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Abstract

Purpose: This research proposes to design a low-cost solar cell performance analyzer that measures voltage, current, and power. The device uses an IRFZ440 MOSFET driver and is controlled by an Arduino UNO board. The system focuses on precise control and straightforward design. The project aims to enhance the understanding of solar panel efficiency in various environments and under different load conditions. With the potential to be developed to support Internet of Things (IoT) technologies and Maximum Power Point Tracking (MPPT) algorithms, the research also seeks to provide a useful and effective tool for monitoring the performance of small-scale solar systems in academic and field settings.

Methodology: Methodology: An electronic circuit was designed, consisting of an Arduino UNO microcontroller to read voltage and current sensor signals. An IRFZ440 MOSFET transistor is used as an electronic switch to control the load via a pulse-width modulation (PWM) signal. The load (small electric motor) was connected in series to the solar panel. The measurement results were displayed using a small OLED display. The Arduino was programmed to generate PWM signals at various percentages (from 0% to 100%) to simulate changes in the load on the solar cell. Data was collected under natural light using an 8 W solar cell. The resulting data were analyzed to verify the system's performance and compare its results with the expected theoretical values.

Findings: After using the designed system to analyze the performance of solar panels based on the Arduino UNO microcontroller and the IRFZ440 MOSFET driver, positive results were achieved in terms of measurement accuracy and performance efficiency. When applying different PWM signal ratios, a clear change in the voltage, current, and power output of the solar cell was recorded, which enables analysis of the relationship between these variables under different load conditions. The designed circuit was demonstrated to be able to automatically change the load using PWM technology, allowing the panel's response to be monitored under varying load conditions without the need for multiple physical resistors. All readings were displayed in real time on an OLED display. The proposed design proved effective in providing a low-cost, accurate, and scalable solution for future use by integrating it with MPPT or IoT technologies.

Unique Contribution to Theory, Practice, and Policy: Presenting a practical, low-cost device that can be used to monitor and analyze solar cell performance in real time. It demonstrates how to use PWM signals to automatically change the load based on the Arduino microcontroller and the IRFZ440 MOSFET driver. Future expansion potential to integrate IoT technologies and MPPT applications. Supporting sustainable and decentralized energy policies by providing simple tools that can monitor small-scale solar systems (such as homes or villages), thus reducing reliance on centralized electricity grids. Potential for use in government or non-profit initiatives seeking to disseminate clean and smart energy solutions in rural communities.

Keywords: *Arduino UNO, IRFZ440 MOSFET, Solar Panel, Voltage, Current Sensors*

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INTRODUCTION

Solar cells are one of the most prominent means of energy conversion in our modern era, effectively contributing to reducing dependence on traditional energy sources derived from fossil fuels. With rapid technological advancements, it has become necessary not only to generate energy from solar cells but also to control how it is stored and consumed efficiently (O. Amusan, et al., 2023 & K. Barhmi, et al., 2024). As is well known, solar cells rely on converting the light energy emitted by the sun into electrical energy. Given the variation in solar radiation intensity across different geographical locations, storing energy during periods of sunshine becomes essential to meet demand during periods of low radiation, such as nighttime. This is accomplished through advanced electrical control systems that regulate storage and consumption processes (M. Dayer, et al. 2024 & T. Trang, et al., 2024). The efficiency of a photovoltaic (PV) system depends on how effectively it converts solar energy into electrical energy. This efficiency directly affects the amount of energy generated and its consumption patterns, and depends on the features of the electrical solar cells and external environmental conditions (Sugianto, 2020 & Rozak et al., 2023).

Several studies have demonstrated the importance of electrical monitoring systems in solar energy, particularly those that monitor PV performance. These studies have examined the impact of environmental factors on panel efficiency, such as light intensity, temperature, light incidence angle, dust accumulation, and sun exposure duration, as well as the efficiency of electrochemical and electronic conversion (O. H. Boucif, et al., 2025 & N. H. Alombah, et al, 2025). One of the most prominent advantages of solar cells is that they produce no emissions during the energy generation process, making them an ideal choice for achieving clean and sustainable energy sources. This technology also enables energy independence, allowing individuals and communities to meet their energy needs without relying on central power plants, and even exporting surplus energy to other consumers when available (M. Mohammed, et al., 2024 & Hartoyo, et al., 2024).

This research focuses on analyzing the performance of solar cells during the day by monitoring their performance under different load levels. This is done by measuring voltage and current variables at various load ratios (0%, 20%, 40%, 60%, 80%, and 100%), allowing for a deeper understanding of the impact of electrical load on solar cell efficiency.

