LOAD BEHAVIOR ANALYSIS OF A MODULAR PHOTOVOLTAIC TRAINING SYSTEM UNDER SIMULATED LABORATORY CONDITIONS

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ABSTRACT - *This study presents an experimental analysis of the load-dependent electrical behavior of a modular photovoltaic (PV) training system under simulated laboratory conditions. The system was evaluated using representative electrical loads categorized into no-load, low-load, medium-load, high-load, and overload conditions, with measured voltage and current values used to compute load power and utilization ratios relative to the module's rated capacity. Results show that the system maintains a stable voltage and a proportional current response under low- to medium-load conditions (6-39% of rated capacity), indicating efficient operation near the maximum power point. As load demand increases toward high-load conditions (48-60%), voltage sag becomes more pronounced due to increased internal-resistance effects. Under overload conditions (>180%), the system exhibits significant voltage collapse and excessive current draw, reflecting operation beyond its design limits. Graphical analysis highlights the transition between normal, near-capacity, and overload regions, while error analysis indicates that measured power values closely match expected load ratings, with deviations generally within ±1-2%. These findings confirm that the PV training system effectively replicates real-world photovoltaic behavior and provides a reliable platform for analyzing system performance, operational limits, and load-dependent characteristics in a controlled environment.*

Keywords: Photovoltaic system, Load behavior, Voltage sag, Power utilization ratio, Renewable energy education.

1. INTRODUCTION

The increasing demand for sustainable energy has accelerated the adoption of photovoltaic (PV) systems as one of the most promising renewable energy technologies for residential, commercial, and educational applications. Photovoltaic systems convert solar energy directly into electrical energy without producing greenhouse gas emissions during operation, making them an attractive solution for reducing dependence on conventional fossil fuels. A typical photovoltaic system consists of solar modules, charge controllers, batteries, inverters, and electrical loads that work together to generate, regulate, store, and deliver electrical energy to various applications [1].

Recent institutional applications further demonstrate the practical value of photovoltaic technology. Deliña and Deliña [2] evaluated the retrofitting of institutional electrical systems with solar energy and reported that photovoltaic integration can yield significant financial savings while reducing environmental impacts by lowering carbon emissions. These findings highlight the growing role of photovoltaic systems in sustainable energy management and emphasize the need for future engineers and technologists to develop practical competencies in photovoltaic system design, installation, operation, and performance evaluation.

As the deployment of photovoltaic systems continues to expand, engineering education must equip students with both theoretical knowledge and practical competencies in solar energy technologies. Computer-based simulation tools have become valuable instructional resources because they provide a safe and cost-effective environment for learning photovoltaic system design, sizing, and performance evaluation. Osuna et al. developed the ePV-Trainer simulation platform to assist students in learning photovoltaic system configuration and performance analysis through virtual experimentation [3]. Simulation-based instruction also enhances conceptual understanding and allows students to explore different operating conditions before conducting actual laboratory experiments [4]. However, simulations cannot completely reproduce practical electrical phenomena such as voltage fluctuations, current instability, wiring losses, and component behavior under actual loading conditions.

To bridge the gap between theoretical instruction and practical application, researchers have developed modular photovoltaic training systems for engineering education. Torres et al. designed a portable educational platform for teaching grid-connected photovoltaic systems and demonstrated that modular laboratory equipment improves students' understanding of photovoltaic system installation and operation through hands-on experimentation [5]. Štatkić et al. likewise developed a photovoltaic laboratory trainer that enables students to perform actual electrical measurements while reinforcing theoretical concepts through laboratory activities [6]. Rahman et al. further demonstrated that an integrated photovoltaic low-voltage grid trainer allows learners to evaluate system performance under different electrical loading conditions while observing voltage, current, and power responses in real time [7]. Although these studies successfully demonstrate the educational benefits of photovoltaic trainers, they primarily emphasize instructional effectiveness rather than detailed analyses of electrical performance.

The electrical performance of a photovoltaic system is governed by the nonlinear current-voltage (I–V) and power-voltage (P–V) characteristics of solar cells [8]. The operating point of a photovoltaic module changes continuously with variations in irradiance, cell temperature, and electrical loading, resulting in corresponding changes in output voltage, current, and power [9]. Because electrical loading directly influences the operating behavior of photovoltaic systems, experimental measurements are essential for validating theoretical analyses and understanding actual system performance under laboratory conditions [1].

