J. Electrical Systems 22-01 (2026): 206-212

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An FPGA-Based Solar Photovoltaic Emulator for Grid-Integrated System Analysis

Abstract: - The widespread deployment of solar photovoltaic (PV) systems in modern grids has driven the need for reliable laboratory testing platforms. Unpredictable climatic factors like temperature swings and variations in irradiance hinder field testing with actual PV panels. Therefore, Solar energy emulators provide a controllable and repeatable alternative by accurately reproducing the electrical characteristics of PV modules. This paper provides a detailed investigation into the modelling and control strategies of a solar energy emulator suitable for grid-integrated PV system. The emulator is based on an accurate PV mathematical model and a power electronic converter controlled to mimic the inherent nonlinear current–voltage and power–voltage responses of a photovoltaic array. The proposed system is suitable for MPPT testing and microgrid integration studies.

Keywords: Solar energy emulator, Photovoltaic systems, PV modelling, MPPT, grid integration

I. INTRODUCTION

Solar Photovoltaic (PV) systems have gained significant attention as a renewable energy option due to their abundance, modular design, and minimal environmental impact. However, the intermittent and nonlinear nature of PV power generation poses challenges for system design, control, and grid integration[1]. Accurate testing of PV converters, maximum power point tracking (MPPT) algorithms, and grid-connected controllers requires a controllable and repeatable source[2]-[3]. Several studies emphasize that laboratory-based testing using real PV panels is affected by uncontrollable weather conditions, leading to poor repeatability and extended development time. Solar emulators overcome these limitations by reproducing the electrical behavior of PV arrays under programmable irradiance and temperature conditions[4]. Prior research on PV emulators, grid-connected PV systems, and hybrid renewable systems demonstrates the effectiveness of emulator-based validation for power electronics and control strategies[5].

II. PRINCIPLE OF SOLAR EMULATION

In general, a programmable DC power supply or a digitally controlled DC–DC converter is used to construct a PV emulator to mimic the electrical behavior of an actual PV panel under various operating and environmental circumstances. Accurately simulating the nonlinear current-voltage and power-voltage characteristics of a PV module without depending on real solar irradiation is the main objective of a PV emulator[6]-[7]. It provides a steady, programmable, and time-independent source in contrast to actual PV panels, whose output is based on unpredictable variables like temperature and sunlight for irradiance[8]. The emulator can simulate fluctuations in load, temperature, partial shade, and irradiance by modifying control variables, While changes in irradiance have an impact on the short-circuit current, temperature variations mostly affect the open-circuit voltage [9]-[[10]. These parameters must be dynamically adjusted by an accurate PV emulator in order to represent realistic operating circumstances over the whole voltage and current range[11].PV emulators provide a number of benefits, such as weather independence, safety, repeatability, and a reduction in the amount of laboratory space needed. They provide a versatile platform for evaluating power electronic converters and control techniques while drastically cutting development time and expense[12].

III. PHOTOVOLTAIC SYSTEM MODELLING

The single-diode model is mostly used to represent the electrical behavior of a PV cell due to its balance between accuracy and simplicity. Fig. 1 depicts the equivalent circuit for the one and two diode models. It comprises of a diode, series resistance, shunt resistance, and a current source that represents the photo-generated current[13]-[9].

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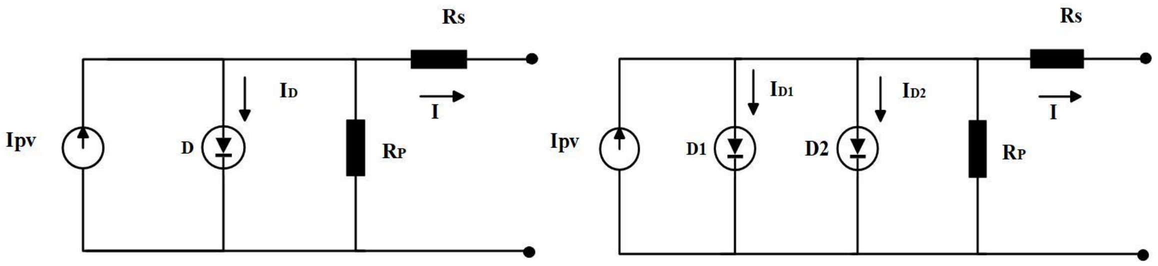

(a) (b)

Fig.1 Single and Two diode model of PV module

The electrical output current of a photovoltaic cell is represented by the equation below[14]:

$$I = I_{pv} - I_0\left(e^{\frac{q(V+IRs)}{\eta KT}} - 1\right) - \left(\frac{V_{OC} - IR_S}{R_P}\right) \qquad \text{“(1)”}$$

In this equation (1), $I_{pv}$is the photo-generated current, $I_o$is the diode saturation current, and $R_S$and $R_P$indicate the series and shunt resistances, respectively. The variations in irradiance primarily affect I_{pv}, while temperature influences I_o [15]-[16].