LITERATURE REVIEW

Here is a review of some previous studies related to the topic:

The paper (R. Anand, et al. 2016) presented the development and implementation of a PV system performance analyzer based on the Arduino UNO platform. This analyzer is designed as an efficient and low-cost option for evaluating the efficiency of solar panels. The researchers presented a system consisting of a set of sensors to measure light intensity, current, voltage, and temperature, to analyze the relationship between current and voltage (I-V), and power and voltage (P-V). The results demonstrated high accuracy (exceeding 99%) for several cells of varying capacities. The experiment also demonstrated the system's ability to accurately calculate fill factor. The project's most notable advantages include its economical and scalable solution, reliable measurements, and improved analysis of solar system performance. It is also scalable in the future by integrating it with solar tracking systems or MPPT technologies to improve the efficiency of the entire solar system.

Reference (V. Gupta, et al., 2017) designed a solar panel performance analyzer using a variable resistor on an Arduino UNO board. This analyzer recorded the electrical performance of the solar panel under various conditions. Excel (PLX DAQ) software was used to store the readings via a data logger. Field testing of the system on a 53W polycrystalline solar panel yielded highly accurate results for temperature, power, current, and voltage. The measurements obtained by the designed device were compared with those of a professional multimeter, and the differences were minimal, proving the reliability and accuracy of the device. The analysis also demonstrated the feasibility of using the collected data to plot (I-V) and (P-V) curves and analyze system efficiency. The project benefits include: very low cost, a reliable alternative to commercial devices, ease of modification and development, practical real-time measurement, support for education and research, and potential for use in remote locations.

The work (A. Jumaat, & M. H. Othman, 2018) aimed to design and implement a portable, low-cost device to measure the performance of solar panels using an Arduino UNO controller and several sensors. Light intensity, temperature, current, and voltage are the four primary parameters that the system measures. These data are gathered as input to the Arduino using a light dimmer (LDR), a temperature sensor, a current sensor, and a voltage divider, respectively. The Liquid Crystal Display (LCD) is used to display all previous variables. The power generated from the 3W polycrystalline solar panel has been recorded at different times. The highest power produced at the sunrise position was 2.4W at 4.00 pm.

The study in reference (E. Lobo, et al., 2022) used an Arduino Uno R3 microcontroller, an ESP8266 wireless communication module, current and voltage sensors (DC/AC), and a BH1750 light intensity sensor. This study aimed to design and develop a real-time monitoring system for a solar power plant utilizing IoT technology. The Blynk smartphone app is used to read the data transmitted from the measurement site. Test results demonstrated high accuracy for the system. The differences between the system's readings and those of conventional multimeters were close to zero, with an error rate of no more than 0.0141% for current DC measurements, 0.0005% for DC voltage, 0.004% for current AC, and 0% for AC voltage. The system also performed best in the afternoon when the sun was high in the sky or close to it. Its worst performance was in the early morning when the sun's rays struck the panels at a horizontal angle, demonstrating its sensitivity to changes in light intensity.

The article (D. Zubov, et al., 2024) explained the reduced energy consumption from the national grid. It described the design and installation of a self-sufficient solar-powered microgrid capable of handling two types of loads: critical loads that need continuous operation, such as an electric heater, and shiftable loads such as LED light bulbs. To maintain load balance, the system uses a dynamic diode from an Arduino UNO. A photoresistor and some reliable relays. So, there are three reliable enablers in the hysteresis algorithm: battery voltage, the number of high-intensity lighting cycles, and the light intensity. The correction parameter is redesigned daily based on the amount of power consumed. The results have shown how efficiently the system provides switchable loads when power is available, while keeping the main loads running.

Previous studies and additional research are summarized in Table 1 for easy comparison. The table demonstrates a clear difference between the studies in terms of complexity, measurement accuracy, cost, scalability, and integration with modern technologies such as the IoT or data loggers.