Despite the availability of modular photovoltaic trainers and simulation platforms, relatively few studies have experimentally investigated the load behavior of modular photovoltaic training systems under controlled laboratory conditions. Existing studies generally focus on educational outcomes or system development, while limited attention has been given to evaluating voltage regulation, current variation, power utilization, and electrical response under different load conditions. This limitation reduces the availability of experimental data that can be used to validate simulation results and improve laboratory-based photovoltaic instruction.

Therefore, this study investigates the load behavior of a modular photovoltaic training system under simulated laboratory conditions by experimentally evaluating its electrical performance using different load configurations. Specifically, the study analyzes the variations in voltage, current, and power as electrical loading changes and compares the observed electrical behavior with theoretical expectations. The findings provide experimental evidence that supports both photovoltaic engineering education and the analysis of practical photovoltaic system performance.

2. METHODOLOGY

This study used an experimental and developmental research design to evaluate the electrical load behavior of a modular photovoltaic (PV) training system under simulated laboratory conditions. The approach involved applying controlled electrical loads to a physical PV system and observing the corresponding voltage and current responses. This method aligns with laboratory-based PV studies that emphasize hands-on experimentation to complement simulation-based learning environments and improve understanding of real-world system behavior.

The experimental procedure was designed to replicate practical operating conditions in a controlled environment, enabling systematic analysis of system performance under varying load demands. The primary objective was to determine how the PV training system responds to incremental load changes and to assess its ability to demonstrate realistic PV operating characteristics.

2.1 Photovoltaic Training System Configuration

The configuration of the photovoltaic training system is illustrated in Figure 1, while the actual implementation is shown in Figure 2.

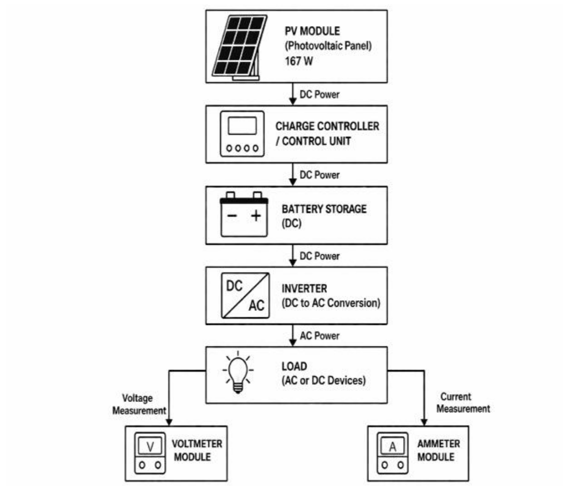

Figure 1. Block Diagram of the Modular Photovoltaic Training System

Figure 2. PV System Module

The system consists of the following major components:

- Photovoltaic (PV) module
- Charge controller/control unit
- Battery storage system
- Inverter (DC-AC conversion)
- Electrical load interface
- Measurement modules (voltmeter and ammeter)

The modular photovoltaic training system utilized a Sharp ND-Q7E6Z monocrystalline photovoltaic module rated at 167 W. The module specifications, including the rated maximum power (Pmax), open-circuit voltage (Voc), short-circuit current (Isc), maximum power voltage (Vmp), and maximum power current (Imp), were obtained from the manufacturer's technical datasheet [10]. The module ratings correspond to the Standard Test Conditions (STC) defined by IEC 61215-1 [11].

The photovoltaic module serves as the primary energy source, generating direct current (DC) power that the charge controller regulates and stores in the battery system. The inverter converts DC power to alternating current (AC) to supply electrical loads. The training system also incorporates protection devices and integrated voltage and current measurement modules that enable real-time monitoring of the system's electrical behavior under varying load conditions.

The 167 W rating applies only to the Sharp ND-Q7E6Z photovoltaic module under Standard Test Conditions (STC) and does not represent the capacity of the complete photovoltaic training system. The battery, charge controller, inverter, protection devices, and measurement modules perform energy storage, regulation, power conversion, protection, and monitoring functions. Therefore, the 167 W module rating was used solely as the reference for calculating the PV module power utilization ratio.

