Design and implementation of PV emulator based on synchronous buck converter using Arduino Nano microcontroller

Ahmad Saudi Samosir, Herri Gusmedi, Alfin Fitrohul Huda
Department of Electrical Engineering, Faculty of Technology, Universitas Lampung, Bandar Lampung, Indonesia

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ABSTRACT

This paper discusses the comprehensive design and implementation of a photovoltaic (PV) emulator hardware using a synchronous buck converter. The primary objective is to simulate the electrical characteristics of a real PV module under varying environmental conditions. The process involves detailed simulations carried out using MATLAB/Simulink software to evaluate the performance and accuracy of the emulator model. Various load values were tested to account for the impact of fluctuations in radiation and temperature. The accuracy of the emulator's output characteristics was validated by comparing them with the actual attributes of the SolarWorld Sun-module SW50 PV module. The final step involves constructing the hardware of the PV emulator using electronic components, with an Arduino Nano employed as the controller.

Corresponding Author:

Ahmad Saudi Samosir
Department of Electrical Engineering, Faculty of Technology, Universitas Lampung
Sumantri Brojonegoro St., No. 1, Bandar Lampung, Lampung 35145, Indonesia
Email: ahmad.saudi@eng.unila.ac.id, saudi.ahmad@gmail.com

1. INTRODUCTION

The growing interest in renewable energy sources has increased the need for efficient and accurate simulation tools to aid the development and testing of photovoltaic systems. One tool that is widely used for this purpose is the photovoltaic (PV) emulator [1]-[5]. The development and application of PV emulators have received great attention in recent years, especially due to increasing research on renewable energy systems and the need for efficient test platforms. PV emulators are designed to mimic the electrical characteristics of solar panels in a variety of environmental conditions without requiring actual sunlight. This enables consistent and repeatable testing of PV systems, including inverters, converters, and other associated electronic devices [6].

PV emulators can be categorized into three main types: analog, digital, and hybrid [7], [8]. Analog PV emulators use analog circuitry to emulate the I-V characteristics of solar panels. These emulators are usually simple and fast but lack flexibility in adapting to different conditions [9]. In contrast, digital PV emulators use a digital signal processor (DSP) or microcontroller to simulate PV characteristics [10]. They offer greater flexibility and precision, enabling the emulation of dynamic environmental conditions such as radiation and temperature variations. Hybrid PV emulators combine analog and digital components to take advantage of both advantages [11]. They offer high performance and adaptability, although they may be more complex and expensive to implement.

To develop accurate PV cell models, extensive research has focused on modeling and simulation using software tools like MATLAB/Simulink and PSpice [12], [13]. Such models are crucial for creating digital emulators that can replicate the I-V characteristics of PV panels under various environmental conditions [14], [15]. For hardware implementation, researchers frequently employ field programmable gate arrays (FPGAs) and microcontrollers to build PV emulators [16]. This approach underscores the trade-offs among cost, complexity, and performance: FPGA-based systems deliver high speed and precision at a higher cost, while microcontroller-based systems are more affordable but often require advanced programming for effective performance.

In this paper, the design of a PV emulator utilizing a synchronous buck converter is presented and developed. The objective of this research is to design and implement a photovoltaic (PV) emulator that accurately replicates the current voltage (I-V) characteristics of a real PV module, ensuring precise and reliable performance under various operating conditions. By integrating a synchronous buck converter and utilizing an Arduino Nano as the central microcontroller, the study aims to develop a control system capable of real-time adjustments to emulate PV behavior accurately. This includes implementing a lookup table (LUT) for characteristic reference, generating precise pulse-width modulation (PWM) signals, and utilizing feedback and proportional-integral-derivative (PID) control to maintain stable and accurate output. Ultimately, this emulator is designed to provide a reliable tool for testing and analysis of PV systems, allowing for controlled and repeatable experiments that simulate real-world PV module responses.

The main contribution of this paper is to provide the design and validate a PV emulator using a synchronous buck converter, which is effectively able to replicate the electrical behavior of real PV modules under various environmental conditions. By utilizing MATLAB/Simulink simulations, this study verifies the ability of the emulator to accurately mimic the I-V and P-V characteristics of the SolarWorld Sun-module SW50 PV module under various load, irradiance, and temperature scenarios. This work offers a valuable tool for testing and development in PV systems without the need for actual solar modules, making it a cost-effective and flexible solution for controlled experimental environments. The hardware implementation with an Arduino Nano controller further demonstrates the emulator's potential for real-time adjustment and practical applications in laboratory or training settings.