Table: Comparison between Previous Studies and Current Research

Reference	Sensors used	IoT Integration	Accuracy or Error rate	Cost and Scalability
R. Anand, et al. 2016	Four sensors (irradiation, temperature, current, and voltage)	No	Accuracy exceeding 99%	Low-cost, portable system
V. Gupta, et al., 2017	Four sensors (Variable resistor, temperature, current, and voltage)	No	Accuracy exceeding 99%	Low-cost, easy to modify, and develop
A. Jumaat, & M. H. Othman, 2018	Four sensors (Light, temperature, current, and voltage divider)	No	------	Low-cost, portable system
N. Sugiartha, et al., 2019	Four sensors (voltage, current, temperature, and humidity)	No	-----	Low-cost
Oladimeji, et al., 2020	Four sensors (Light, temperature, Pressure, current, and voltage divider)	No	good agreement with measuring instruments	cost-effective
Rimbawati, et al, 2021	Four sensors (Variable resistor, temperature, current, and voltage)	Yes	error reading less than 3.3%	Low-cost, can be developed to reduce error
E. Lobo, et al., 2022	Three sensors (Light, current, and voltage)	Yes	Average Error less than 0.02%	Low-cost, monitoring solar power plants remotely
R. Daoud, et al, 2023	Temperature sensors	No	-----	Can be developed with online decision maker
D. Zubov, et al., 2024	Two sensor (Photoresistor, voltage)	No	-----	Low-cost, easy to modify, and develop
Current study	Four sensors (voltage and current sensor with IFRZ440 drive, temperature, and Light)	Central monitoring with IoT will be the future of business.	The reading is very close to the accuracy of a precision multimeter.	Low-cost portable system

System Design

The solar cell efficiency meter was designed using Arduino Uno R3, a current sensor (ACS712), and a voltage sensor. The driver (IRFZ440) is controlled by changing the amplitude of the square wave from the Arduino PWM pin (Q. Jalil2015 & B. Pramono 2025). It is connected in series between the solar cell and the load (DC motor) as shown in Figure 1.

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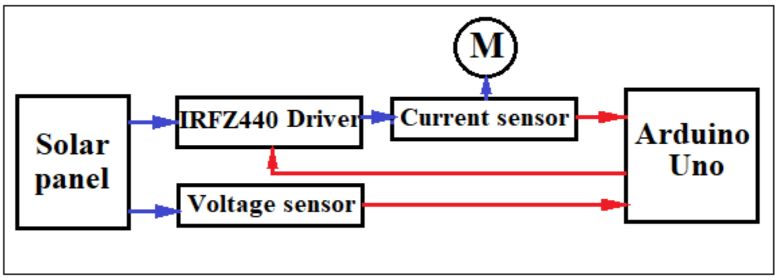

Figure 1: Basic Block Diagram

The IRFZ440 transistor, due to its technical and functional characteristics, is highly suitable for power control applications, especially in systems where solar panel performance is analyzed using microcontrollers such as the Arduino. This MOSFET transistor boasts high current and operating voltage tolerances, capable of handling currents up to approximately 49 A and voltages up to 55 volts. The IRFZ440 is widely available and inexpensive, making it economical and suitable for low-cost or educational systems, without the need for complex driver circuits or high-powered operation, as in the case of high-load applications. It can be connected directly to the digital output of an Arduino board to control it using PWM signals, simplifying system design without the need for intermediate circuits (IRFZ44N: Features, Applications, and Circuit Design Guide).

In this work, IRFZ440 was used in the system to drive a load applied to the solar panel. A PWM signal generated by Arduino is used to control the gate bias of the transistor. Each PWM level represents a specific percentage of load (0%, 20%, 40%, up to 100%). During each load condition, voltage and current are measured by the dedicated sensors. The instantaneous power is calculated using the equation P = V × I. Electrical efficiency is then calculated by comparing the output power with the input power.

As for the calibration logic, the system relies on comparing the measurements obtained from the sensors connected to the Arduino with readings taken from precision measuring devices such as multimeters or professional measuring systems. This process ensures better measurement accuracy and enhances the reliability of the analysis.

Hardware Description

The central unit for processing data is Arduino, as given in Figure 2 (R. Daoud, et al., 2023 & S. Jumaat, et al. 2018). It is characterized by its ability to receive analog signals (A0-A5) and generate PWM signals.