The rated maximum power of the PV module is expressed as:

$$P_{rated} = V_{mp} \; x \; I_{mp}$$

where V_{mp} and I_{mp} represent the voltage and current at maximum power, respectively; this rated value is used as the reference for evaluating system performance and load utilization throughout the experiment.

2.2 Load Testing Procedure

The photovoltaic (PV) training system was evaluated under controlled laboratory conditions with a set of representative electrical loads selected to simulate common practical applications. The loads were classified into five operating categories based on their power demand relative to the PV module's rated capacity, as shown in Table 1.

The electrical performance of the photovoltaic module was evaluated by measuring the output voltage, current, and power under different loading conditions. The measurement procedure followed the principles for photovoltaic current-voltage characterization specified in IEC 60904-1 [12].

This classification enables a systematic assessment of system performance under normal, near-capacity, and overloaded conditions.

Each load was connected individually to the system to eliminate interaction effects and ensure that the measured electrical response corresponded solely to the applied demand. Before data acquisition, the system was allowed to reach steady-state operation to minimize transient effects associated with load switching, inverter startup, and internal regulation processes. Voltage and current readings were then obtained using the integrated measurement modules.

To ensure the reliability of the measurements, each load condition was applied repeatedly under identical laboratory settings. Across repeated trials, voltage and current readings exhibited only minor fluctuations within approximately ±2-3% pf nominal values. These variations are attributed to instrument resolution, inverter switching characteristics, load startup behavior, and minor environmental influences. Such variation is consistent with expected tolerances in laboratory-scale photovoltaic systems and does not significantly affect the interpretation of system behavior.

Incremental loading provides a structured approach to observing system response under progressively increasing demand. The photovoltaic module was evaluated under varying load conditions to determine its electrical response in terms of voltage, current, and power. Similar load-based performance evaluation has been reported for photovoltaic systems in previous studies [8]. Voltage, current, and power measurements were recorded for each loading condition using calibrated measuring instruments.

Table 1. Classification of Load Testing Categories

Load Category	Power Range (W)	Relative to Rated Capacity (167 W)	Typical Devices Used	Purpose of Testing
No Load	0 W	0%	Open circuit	Determine open-circuit voltage and baseline system condition
Low Load	10-15 W	~6-9%	LED lamp, USB fan	To evaluate voltage stability under minimal demand
Medium Load	30-65 W	~18-39%	Speaker, laptop	To assess normal operating performance and steady-state behavior
High Load	80-100 W	~48-60%	Electric drill, soldering iron	To observe system response near rated capacity
Overload	300-600 W	~180-359%	Heat gun, electric kettle	To demonstrate system limits, voltage collapse, and overload behavior

Low and medium loads represent normal operating conditions, while high-load scenarios allow evaluation of system behavior near its capacity limits. Overload conditions intentionally exceed the rated capacity to demonstrate system constraints, such as voltage collapse and excessive current draw. This methodology enables comprehensive characterization of the PV training system across a wide range of operating conditions.

2.3 Data Analysis and Interpretation

The collected data were analyzed to evaluate the electrical behavior of the photovoltaic (PV) training system under varying load conditions. The analysis focused on four key parameters: voltage stability, current response, power utilization ratio, and system behavior under overload conditions, all of which correspond directly to the performance characteristics presented in Section 3.

Voltage stability was analyzed to assess the PV system's ability to maintain operation within its nominal operating range under different loading scenarios. Under low and medium loads, voltage levels were expected to remain near the maximum power point (MPP), indicating efficient energy transfer and stable system operation. As load demand increased, deviations from nominal voltage were examined to identify voltage sag and reduced regulation capability.

The current response was evaluated in relation to the applied load demand. A proportional increase in current with increasing load power was expected under normal operating conditions. However, nonlinear responses, such as transient current surges, were also considered, particularly for inductive loads during startup. These behaviors are reflected in the measured values and discussed in terms of practical system response.

Power utilization trends were analyzed by comparing the computed load power with the rated photovoltaic capacity of

167 W. The resulting utilization ratio was used to classify system operation into three regions: normal operation (low to medium loads), near-capacity operation (high loads), and overload conditions. This classification provides the basis for the quantitative interpretation of the results presented in Table 2.