2. METHOD

This research utilizes techniques such as implementing a lookup table (LUT) for real-time I-V characteristic emulation, employing a PID controller to enhance feedback accuracy and stability, and integrating a synchronous buck converter to efficiently regulate output voltage and current. Simulation results and efficiency measurements validate the emulator’s performance in comparison to the reference PV module, ensuring precise, and reliable emulation.

2.1. Solar PV characteristic

Solar photovoltaic (PV) modules convert direct sunlight into dc electricity through the photovoltaic effect [17]. Solar PV modules have special characteristics that are very important to know for designing and optimizing solar PV energy systems. These characteristics are usually represented by current-voltage (I-V) and power-voltage (P-V) curves, which provide an idea of the performance of the PV module under various conditions [18], [19].

The I-V curve of the PV module in Figure 1 illustrates the relationship between output current and output voltage for certain radiation and temperature. Important points and areas on the I-V curve include short-circuit current (Isc), which is the maximum current the PV module can produce when the output terminals are shorted (zero voltage). The Isc is directly proportional to the irradiance level; higher sunlight intensity results in a higher Isc. The open-circuit voltage (Voc) is the maximum voltage the PV module can produce when there is no load connected (zero current). The Voc increases with higher irradiance and decreases with higher temperatures. The maximum power point (MPP) is the point on the I-V curve where the product of current and voltage ($P = I \times V$) is maximum [20]. The corresponding current and voltage at this point are referred to as Imp (current at MPP) and Vmp (voltage at MPP), respectively. The MPP varies with changes in irradiance and temperature [21].

The P-V curve of a PV module in Figure 2 shows the relationship between the output power and the output voltage. It highlights the power output behavior of the PV module and is derived from the I-V curve. The peak of the P-V curve represents the maximum power point (MPP), where the PV module operates most efficiently [22]. This point is crucial for optimizing the energy yield from the module. As irradiance increases, the overall power output of the PV module increases, shifting the P-V curve upwards. Conversely, lower irradiance levels reduce the power output. Higher temperatures typically reduce the open-circuit voltage (Voc) and slightly increase the short-circuit current (Isc), leading to a decrease in the overall power output. The P-V curve shifts downward with increasing temperature [23], [24].

Environmental conditions significantly influence the performance of PV modules. Irradiance, or the power of sunlight per unit area, has a direct impact on the current output of the PV module. Higher irradiance results in higher current and power output, while lower irradiance decreases them. Temperature primarily affects the voltage output of the PV module. Higher temperatures reduce the Voc and hence the overall efficiency, while lower temperatures can enhance the voltage output and efficiency.

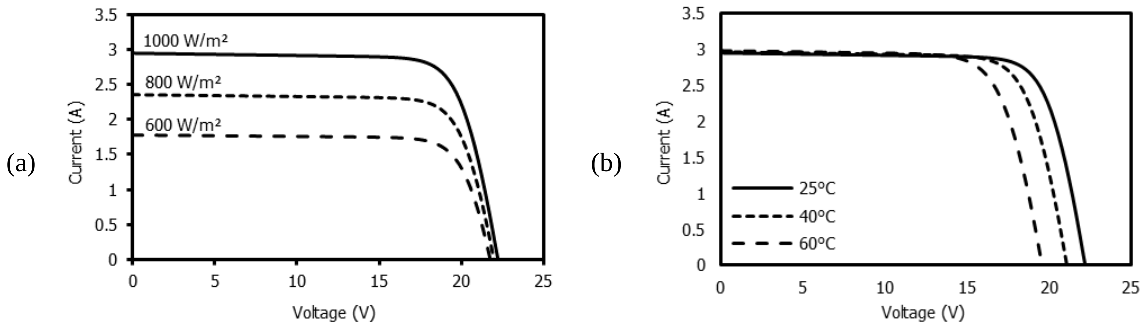

Figure 1. Effect of changes in (a) irradiation and (b) temperature on the I-V curve of solar PV