IV. SOLAR ENERGY EMULATOR ARCHITECTURE

The fig. 2 represents a grid-connected solar photovoltaic emulator–based energy system with coordinated control and storage. The Solar Photovoltaic Emulator (SPVE) emulates the electrical characteristics of a real PV module and feeds power to a boost converter, which regulates the PV operating point by controlling the voltage and current.

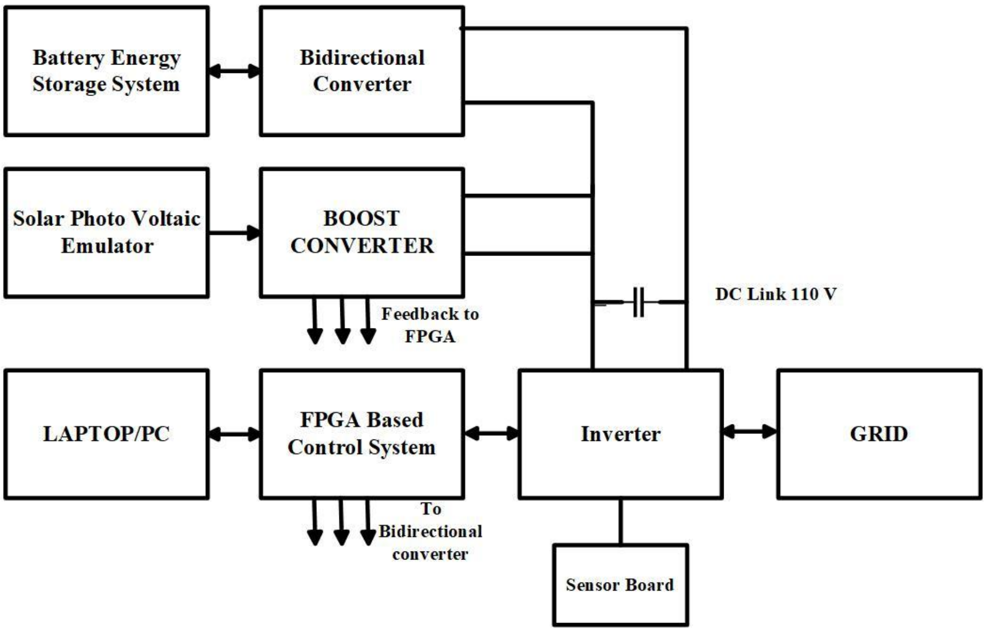

Fig.2 Architecture of Solar Photo Voltaic Emulator

This system demonstrates the integration of a shared DC link with a utility grid interface, a battery energy storage system (BESS), and a photovoltaic source emulator, resulting in a grid-connected DC microgrid. A DC–DC boost converter, which rises up and regulates the PV voltage while providing MPPT through closed-loop control developed on an FPGA-based control platform. LabVIEW is used to simulate the PV model, and a data-acquisition system is used to connect it with the real environment. Fig. 3 shows the hardware of Solar Photo Voltaic Emulator.