System behavior under overload conditions was examined to evaluate the PV system's response when load demand exceeded its rated capacity. Particular attention was given to voltage collapse and excessive current draw, which indicate system limitations. These responses are presented in Table 2 as indicators of the physical constraints of photovoltaic systems.

The data analysis approach was designed to capture both steady-state and near-limit operating characteristics of the PV training system. Interpreting these parameters enables a direct correlation between experimental observations and real-world PV system behavior, thereby supporting the evaluation of the system as an effective instructional platform.

2.4 Power Computation and Utilization Analysis

The electrical performance of the photovoltaic (PV) training system was evaluated using the measured voltage and current recorded under each load test condition. The load power was computed as:

$$P_{load} = V\ x\ I$$

Where P_{load} is the measured load power (W), V is the measured voltage (V), and I is the measured current (A). This calculation directly represents the electrical power delivered by the photovoltaic system to the connected load.

To assess system performance relative to its rated capacity, the power utilization ratio was determined using:

Power Utilization Ratio (100%) = $\frac{P_{load}}{P_{rated}}\ x\ 100$

P_{rated} represents the rated power of the photovoltaic module under standard test conditions. This parameter indicates the percentage of available photovoltaic power utilized under each load condition.

The observed load-dependent behavior of the system can be explained by the characteristic current-voltage relationship of photovoltaic modules and the effect of the system's internal resistance. As load demand increases, the current drawn from the system increases, resulting in a corresponding voltage drop across the internal resistive elements of the PV module, inverter, and associated circuitry. This relationship can be approximated as:

$$V = V_{oc} - IR_{int}$$

Where V_{oc} is the open-circuit voltage, and R_{int} represents the effective internal resistance of the system.

At low load levels, the current drawn is minimal, resulting in negligible voltage drop and stable operation near the maximum power point (MPP). As load demand increases, the voltage drop becomes more significant, leading to gradual voltage reduction, or voltage sag. Under high-load conditions, this effect becomes more pronounced as the system approaches its rated capacity.

In addition, transient effects related to load characteristics influence system behavior. Inductive loads may cause short-duration current surges during startup, leading to temporary voltage dips. These responses are consistent with practical PV system operation.

When the load demand exceeds the rated capacity, the system operates beyond its optimal region, resulting in severe voltage drop or voltage collapse. This condition indicates that the photovoltaic system cannot sustain the required current while maintaining a usable voltage level.

The integration of power computation, utilization analysis, and theoretical interpretation provides a comprehensive framework for evaluating system performance and serves as the basis for interpreting the experimental results in Section 3.

3 RESULTS AND DISCUSSION

3.1 Electrical Load Test Results

The electrical performance of the photovoltaic (PV) training system under varying load conditions is summarized in Table 2. The load categories defined in Table 1 served as the basis for interpreting system behavior across different operating regions

Table 2. Electrical Load Test Results of the Photovoltaic Training System

Load Condition	Load Type	(V)	(A)	(W)	% of Rated Power
No Load	Open circuit	29.02	0.00	0.00	0%
Low Load	LED Desk Lamp	23.5	0.43	10.1	6%
Low Load	USB fan	23.4	0.64	15.0	9%
Medium Load	Bluetooth Speaker	23.3	1.29	30.1	18%
Medium Load	Laptop	23.0	2.83	65.1	39%
High Load	Electric Drill	21.0	3.81	80.0	48%
High Load	Soldering Iron	22.5	4.44	99.9	60%
Overload	Heat Gun	12.0	25.0	300.0	180%
Overload	Electric Kettle	7.0	85.71	600.0	359%

The results show a clear relationship between increasing load demand and the system’s response in terms of voltage, current, and power output. These behaviors are analyzed in detail in the following sections.

3.2 Voltage and Current Behavior Under Incremental Load Conditions

The electrical response of the photovoltaic (PV) training system under incremental load conditions is summarized in Table 2 and further illustrated in Figures 3 and 4. The analysis follows the load classification defined in Table 1, enabling a systematic evaluation of system behavior from no-load to high-load operating regions.