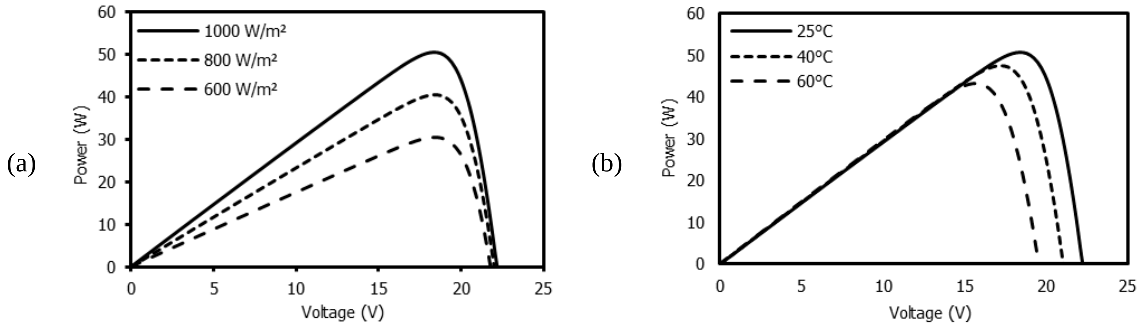

Figure 2. Effect of changes in (a) irradiation and (b) temperature on the P-V curve of solar PV

2.2. Synchronous buck converter-based PV emulator: operation principle

A synchronous buck converter-based PV emulator operates on the principle of converting a higher DC input voltage to a lower DC output voltage with high efficiency and precise control, effectively emulating the electrical behavior of a photovoltaic (PV) panel [25], [26]. The basic operation of the synchronous buck converter involves two metal-oxide-semiconductor field-effect transistor (MOSFETs), an inductor, and a capacitor. The first MOSFET acts as the main switch, and the second MOSFET replaces the diode found in a traditional buck converter, enhancing efficiency by reducing power losses during the switch-off phase.

When the main MOSFET is turned on, the input voltage is applied to the inductor, causing current to build up and store energy in the magnetic field of the inductor. During this time, the output capacitor supplies current to the load. When the switch is turned off, the stored energy in the inductor is released to the load and the capacitor, maintaining the output voltage. This process is regulated through pulse-width modulation (PWM), where the duty cycle of the main switch is adjusted to control the average output voltage, ensuring it matches the desired voltage of the PV emulator.

The PV emulator employs a feedback control loop, typically managed by a microcontroller or digital signal processor (DSP), to monitor output voltage and current [4]. It dynamically adjusts the PWM signal to accurately follow the I-V characteristics of the target PV module, using pre-defined I-V and P-V curves stored in its memory. These curves represent the behavior of a real PV module under different irradiance and temperature conditions [27]. By adjusting the duty cycle based on these stored curves and current load conditions, the emulator can mimic the changing output of a real PV panel, including the effects of variations in sunlight intensity [28]. Figure 3 presents a detailed schematic diagram of the synchronous buck converter-based PV emulator. This diagram illustrates the essential components and their connections that form the core of the device's electronic circuitry.

2.3. Design of the proposed PV emulator

At this stage, the hardware and control system design of the PV emulator, based on a synchronous buck converter, is implemented. The PV emulator's hardware architecture consists of three primary components: a synchronous buck converter circuit, a gate driver circuit, and a control circuit featuring an Arduino Nano microcontroller.

In this research, the Arduino Nano is selected as the core microcontroller to handle key control tasks within the PV emulator system. Specifically, it facilitates real-time control and monitoring functions critical to the emulator's accuracy and stability. The microcontroller's responsibilities include:

a. Lookup table control: The Arduino Nano utilizes a pre-stored lookup table (LUT) containing current-voltage (I-V) characteristics data of the reference PV module. By referencing this LUT, the emulator can dynamically replicate the I-V behavior of a real PV module under different conditions, allowing for accurate emulation.
b. PWM signal generation: To regulate the output of the synchronous buck converter, the Arduino generates high-frequency pulse-width modulation (PWM) signals. These PWM signals control the switching operation of the converter, enabling precise voltage and current adjustments to match the desired output characteristics.
c. Feedback control: The Arduino continuously monitors the output voltage and current of the PV emulator, comparing them with the target values from the LUT. This real-time feedback ensures that any deviation from the reference PV module characteristics is quickly corrected, maintaining accuracy.
d. PID control processing: The microcontroller executes a PID control algorithm to enhance stability and response time. The PID controller dynamically adjusts the PWM duty cycle based on feedback, ensuring smooth and accurate emulation of the reference PV module, even under changing load conditions [29].