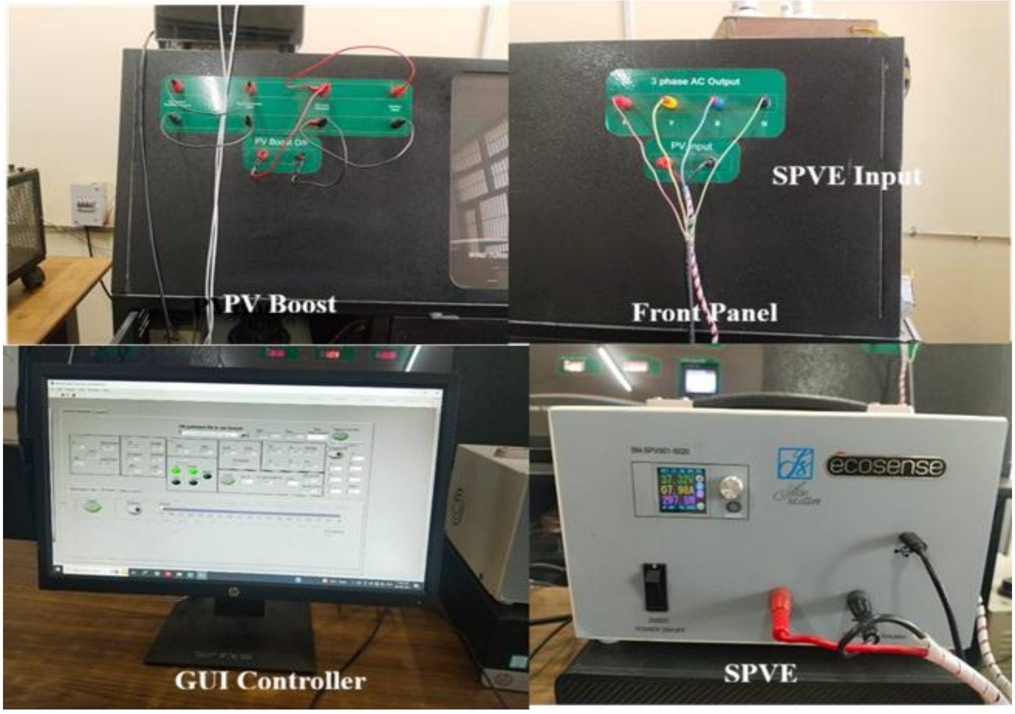

Fig.3 Hardware of SPVE

The FPGA communicates with a laptop/PC for real-time monitoring, parameter setting, data logging, and analysis[3]. A battery energy storage system is interfaced through a converter, enabling energy buffering, power balancing, and support during transients or low PV conditions. The regulated DC power from both the PV emulator and battery side is supplied to a DC–AC inverter, which converts it into AC power synchronized with the utility grid. Overall, the architecture enables controlled power injection into the grid while allowing flexible testing of PV behavior, storage integration, and advanced control strategies.

A. *Import and Export of Power to Grid*

The variation of PV system parameters as the PV duty cycle is varied at a fixed open-circuit voltage (Voc = 36 V) and irradiance (G = 1000 W/m^2) is shown in Table 1.At very low duty cycles (0–0.3), the PV operates close to open-circuit conditions: the PV voltage remains around 36 V, current is very small, and hence the PV power is almost negligible. The negative grid power indicates power is imported from the grid. As the duty cycle increases beyond about 0.4–0.5, the converter begins to draw more current from the PV, leading to a noticeable rise in PV current and power. Around duty = 0.65–0.7, the system transitions toward effective power extraction, with PV power and grid power increasing sharply.This indicates operation closer to the maximum power point region. At duty 0.65, the emulator starts exporting power to the grid. At higher duty cycles (0.8 and above), the PV voltage drops significantly while current increases substantially, resulting in a large increase in PV power . To increase the PV power generated, Isc must be increased. This reflects a shift from voltage-dominated to current-dominated operation. The gradual increase in maximum I_{SC} values at different loading conditions confirms that higher duty cycles force the PV to deliver more current and power to the grid. Overall, the table demonstrates the strong dependence of PV current, voltage and power transfer on the duty cycle of the power converter. MPPT algorithms like Incremental Conductance and Perturb and Observe (P&O) can be tested easily with this approach.

Table 1. Effect of Converter Duty Cycle on PV and Grid Power under Standard Irradiance Conditions

Variation of several parameters at Voc =36 and G=1000 with PV duty						
Sr No.	PV Duty	V_{PV} (Volts)	I_{PV} (Amps)	PV Power (Watts)	Grid Power (Watts)	Maximum I_{SC} (Amps)
1	0	36	0.11	0	-19	6
2	0.1	36.42	0.14	5.13	-16	6
3	0.15	36.43	0.15	5.54	-15	6
4	0.2	36.46	0.11	4.17	-14	6
5	0.3	24.50	0.16	4.05	-14	6
6	0.4	31.80	0.26	8.29	-13	6
7	0.5	33.33	0.44	14.68	-11	6
8	0.65	34.27	0.55	19.43	86	6
9	0.7	34.28	4.6	158	87	6
10	0.8	24.37	5.92	144.48	88	6
11	0.85	34.73	3.97	137.92	90	6
12	0.65	36.43	0.64	23.50	0	7
13	0.65	36.40	0.68	24.88	2	8
14	0.65	36.30	0.64	22.29	117	9
15	0.65	36.39	0.66	24.14	125	10
16	0.7	36.53	5.9	204.39	108	10
17	0.7	34.84	5.34	186.43	159	11
18	0.8	24.63	10.76	265.95	172	11
19	0.8	24.74	11.70	289.71	187	12
20	0.8	25.42	13.63	346.60	210	14

V. SIMULATED RESULTS

The performance of the solar energy emulator was evaluated by hardware assessment under different operating situations. The results confirm that the emulator can support grid-integrated research and accurately replicate the electrical properties of a real photovoltaic (PV) module. A 1kW solar panel is modelled in LabVIEW. A couple of variables, including duty of boost converter, diode quality factor and series resistance are modified, while its performance is investigated. Fig. 4 and 5 illustrate the current–voltage and power–voltage characteristics of the photovoltaic module when operating under MPPT control and manual mode.

