mothafar, and S. M. Radaideh, "Input current control of boost converters using current-mode controller integrated with linear quadratic regulator," *International Journal of Renewable Energy Research (IJRER)*, vol. 2, pp. 262-268, 2012.
- [139] D. Chariag and L. Sbita, "Design and simulation of photovoltaic emulator," in *2017 International Conference on Green Energy Conversion Systems (GECS)*, 2017, pp. 1-6.
- [140] N. S. Nise, *Control Systems Engineering* vol. 6th Edition. California State Polytechnic University, Pomona WJohn Wiley & Sons, Inc., 2011.
- [141] C. P. Ugale and V. V. Dixit, "Buck-boost converter using Fuzzy logic for low voltage solar energy harvesting application," in *2017 11th International Conference on Intelligent Systems and Control (ISCO)*, 2017, pp. 413-417.
- [142] J. Lorenzo, J. C. Espiritu, J. Mediavillo, S. J. Dy, and R. B. Caldo, "Development and implementation of fuzzy logic using microcontroller for buck and boost DC-to-DC converter," in *IOP Conference Series: Earth and Environmental Science*, 2017.
- [143] B. U. Patil and S. R. Jagtap, "Adaptive fuzzy logic controller for buck converter," in *2015 International Conference on Computation of Power, Energy, Information and Communication (ICCPEIC)*, 2015, pp. 0078-0082.
- [144] S. Vinod, M. Balaji, and M. Prabhakar, "Robust control of parallel buck fed buck converter using hybrid fuzzy PI controller," in *2015 IEEE 11th International Conference on Power Electronics and Drive Systems*, 2015, pp. 347-351.
- [145] C. S. Betancor-Martin, J. Sosa, J. A. Montiel-Nelson, and A. Vega-Martinez, "Gains tuning of a PI-Fuzzy controller by genetic algorithms," *Engineering Computations (Swansea, Wales)*, vol. 31, pp. 1074-1097, 2014.
- [146] M. C. Di Piazza and G. Vitale, "Photovoltaic field emulation including dynamic and partial shadow conditions," *Applied Energy*, vol. 87, pp. 814-823, 3// 2010.
- [147] S. Jin, D. Zhang, and C. Wang, "UI-RI Hybrid Lookup Table Method with High Linearity and High-Speed Convergence Performance for FPGA-based Space Solar Array Simulator," *IEEE Transactions on Power Electronics*, 2017.
- [148] I. D. G. Jayawardana, C. N. M. Ho, M. Pokharel, and G. Escobar, "A fast dynamic photovoltaic simulator with instantaneous output impedance matching controller," in *2017 IEEE Energy Conversion Congress and Exposition (ECCE)*, 2017, pp. 5126-5132.

- [149] H. Nagayoshi, "Characterization of the module/array simulator using IV magnifier circuit of a pn photo-sensor," in *Photovoltaic Energy Conversion, 2003. Proceedings of 3rd World Conference on*, 2003, pp. 2023-2026.
- [150] H. Nagayoshi, S. Orio, Y. Kono, and H. Nakajima, "Novel PV array/module I-V curve simulator circuit," in *Photovoltaic Specialists Conference, 2002. Conference Record of the Twenty-Ninth IEEE*, 2002, pp. 1535-1538.
- [151] P. Wei, B. Tan, H. Zhang, and Y. Zhao, "Research on maximum power point tracker based on solar cells simulator," in *Advanced Computer Control (ICACC), 2010 2nd International Conference on*, 2010, pp. 319-323.
- [152] A. K. Mukerjee and N. Dasgupta, "DC power supply used as photovoltaic simulator for testing MPPT algorithms," *Renewable Energy*, vol. 32, pp. 587-592, 4// 2007.
- [153] L. A. Lopes and A.-M. Lienhardt, "A simplified nonlinear power source for simulating PV panels," in *Power Electronics Specialist Conference, 2003. PESC'03. 2003 IEEE 34th Annual*, 2003, pp. 1729-1734.
- [154] Z. Zhou and J. Macaulay, "An Emulated PV Source Based on an Unilluminated Solar Panel and DC Power Supply," *Energies*, vol. 10, p. 2075, 2017.
- [155] M. Ünlü and S. Çamur, "Solar irradiance emulator based on DC power supply for photovoltaic panels," in *2017 9th International Conference on Electronics, Computers and Artificial Intelligence (ECAI)*, 2017, pp. 1-4.
- [156] M. Ünlü and S. Çamur, "A simple Photovoltaic simulator based on a one-diode equivalent circuit model," in *2017 4th International Conference on Electrical and Electronic Engineering (ICEEE)*, 2017, pp. 33-36.