The synchronous buck converter circuit is responsible for converting the input voltage to a desired output voltage efficiently. The gate driver circuit, designed with precision, controls the switching of the MOSFETs within the buck converter. The controller circuit, centered around the Arduino Nano, employs the ATMega328P microcontroller to implement the PID-based control algorithm. This ensures that the emulator can accurately replicate the behavior of a real photovoltaic module under various conditions.

The overall design of the PV emulator system, based on the synchronous buck converter, is illustrated in Figure 4. This schematic provides a comprehensive overview of how the different components are interconnected to form a cohesive and functional PV emulator. Through careful design and integration of these components, the system aims to provide a reliable tool for simulating the electrical characteristics of photovoltaic modules, thereby facilitating research and development in solar energy technologies.

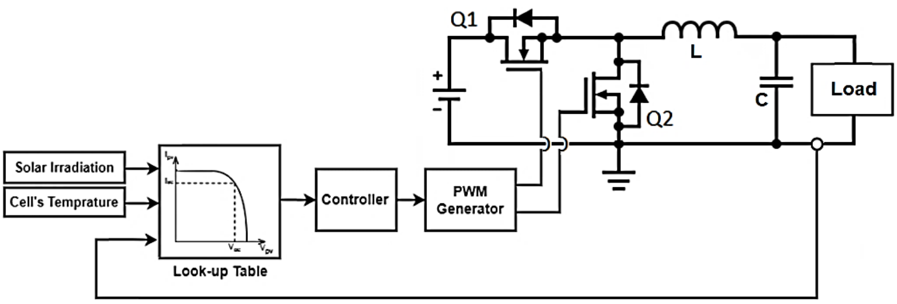

Figure 3. Synchronous buck converter-based PV emulator schematic diagram

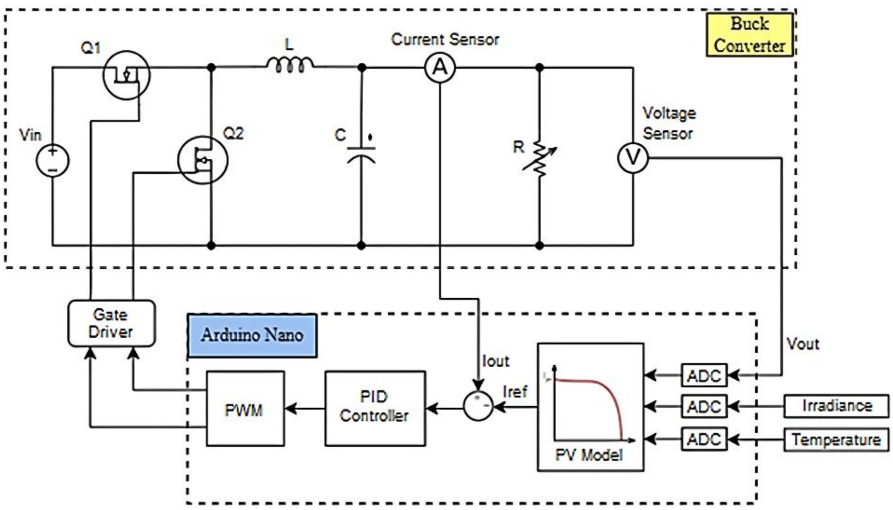

Figure 4. The overall design of the PV emulator system

The synchronous buck converter circuit generates output voltage and current that closely match the I-V characteristics of an actual PV module. This output is fed back to the Arduino Nano controller for processing, where the output voltage (Vout) is converted into a reference current (Iref) using a look-up table program. The reference current (Iref) is then compared to the output current (Iout) of the synchronous buck converter, resulting in an error value. This error value is processed by the Arduino Nano microcontroller as input for the PID controller.

The PID controller's output is used to generate PWM pulses through the Arduino Nano microcontroller. However, these PWM pulses initially have a low amplitude and must be amplified using the IR2110 IC gate driver circuit. This circuit boosts the amplitude of the pulses to appropriately drive the MOSFET switching in the synchronous buck converter circuit. This closed-loop process continuously adjusts, ensuring that the output current and voltage remain similar to the I-V characteristics of the actual PV module. Through this iterative feedback mechanism, the PV emulator system maintains precise control over the output, effectively simulating the behavior of a real PV module under varying conditions. This accuracy is crucial for the reliable testing and development of photovoltaic systems.