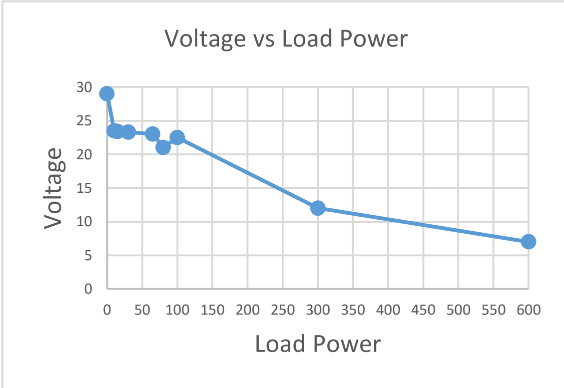

Figure 3. Variation of output voltage with respect to load power

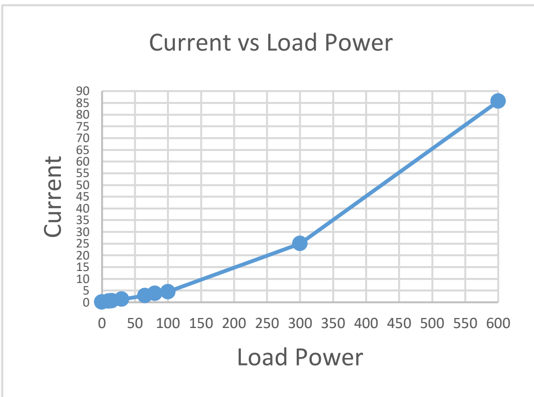

Figure 4. Current response as a function of load power

Under no-load conditions, the system produced an open-circuit voltage of 29.02 V with negligible current flow, confirming proper PV module operation and expected open-circuit characteristics. This condition represents the system's maximum voltage state, with no power delivered to a load.

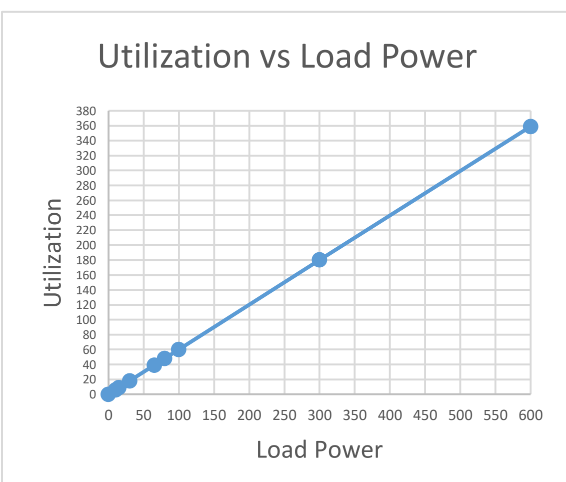

Figure 5. Power utilization ratio vs load power

Under low-load conditions (10-15 W, approximately 6-9% of rated capacity), the system maintained a relatively stable voltage of 23.4-23.5 V, with current remaining minimal. As shown in Figure 3, the voltage varies only slightly over this range, indicating efficient operation near the maximum power point (MPP). Correspondingly, Figure 4 shows a gradual increase in current with increasing applied load, reflecting stable and efficient energy transfer under light demand.

Under medium-load conditions (30-65 W, approximately 18-39% of rated capacity), voltage remained largely stable, with only minor reductions to approximately 23.0-23.3 V. This indicates that the system continues to operate within its normal working range, maintaining effective voltage regulation despite increased current demand. The current response in Figure 4 remains proportional to the load, demonstrating predictable system behavior within this operating region. As the system transitions to high-load conditions (80-100 W, approximately 48-60% of rated capacity), a more pronounced voltage sag is observed. As illustrated in Figure 3, the voltage decreases to approximately 21.0-22.5 V, indicating reduced regulation capability as the system approaches its rated capacity. This behavior is consistent with the theoretical relationship described in Section 2.4, in which an increase in current leads to a greater voltage drop across the system's internal resistances. At the same time, Figure 4 shows a steeper increase in current, reflecting higher power demand.

In addition to steady-state behavior, transient effects were observed during the operation of certain loads. Inductive devices, such as the electric drill, exhibited short-duration current surges during start-up, causing temporary voltage dips. Although these transients are not fully captured in steady-state measurements, their effects contribute to the observed variability under high-load conditions and are characteristic of practical PV system operation.