A. *MPPT and Manual Control*

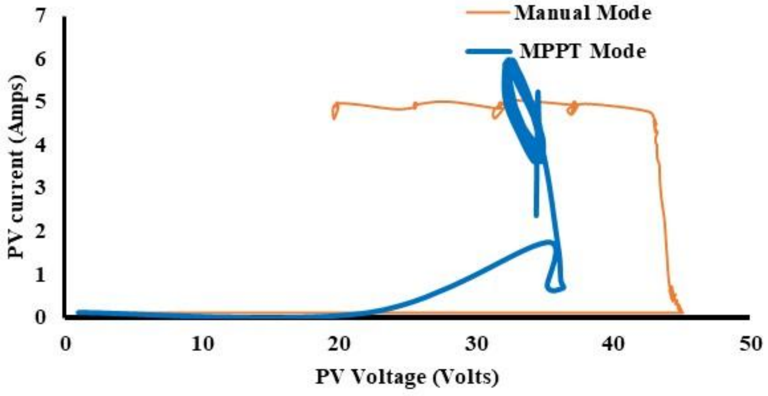

Fig.4 I–V characteristics comparing MPPT and Manual operating modes

The measured PV current vs voltage characteristics easily differentiate manual mode from MPPT mode. The operating points in MPPT mode concentrate around the I-V curve's knee, signifying that the maximum power region has been successfully tracked. On the other hand, the operating point can move over the whole voltage range in manual mode, including areas near open-circuit voltage.

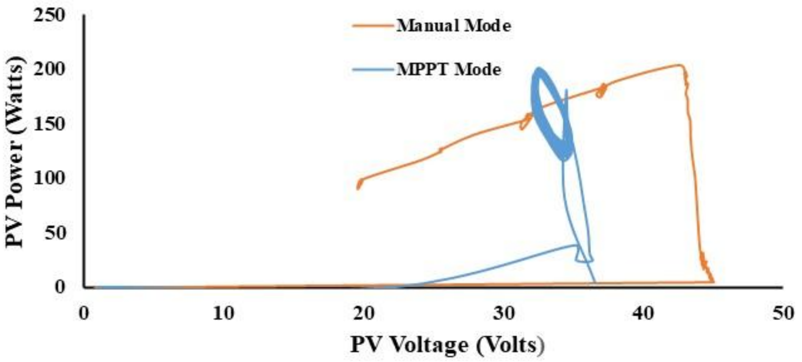

Fig.5 P-V characteristics comparing MPPT and Manual operating modes

Emulator performance is further validated by the power–voltage characteristics. Effective power extraction is demonstrated in MPPT mode, where the output power stays focused close to the maximum possible value. A greater range of operating points is produced by manual mode, and power dramatically drops when the voltage deviates from the MPP.

B. *Effect of Temperature Variation*

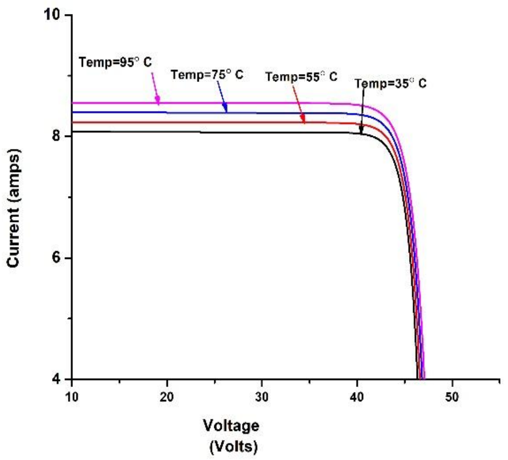

Fig.6 Variation of I–V Characteristics with Temperature

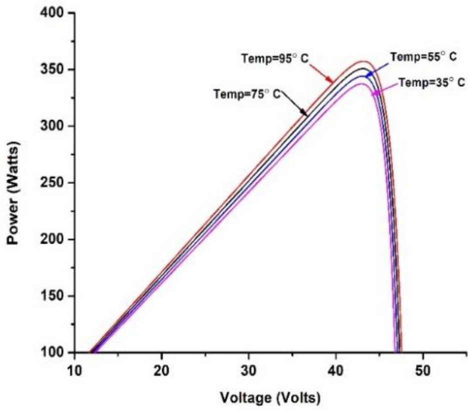

Fig.7 Variation of P–V Characteristics with Temperature

Fig. 6 and 7 illustrates the variation of current-voltage and power -voltage characteristics from 35 °C to 95 °C different temperature. As temperature increases, the value of current rises slightly, with the highest current observed at 95 °C and the lowest at 35 °C whereas the voltage decreases as temperature rises. The peak power increases and moves significantly with temperature. The maximum power is observed at highest at 95 °C and lowest at 35 °C.