3. RESULTS AND DISCUSSION

3.1. Simulation results

A comprehensive simulation analysis was conducted to verify the performance of the synchronous buck converter-based PV emulator. This emulator circuit integrates a synchronous buck converter with a feedback control system utilizing a PID controller. The primary aim was to assess how effectively the emulator's control system operates under various load conditions. The simulations were executed using MATLAB/Simulink, providing a robust platform for testing and validation. Figure 5 illustrates the circuit model of the synchronous buck converter-based PV emulator utilized in the simulation. The specific model parameters for the synchronous buck converter are outlined in Table 1, while Table 2 lists the parameters for the PID controller system of the PV emulator.

The control objective of this system is to produce output voltage and current that align with the values provided in a pre-defined lookup table. These reference values are derived from the output voltage and current data of a real solar PV module. Thus, the controller ensures the buck converter's output mirrors a real solar PV module. This approach is crucial for accurate emulation, allowing reliable testing and development of PV systems.

Figure 6 presents the simulated results of the PV emulator's current-voltage (I-V) (Figure 6(a)) and power-voltage (P-V) (Figure 6(b)) characteristics under varying irradiation levels, with a constant temperature of 25 °C. Both the I-V and P-V curves clearly illustrate that as irradiation levels increase, the PV current (Isc), maximum power (Pmp), and open-circuit voltage (Voc) all show corresponding increases. Conversely, when irradiation decreases, these values tend to decreases. At an irradiation level of 1000 W/m², the short-circuit current (Isc) reaches 2.95 A, the maximum power (Pmp) is 50.29 W, and Voc is 22.32 V. At 600 W/m², Isc drops to 1.77 A, Pmp to 30.46 W, and Voc to 21.69 V. At the lowest tested irradiation level of 200 W/m², Isc is 0.59 A, the Pmp decreases to 9.87 W, and Voc reduces to 20.67 V.

Figure 7 illustrates the simulated results of the PV emulator's current-voltage (I-V) (Figure 7(a)) and power-voltage (P-V) (Figure 7(b)) characteristics under varying temperature conditions, with irradiation held constant at 1000 W/m². The curves reveal that as temperature increases, the PV current (Isc) remains relatively stable around 2.97 A, while both the maximum power (Pmp) and open-circuit voltage (Voc) exhibit a decreasing trend. Specifically, at 25 °C, the short-circuit current (Isc) reaches 2.95 A, the maximum power output (Pmp) is 50.29 W, and Voc is 22.1 V. When the temperature rises to 35 °C, Isc slightly increases to 2.96 A, while Pmp decreases to 47.7 W and Voc to 21.43 V. At the highest tested temperature of 50 °C, Isc reaches 2.97 A, but Pmp drops further to 45.31 W, with Voc decreasing to 20.24 V. These simulation results indicate the ability of the synchronous buck converter-based PV emulator to accurately replicate the performance of real PV modules under varying irradiance and temperature conditions, validating its effectiveness for applications in solar energy research and development.

3.2. Experimental result

To validate the effectiveness of the proposed PV emulator circuit, a hardware prototype has been developed. This prototype of the synchronous buck converter-based PV emulator hardware is depicted in Figure 8. The schematic of the proposed PV emulator prototype comprises three essential circuit parts. The first part constitutes the power circuit, assembled using two of IRF3205 power MOSFET components, 0.5 mH power inductors, and 2×220 uF electrolytic capacitors. In the second part, the gate driver circuit is designed with the IR2110 IC. Finally, the controller circuit features the Arduino Nano, supported by the Atmega328P microcontroller, serving as the main controller.

The Atmega328P microcontroller is an 8-bit AVR with low power consumption, offers high performance with throughput up to 16 MIPS at 16 MHz. Additionally, it includes two 8-bit timer/counters, one

16-bit timer/counter with a separate prescaler, 6 PWM channels, and 8 10-bit ADC channels. Experimental studies have been conducted on the developed PV emulator hardware. Figure 9 shows the waveforms representing the output voltage, output current, and output power of the PV emulator when tested with a resistive load with a resistance value of 6.6 ohms.