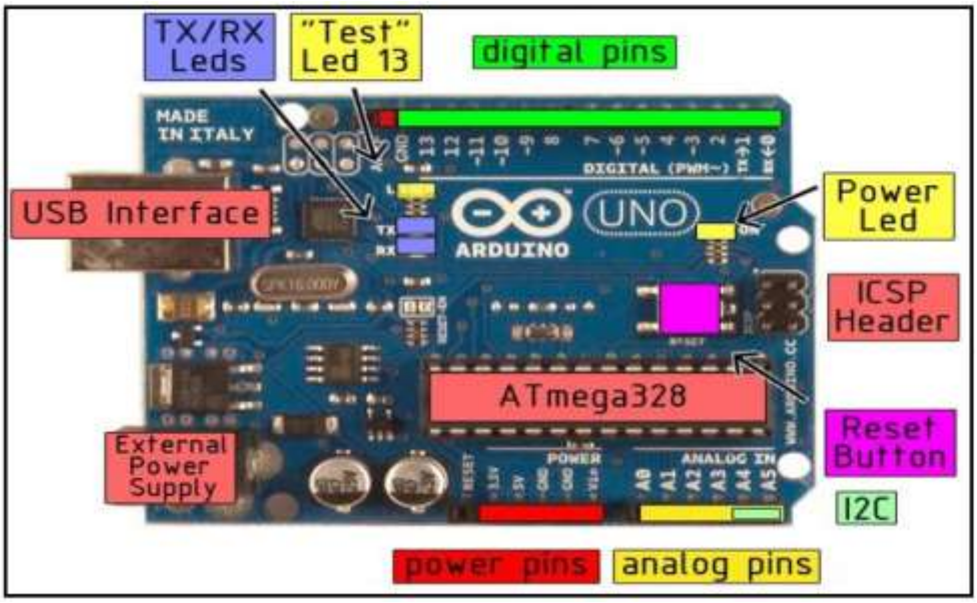

Figure 2: Arduino Uno Board Layout With Main Connections

The basic work of the Arduino processor is to generate a variable signal PWM from pin D9, as shown in Figure 3. The signal changes from (0-5) V, which is equivalent in the programming (0-1024). The signal drives the IRFZ440. The driver functions as a variable resistor (pot). The driver connects the load and the source in series. The PWM signal is in the form of a square wave with a variable time between cutting and connecting (ON/OFF time).

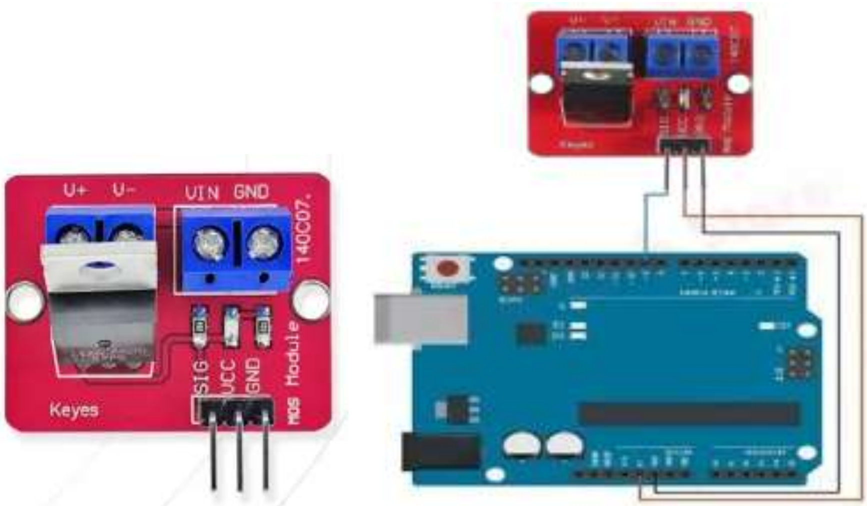

Figure 3: Driver IRFZ440 and interfacing with Arduino UNO

The current sensor (ACS712) is a unit for measuring direct and alternating current (A. Effendi, A. Dewi and Antonov 2022). This unit is characterized by ease of installation and high accuracy. The sensor works on the principle of "a magnetic field is generated around a copper conductor in which a current is flowing in a closed circuit. The sensor converts the magnetic field into an analog voltage. By reading and calibrating this voltage, the value of the current can be known. The sensor is used with programmable control units such as Arduino or

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Raspberry Pi. Each microcontroller has its own method of connecting and programming the sensor, illustrated in Figure 4 (User Manual For ACS712).

Figure 4: ACS712 Current Sensor

The voltage sensor measures the voltage by connecting it directly to the solar cell. This sensor can read a maximum voltage of 25V. The output is in the form of a voltage range between 0 V and 5 V, as programmed in advance in the microcontroller unit. Figure 5 shows the voltage sensor used in this work (A. Gunadhi, et al., 2020).