- [157] H. B. Mustafa, "Design and Control Of A Photovoltaic Simulator," Bachelor of Electrical Engineering, Department of Electrical Power Engineering, Universiti Teknologi Malaysia, Skudai, Johor, Malaysia, 2016.
- [158] A. Solar, "Ameresco Solar 80W (24V) Photovoltaic Modules - 80J-B (24V)," ed: Ameresco Inc., 2014.
- [159] R. Kadri, H. Andrei, J.-P. Gaubert, T. Ivanovici, G. Champenois, and P. Andrei, "Modeling of the photovoltaic cell circuit parameters for optimum connection model and real-time emulator with partial shadow conditions," *Energy*, vol. 42, pp. 57-67, 6// 2012.
- [160] R. Sedgewick and K. Wayne, *Algorithms*, 4th Edition ed. Boston, Massachusetts: Pearson Education, 2011.
- [161] N. Shiota, V. Phimmason, T. Abe, and M. Miyatake, "A MPPT algorithm based on the binary-search technique with ripples from a converter," in *2013 International Conference on Electrical Machines and Systems (ICEMS)*, 2013, pp. 1718-1721.
- [162] A. Marquez, J. I. Leon, S. Vazquez, L. G. Franquelo, J. M. Carrasco, and E. Galvan, "Binary search based MPPT algorithm for high-power PV systems," in *2016 10th International Conference on Compatibility, Power Electronics and Power Engineering (CPE-POWERENG)*, 2016, pp. 168-173.
- [163] C. T. Phan-Tan and N. Nguyen-Quang, "A P&O MPPT method for photovoltaic applications based on binary-searching," in *2016 IEEE International Conference on Sustainable Energy Technologies (ICSET)*, 2016, pp. 78-82.
- [164] Panasonic, "EEUFR1J180B - Electrolytic Capacitor, 18  $\mu$ F, 63 V, FR Series,  $\pm$  20%, Radial Leaded, 5 mm," ed: PANASONIC ELECTRONIC COMPONENTS.

- [165] Bourns, "1140-182K-RC - High Current Choke, 1.8MH, 4.5A 10%," B. J. Miller, Ed., ed. Bourns JW Miller, 2014.
- [166] O. Semiconductor, "IRF644B N-Channel BFET MOSFET 250 V, 14 A, 280 mOhm," O. Semiconductor, Ed., ed, 2013.
- [167] IXYS, "DSEI30-10A - Fast / Ultrafast Diode, 1 kV, 30 A, Single, 2.4 V, 35 ns, 200 A," ed: IXYS SEMICONDUCTOR, 1997.
- [168] S. Srivastava, Y. Kumar, A. Misra, S. K. Thakur, and V. S. Pandit, "Optimum design of buck converter controller using LQR approach," in *2013 15th International Conference on Advanced Computing Technologies (ICACT)*, 2013, pp. 1-6.
- [169] M. C. D. Piazza and G. Vitale, *Photovoltaic Sources: Modeling and Emulation*. Verlag, London, United Kingdom: Springer, 2013.
- [170] J. Ahmed and Z. Salam, "An improved perturb and observe (P&O) maximum power point tracking (MPPT) algorithm for higher efficiency," *Applied Energy*, vol. 150, pp. 97-108, 7/15/ 2015.
- [171] M. T. Outeiro, G. Buja, and D. Czarkowski, "Resonant Power Converters: An Overview with Multiple Elements in the Resonant Tank Network," *IEEE Industrial Electronics Magazine*, vol. 10, pp. 21-45, 2016.
- [172] Ferroxcube, "Ferroxcube ETD49/25/16-3C95 114 mm, 211 mm<sup>2</sup>," ed: Ferroxcube A Yageo Company, 2008.
- [173] Vishay, "MAL215262479E3 - Electrolytic Capacitor, 47  $\mu$ F, 200 V, 152 RMH Series,  $\pm$  20%, Radial Leaded, 12.5 mm," ed, 2012.
- [174] LEM, "Current Tranducer LEM HY 5..25-P/SP1 Version 9," ed, 2014.
- [175] LEM, "Voltage Tranducer LV 25-P," ed, 2014.
- [176] X. POWER, "IH0515S - 2 Watt SIP Dual Output DC/DC Converter, Input 5V, Output  $\pm$ 15V/66mA," X. POWER, Ed., ed, 2017.
- [177] T. L. Floyd, *Electronic Devices*, 9th Edition ed. Prentice Hall, 1 Lake Street, Upper Saddle River, New Jersey: Pearson, 2012.
- [178] X. POWER, "IA0509S - 1 Watt DIP Single Output DC/DC Converter, Input 5V, Output 9V/55mA," X. POWER, Ed., ed, 2017.