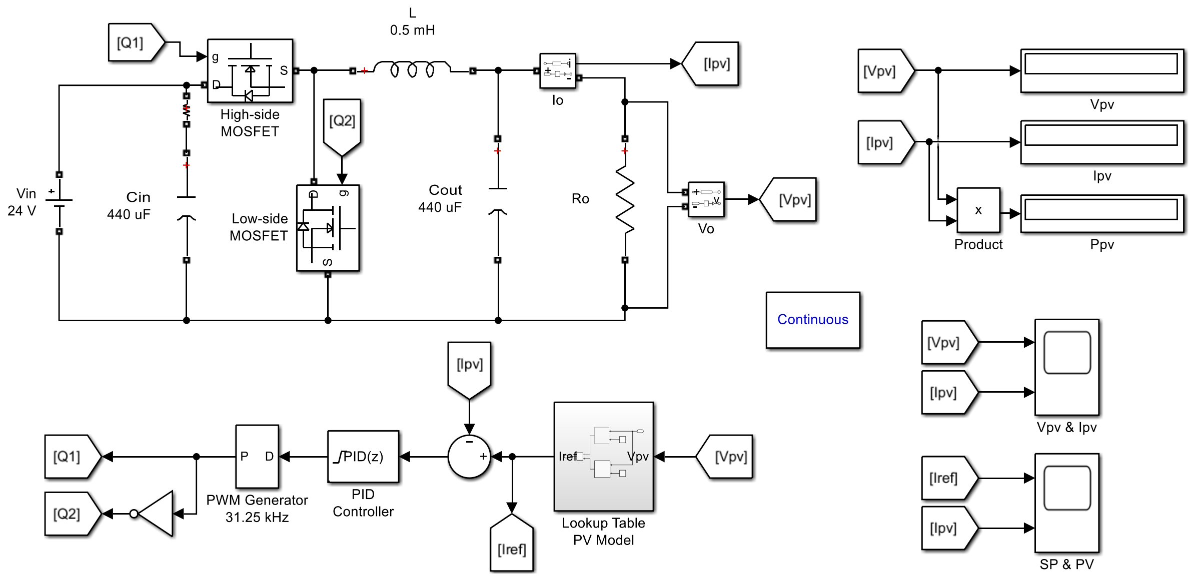

Figure 5. PV emulator simulation circuit based on synchronous buck converter

Table 1. Synchronous buck converter model parameters

Parameter	Symbol	Value	Parameter	Symbol	Value
Input voltage	V_{in}	24 V	Inductor	L	0.5 mH
Maximum output voltage	$V_{out(max)}$	22.1 V	Input capacitor	C_{in}	440 µF
Maximum output current	$I_{out(max)}$	2.95 A	Output capacitor	C_{out}	440 µF
Switching frequency	f_{sw}	31,250 Hz			

Table 2. PV emulator controller system parameters

Parameter	Symbol	Value
Proportional gain	Kp	5×10^{-3}
Integral gain	Ki	20
Derivative gain	Kd	$4,4\times10^{-4}$

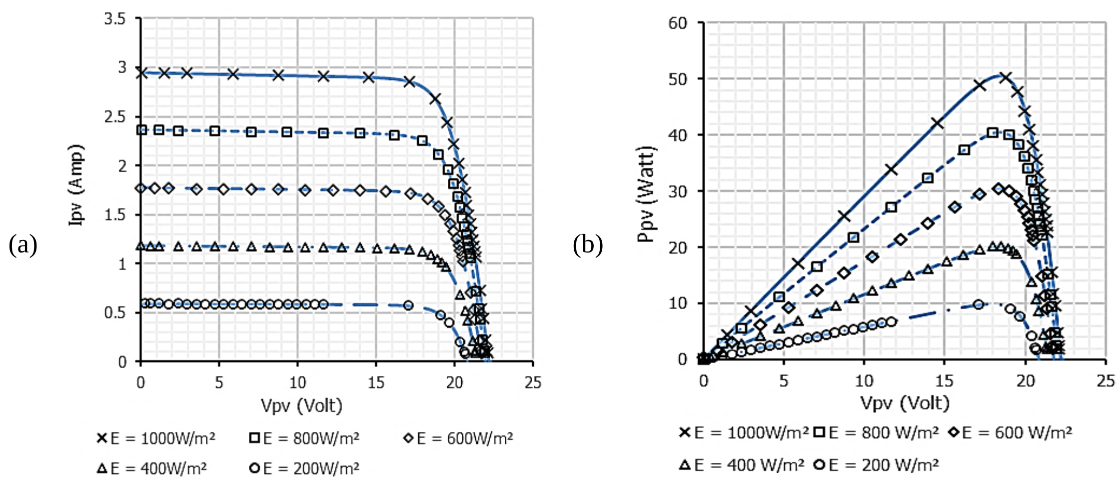

Figure 6. PV characteristic curve for varying irradiation at 25 °C temperature: (a) I-V curve and (b) P-V curve