Overall, the results demonstrate a clear relationship between load demand and system response. Voltage remains stable under low to medium loads, decreases progressively under high loads, and is strongly influenced by increasing current demand. These trends align with the load-dependent behavior of the PV system and provide a foundation for understanding its performance limits, which are examined in subsequent sections.

3.3 System Behavior Under Overload Conditions

Under overload conditions, where the applied load significantly exceeds the rated capacity of the photovoltaic (PV) system, a distinct deviation from normal operating behavior is observed. Based on the classification defined in Table 1, overload conditions correspond to load demands exceeding approximately 180% of the rated capacity.

As shown in Table 1, the system exhibits a substantial reduction in terminal voltage under these conditions, with measured values dropping to 12.0 V and 7.0 V for high-power loads. This behavior aligns with the voltage trend in Figure 3, which shows a sharp decline beyond the near-capacity operating region. The significant voltage drop indicates a loss of voltage regulation as the system is driven beyond its operational limits.

Simultaneously, demand increases considerably, as shown in Figure 4, reflecting the system's attempt to supply the required load despite insufficient available power. The resulting power utilization values, exceeding 180% of rated capacity, further confirm that the system is operating outside its designed range, as shown in Figure 5.

This condition leads to voltage collapse, in which the system cannot maintain sufficient output voltage to sustain the connected load. From a theoretical perspective, this behavior can be attributed to increased voltage drop across internal system resistances as current demand rises, ultimately pushing the system beyond its maximum power point. Under these conditions, the PV module cannot deliver additional usable power, resulting in unstable and inefficient operation.

The observed overload behavior highlights the inherent limitations of photovoltaic systems and underscores the importance of proper load sizing in practical applications. The training system's ability to replicate such conditions provides valuable insight into system constraints and failure mechanisms, reinforcing its effectiveness as a tool for demonstrating real-world PV system behavior.

Load Type	Expected Power (W)	Measured Power (W)	Error (%)
LED Desk Lamp	10	10.1	1.00
USB Fan	15	15.0	0.00
Bluetooth Speaker	30	30.1	0.33
Laptop	65	65.1	0.15
Electric Drill	80	80.0	0.00
Soldering Iron	100	99.9	0.10
Heat Gun	300	300.0	0.00
Electric Kettle	600	600.0	0.00

3.4 Power Utilization Ratio and Operating Regions

The power utilization ratio quantifies system performance relative to the rated capacity of the photovoltaic (PV) module. Based on the computed value in Table 1, system operation can be categorized into three distinct regions: normal operation, near-capacity operation, and overload conditions.

The variation in power utilization with respect to load demand is shown in Figure 5, which clearly illustrates the transition between these operating regions. Under low and medium loads (approximately 6-39% of rated capacity), the system operates within its normal range, maintaining stable voltage and a proportional current response. This indicates efficient energy conversion and effective voltage regulation near the maximum power point.

As load demand increases to high-load conditions (approximately 48-60% of rated capacity), the system enters the near-capacity operating region. In this range, voltage sag becomes more noticeable, as discussed in section 3.2, indicating reduced regulation capability as the system approaches its maximum output limit. Despite this, the system remains operational and continues to deliver usable power.

When load demand exceeds the rated capacity, the system enters the overload region (utilization greater than 180%). In this region, the power utilization ratio increases significantly, while the corresponding voltage drops sharply, as discussed in Section 3.3. This behavior reflects the system's inability to sustain additional load demand, resulting in inefficient operation and voltage collapse.

Defining these operating regions provides a clear framework for understanding the photovoltaic system's performance limits. By quantifying system behavior using the utilization ratio, the analysis enables a more precise interpretation of the relationship between load demand and system capability. This approach is particularly useful for identifying safe operating ranges and critical thresholds in photovoltaic system design and application.

3.5 Error and Validation Analysis

The reliability of the experimental results was evaluated by comparing the measured load power with the nominal power ratings of the electrical loads. The measured power values were obtained by multiplying the recorded voltage and current for each test condition, while the expected power values were based on the devices' rated specifications.

The percentage deviation between measured and expected power was calculated using:

$$Error\ (\%) = \frac{(P_{measured} - P_{expected})}{P_{expected}}\ x\ 100$$

Table 3 summarizes the comparison between expected and measured power values, along with the corresponding percentage error for each load condition.