Figure 5: Voltage Sensor

TEST AND RESULTS

Figures 6 and 7 show a block diagram and a practical connection of the circuit using the following components: four solar cells, an Arduino board, an IRFZ440 driver, a current sensor, a voltage sensor, and a load. Each solar cell has specifications: Pm = 2 W, Vm = 2 V, and Im=220 mA, and they are connected in parallel. Therefore, the maximum power, voltage, and

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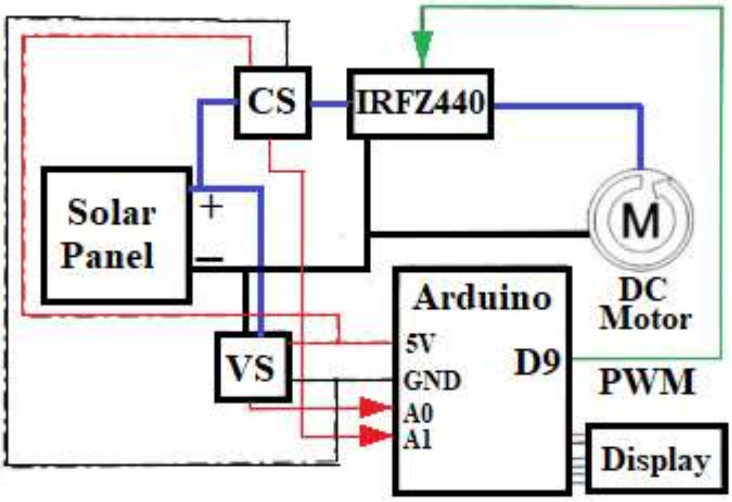

Figure 6: Schematic Diagram Circuit

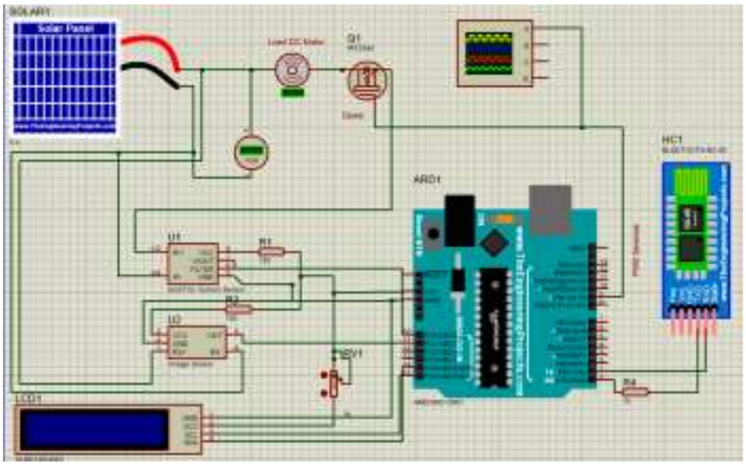

Figure 7: Practical Circuit Diagram in Proteus Software.

Figure 8 illustrates the practical circuit connection. The list of numbered components and their specifications is explained in Table 2. The circuit was connected, and the results were obtained in the laboratories of the Communications Engineering Technology Department, Najaf Technical College, Al-Furat Al-Awsat Technical University in Iraq.

Table 2: The List of Numbered Components and their Specifications

No. of components	Component	Specifications
1	Arduino UNO ATmega328P	Operating Voltage: 5V, 14 Digital I/O Pins: (6 provide PWM output), 6 PWM Digital I/O Pins, 6Analog Input Pins, DC Current per I/O Pin: 20 mA, DC current for 3.3V Pin: 50 mA, Memory: 32KB, Clock Speed: 16 MHz.
2	OLED Display	SSD1306 128×64, 3 V power supply
3	IRFZ440 Load Driver	N-channel MOSFET, VDS: 55 V, ID: 49A, RDS(on): 17.5mΩ, VSG: ±20V, Operating Temperature Range: -55℃ to +175℃.
4	Voltage sensor	maximum voltage of 25V
5	ACS712 Current sensor	Measure current from 0 A to 20 (both AC and DC), The sensitivity of the system is 100 mV/A. Powered by 5V.
6	HC05 Bluetooth Module	Working voltage: 3.3 V, communicates over a serial UART interface (RX, TX), supports the AT command. Maximum transmitter power is + 4 dBm, receiver sensitivity - 85 dBm.
7	DC motor	6-12V, 5000RPM, Large Torque.
8	4 solar panel (Pm=2W,Vm=9V,Im=220mA)	Each has Pm=2W,Vm=9V,Im=220mA, Voc=10.8V, Isc=240mA at STC