C. *Effect of Series Resistance Variation*

The effect of variation of series resistance is shown in fig. 8. It indicates how the power output the of a solar panel varies with voltage under different series resistance values (Rs).

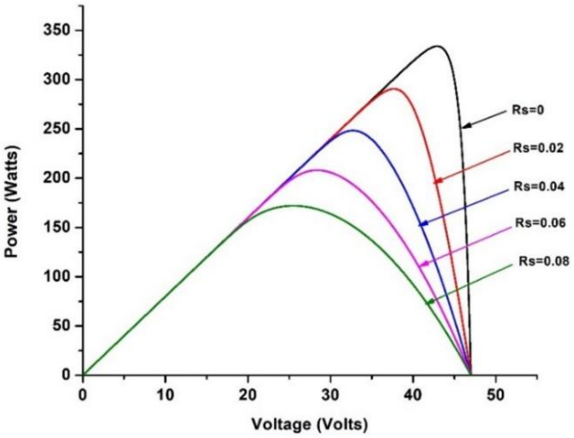

Fig.8 Effect of Series Resistance (Rs) on PV Module Output Power

Each curve represents a different Rs value, ranging from 0 to 0.08 ohms. At Rs = 0, the power increases dramatically with rise in voltage before rapidly declining. The peak power decreases and appears at slightly reduced voltages as the series resistance increases. Thus, the graph demonstrates the detrimental effects of resistance on solar panel performance by showing that increasing series resistance results in both a decrease in maximum output and a movement of the ideal operating voltage toward lower values.

D. *Effect of Diode Quality factor Variation*

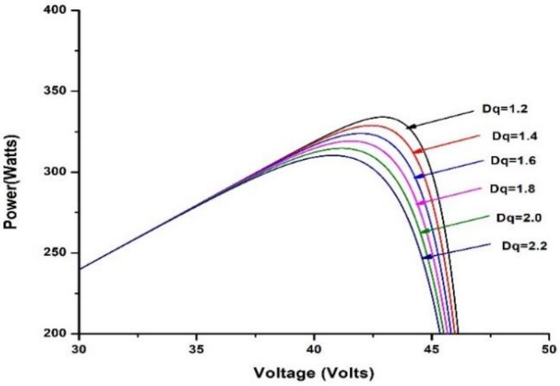

Fig.9 Effect of Dq on PV Module Output Power

The control parameter Dq is changed to simulate temperature variation as shown in fig. 9. As Dq increases, the resulting P-V curves clearly demonstrate a decrease in maximum power and a shift in the voltage at which the peak occurs. This pattern is consistent with the effect of rising temperatures on PV modules, which is known to lower open-circuit voltage and total power production. The emulator can successfully recreate environmental variations without requiring physical hardware modifications.

VI. CONCLUSION

This paper presented a solar energy emulator framework for photovoltaic system and grid integration studies. By combining an accurate PV mathematical model with a controlled power electronic converter, the emulator effectively reproduces the nonlinear electrical behavior of PV arrays. The proposed approach enables reliable laboratory testing of MPPT algorithms. At higher duty cycles, the system exhibits reliable power export and stable performance over an extended working range. The emulator successfully supports MPPT testing, as shown by a comparison between manual and MPPT operation. In manual mode, power extraction is inefficient; in MPPT mode, the operating point continuously stays close to the maximum power point. The impact of series resistance, temperature and Dq on PV performance was also analyzed. In summary, the study finds that the proposed solar energy emulator offers a reliable, accurate, and repeatable laboratory platform for grid-integration studies, MPPT evaluation, and PV system testing without relying on actual environmental circumstances.

CONFLICT OF INTERESTS

The authors declare that they have no conflict of interest.

ACKNOWLEDGMENT

I would like to express my sincere thanks to my Ph.D. work supervisor Dr Vijay Kumar Garg for his extensive guidance. I am also thankful to the Department of Electrical Engineering UIET, Kurukshetra for providing hardware environment for this research work.

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