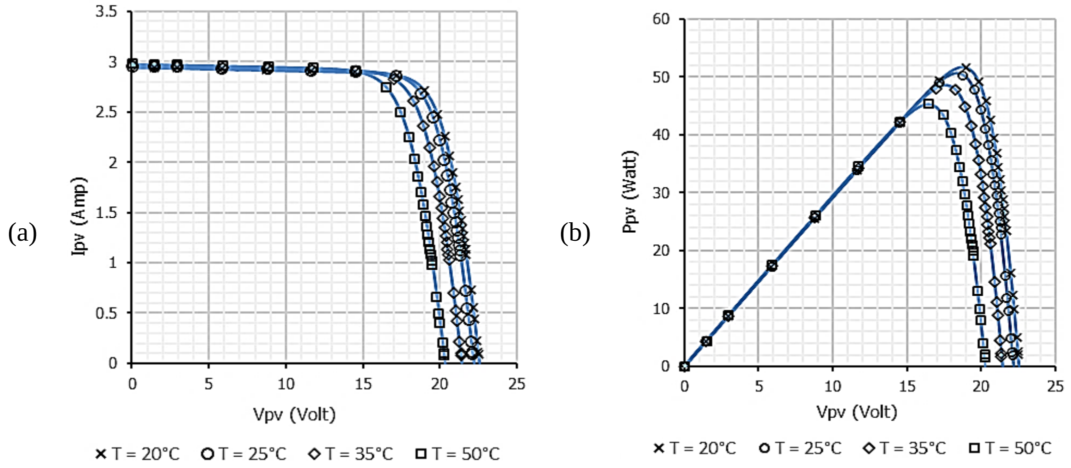

Figure 7. PV characteristic curve for varying temperature at 1000 W/m^2 irradiation:
(a) I-V curve and (b) P-V curve