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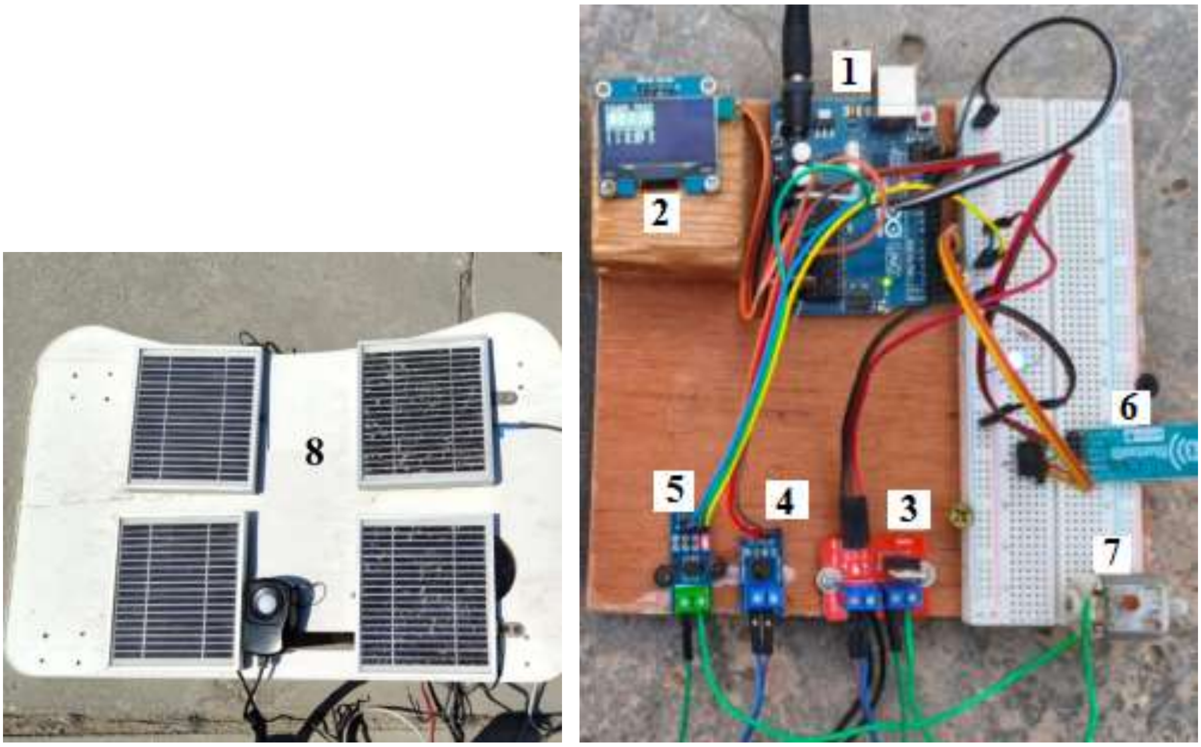
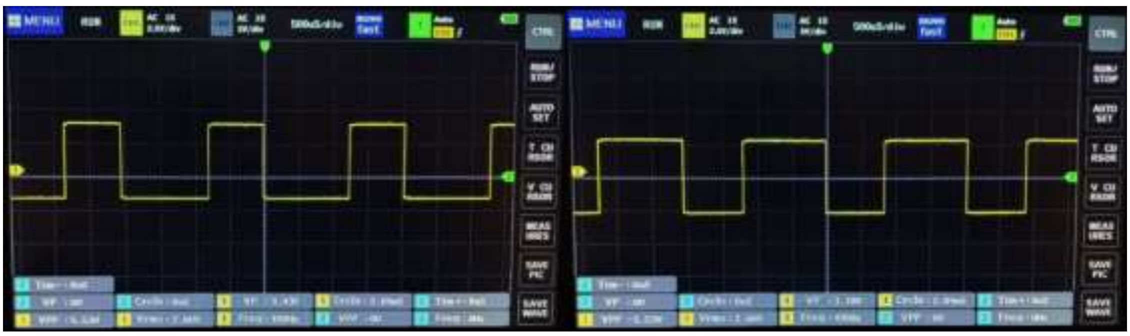


Figure 8: Practical circuit

The experimental part was implemented by testing the circuit to control the solar cell's output power. The measurements were made at different solar radiation levels (600, and 800) W/m2. The temperature was assumed to be constant at 35°C. Figure 9 shows different pulse width ratios (0, 20, 40, 60, and 80%) under test.