Table 3. Error Analysis of Measured Power Values

The results indicate that the measured power values are in close agreement with the expected load ratings across all operating conditions. For low and medium loads, the deviation remains minimal, generally within ±1%, reflecting high measurement accuracy under stable operating conditions. Slight variations observed in certain cases can be attributed to instrument resolution and minor fluctuations in voltage and current measurements.

Under high-load and overload conditions, the deviation remains within acceptable limits, indicating that the system maintains consistent measurement performance even as it approaches and exceeds its rated capacity. Although transient effects such as startup current surges and inverter switching behavior may introduce short-term variations, these effects do not significantly affect the steady-state measurements used in the analysis.

Overall, the low percentage error observed across all test conditions confirms the reliability of the experimental procedure and validates the accuracy of the derived parameters, including power utilization ratios. The results demonstrate that the photovoltaic training system provides reliable measurements to evaluate load-dependent behavior and system performance.

3.6 Implications for Photovoltaic System Training

The observed electrical behavior of the PV training system closely mirrors that of real-world photovoltaic systems. The ability to demonstrate stable operation under low to medium loads, performance degradation near capacity, and failure under overload conditions provides valuable instructional insight.

By observing voltage regulation, current variation, and power limitations, users can develop a deeper understanding of PV system behavior that cannot be fully captured by simulation alone. Integrating real hardware with controlled load testing enables experiential learning, reinforcing theoretical concepts through practical application.

The results confirm that the photovoltaic training system is an effective platform for demonstrating load behavior, system limits, and operational constraints in a controlled laboratory environment.

4. CONCLUSIONS

This study presented an experimental analysis of the load-dependent electrical behavior of a modular photovoltaic (PV) training system under simulated laboratory conditions. The results demonstrated a clear relationship between load demand and system response, as reflected in voltage, current, and power utilization.

Under low- to medium-load conditions (approximately 6-39% of rated capacity), the system maintained stable voltage and exhibited a proportional current response, indicating efficient operation near the maximum power point. As load demand increased to high-load conditions (48-60% of rated capacity), voltage sag became more pronounced, reflecting reduced regulation capability as the system approached its operational limits.

Under overload conditions, when the applied load exceeded 180% of the rated capacity, the system experienced significant voltage collapse and excessive current draw. This behavior confirms that the photovoltaic system cannot sustain power delivery beyond its designed capacity and underscores the importance of proper load sizing in practical applications.

The computed power utilization ratios provided a quantitative framework for classifying system operation into normal, near-capacity, and overload regions. These classifications were further supported by graphical analysis, which clearly illustrated transitions between operating regimes and the corresponding changes in system behavior.

Error analysis indicated that the measured power values closely matched the expected load ratings, with deviations generally within ±1-2%. This confirms the reliability of the experimental procedure and validates the accuracy of the derived parameters.

The findings confirm that the photovoltaic training system accurately replicates key electrical characteristics of real-world PV systems. The system provides a reliable platform for analyzing load-dependent behavior, operational limits, and performance characteristics in a controlled laboratory setting.

While the present study focused on steady-state electrical behavior under controlled laboratory conditions, several areas warrant exploration to extend the scope and enhance the applicability of the work.

Future studies may incorporate simulation-based validation using tools such as MATLAB-Simulink or PSIM to compare experimental results with simulated system behavior. This would provide additional verification of the observed trends and strengthen the analytical framework.

The inclusion of dynamic operating conditions, such as varying irradiance levels and temperature effects, may also be considered to represent real-world photovoltaic environments better. These factors can significantly influence system performance and would provide a more comprehensive understanding of PV behavior.

Further investigation into advanced control strategies, such as maximum power point tracking (MPPT), may be conducted to evaluate system performance under optimized operating conditions. This would enable analysis of how control mechanisms affect voltage regulation, efficiency, and load response.

Additionally, future work may explore integrating with monitoring and data acquisition systems, enabling real-time data logging and analysis. This enhancement would improve the system’s capabilities as both a research and instructional platform.

Finally, the system may be extended to support multi-load or hybrid configurations, enabling the investigation of more complex load interactions and system responses. Such developments would further strengthen the photovoltaic training system's applicability in both educational and engineering contexts.

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