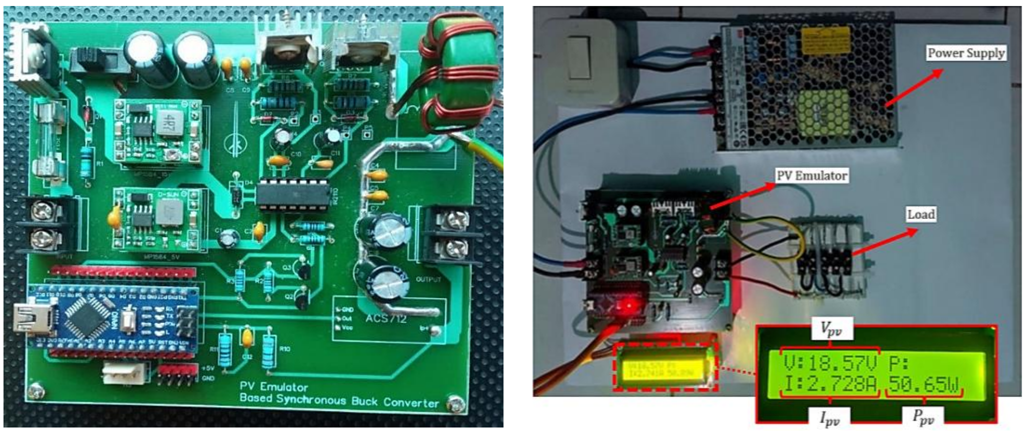

Figure 8. Hardware prototype of synchronous buck converter-based PV emulator

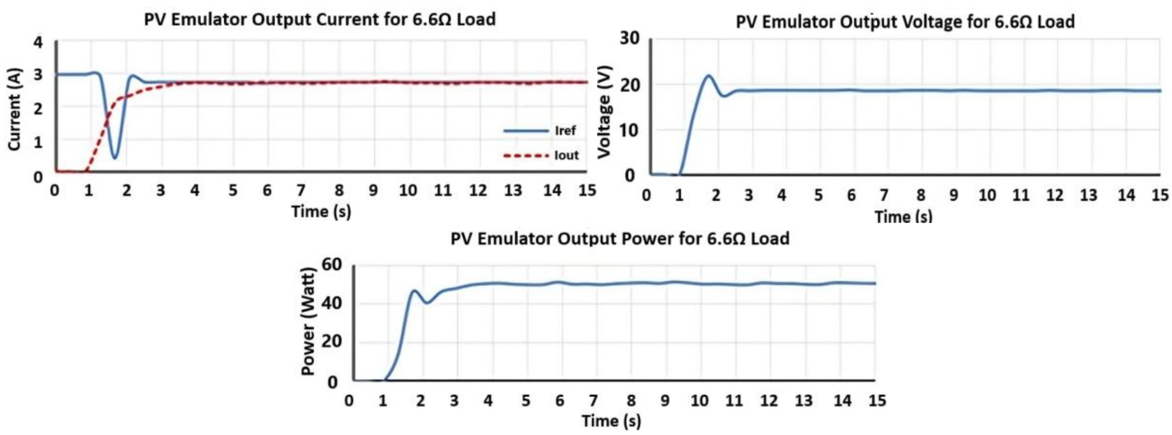

Figure 9. Test results of the PV emulator output for 6.6-ohm load

4. CONCLUSION

This paper presents the designed and implemented a photovoltaic (PV) emulator based on a synchronous buck converter, utilizing an Arduino Nano microcontroller for effective control. The emulator was rigorously tested through simulations that evaluated its performance under varying irradiation levels and temperature conditions. The results demonstrated that the emulator accurately replicates the expected current-voltage (I-V) and power-voltage (P-V) characteristics of real PV modules.

Specifically, as irradiation levels increased from 200 W/m² to 1000 W/m², the short-circuit current (Isc) rose significantly, reaching 2.95 A at maximum irradiation, with a corresponding peak power output of 50.29 W. Conversely, under decreasing irradiation, both the Isc and open-circuit voltage (Voc) declined, affirming the emulator's capability to reflect the dynamic behavior of actual PV systems. Additionally, simulations showed that as temperature increased from 25 to 50 °C, Isc remained relatively constant while the maximum power and Voc decreased, confirming the influence of temperature on PV performance.

The comprehensive results affirm that the synchronous buck converter-based PV emulator effectively mimics the behavior of real PV modules across a range of operating conditions. This emulator represents a valuable tool for researchers and engineers in the field of solar energy, facilitating controlled experiments and optimizations in PV system performance without the constraints of physical PV modules. Overall, the findings underscore the emulator's potential in advancing solar energy research and development, making it a significant contribution to the field.

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BIOGRAPHIES OF AUTHORS

Ahmad Saudi Samosir is a lecturer in Electrical Engineering Department at the Universitas Lampung, Lampung, Indonesia. He received his B.Eng., M.Eng., and Ph.D. degrees in in Electrical Engineering from Universitas Sumatera Utara, Institut Teknologi Bandung and Universiti Teknologi Malaysia, in 1995, 1999, and 2010, respectively. He has been a Professor in Universitas Lampung Indonesia since 2017. He is currently a Dean of Postgraduate Faculty of Universitas Lampung. His research interests include power electronics design, controller and its applications in renewable energy, electric vehicle, and industrial applications. He can be contacted at email: ahmad.saudi@eng.unila.ac.id or saudi.ahmad@gmail.com.

Herri Gusmedi is a lecturer in Electrical Engineering Department at the Universitas Lampung, Lampung, Indonesia. He received his B.Eng., M.Eng. degree in Electrical Engineering from Universitas Sriwijaya and Institut Teknologi Bandung respectively in 1995, 2000. Served as Head of Electric Power System Laboratory at Universitas Lampung, Indonesia since 2020. His research interests include system reliability design, economical operation, power converter and renewable energy, especially photovoltaic. He can be contacted at email: herri.gusmedi@eng.unila.ac.id.

Alfin Fitrohul Huda is a final-year student in the Department of Electrical Engineering at the University of Lampung, Lampung, Indonesia. He is on track to complete his B.Eng. degree by 2024. His research interests focus on power electronics, controllers, and their applications. He can be contacted at email: alfin.huda@gmail.com.