a) 0% PWM

b) 20% PWM



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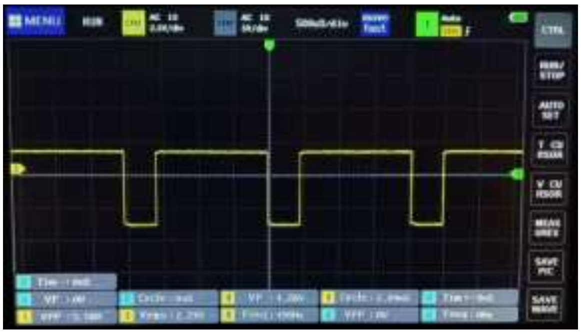
c) 40% PWM

d) 60% PWM



e) 80% PWM

Figure 9: PWM Percentage of Pulses

Table 3 shows the solar cell output current and voltage measurements for all cases. Through practical results of the system, we found that the measurements were very close to the readings recorded by the precision multimeter. The average error rate for voltage measurements was less than 0.01%, and for current measurements, about 0.05% in all cases. Figures 10 and 11 show a comparison between the measurement results in Table 3, which were made by the designed device, and the practical measurements with a multimeter at 800 W/m^2.

Table 3: Experiment Result of the System at Different Conditions

PWM Level	Parameter	600 W/m^2 solar radiation levels			800 W/m^2 solar radiation levels		
		Arduino Reading	Multimeter Reading	Deviation (±)	Arduino Reading	Multimeter Reading	Deviation (±)
0%	Voltage (V)	7.8	7.8	0.0 V	8.1	8	0.1 V
	Current (mA)	0.0	0.0	0.0 mA	0.0	0.0	0.0 mA
20%	Voltage (V)	7.6	7.6	0.0 V	8.0	8.0	0.0 V
	Current (mA)	95	100	-5.0 mA	126	132	-6.0 mA
40%	Voltage (V)	7.6	7.5	0.1 V	8.0	7.9	0.1 V
	Current (mA)	190	197	-7.0 mA	253	260	-7.0 mA
60%	Voltage (V)	7.4	7.3	0.0 V	7.9	7.9	0.0 V
	Current (mA)	285	290	-5.0 mA	380	187	-7.0 mA
80%	Voltage (V)	7.2	7.2	0.1 V	7.7	7.6	0.1 V
	Current (mA)	380	385	-5.0 mA	506	512	-6.0 mA

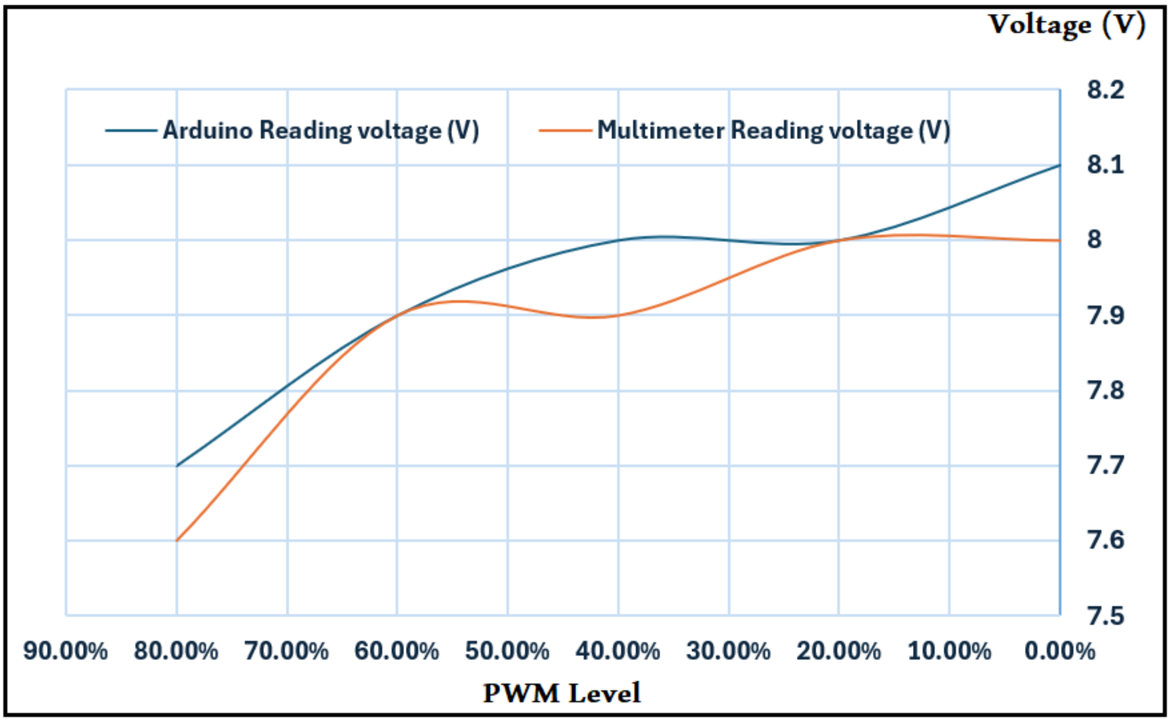


Figure 10: Voltage Measurement by the Designed Device and the Multimeter at 800 W/m^2 Radiation

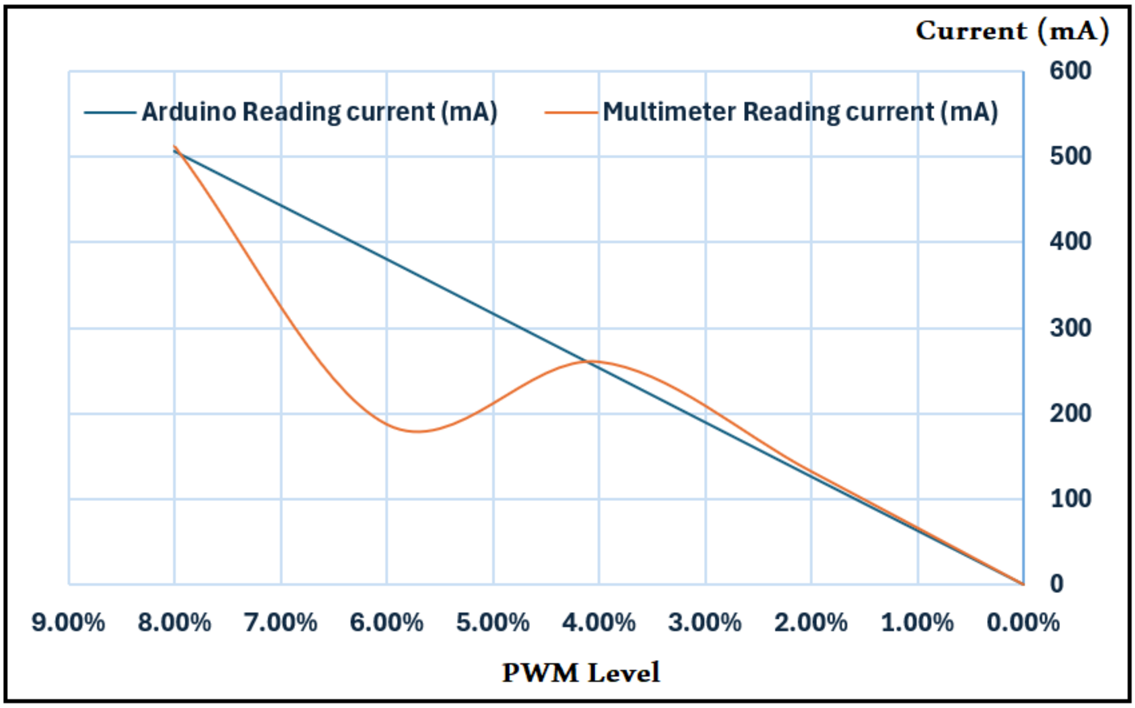


Figure 11: Current Measurement by the Designed Device and the Multimeter at 800 W/m^2 Radiation

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CONCLUSION

This research presents the design and implementation of a low-cost solar panel performance analyzer using an IRFZ440 MOSFET. This research aims to automatically detect and change the load resistance using a programmable PWM method. The design and implementation of the circuit aim to analyze the performance of PV panels by recording current and voltage values under different load conditions. The system consists of low-cost components such as an Arduino, an IRFZ440 MOSFET, current and voltage sensors, and an OLED display. The device was tested on an 8W PV system, and the results demonstrated the system's ability to record accurate readings in real-time, automatically detect the load. The results demonstrate the system's efficiency and suitability for use in educational and research purposes, as well as for monitoring small PV systems. The research offers the following benefits: scalability and future upgradeability with larger power systems, the integration of additional sensors or IoT technologies, storage and analysis capabilities, intelligent load control based on power availability, ensuring continuous operation of the primary loads, and reducing unnecessary power consumption.

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