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Experimental validation of Single-Phase Single-Stage Grid Connected Photovoltaic System using RT-LAB under real atmospheric conditions

***Abstract**. This paper presents an experimental validation of a single-phase single-stage grid connected photovoltaic (PV) system using the RT-LAB OP5700 real-time simulator. The study is divided into two main parts. In the first part, we introduce the characteristics of the GALIX JW-G2100 model photovoltaic panel. The second part focuses on configuring and implementing the single-phase single-stage grid connected PV system in two different topologies. The objectives are to fulfill electrical demands and maximize the power output of the PV panel. We employ the OP-5700 for analyzing the results obtained from various tests. To enhance power extraction from the solar panel, it is crucial to operate the photovoltaic system at the maximum power point (MPP). We present and discuss the experimental results of the photovoltaic system under real atmospheric conditions, which was constructed at the Electrotechnical Laboratory of the National Polytechnic School of Constantine.*

Streszczenie.** W artykule przedstawiono eksperymentalną walidację jednofazowego, jednostopniowego systemu fotowoltaicznego (PV) podłączonego do sieci z wykorzystaniem symulatora czasu rzeczywistego RT-LAB OP5700. Opracowanie podzielone jest na dwie główne części. W pierwszej części przedstawiamy charakterystykę panelu fotowoltaicznego model GALIX JW-G2100. Druga część koncentruje się na konfiguracji i implementacji jednofazowego, jednostopniowego systemu fotowoltaicznego podłączonego do sieci w dwóch różnych topologiach. Celem jest spełnienie wymagań elektrycznych i maksymalizacja mocy wyjściowej panelu fotowoltaicznego. Do analizy wyników uzyskanych z różnych testów wykorzystujemy OP-5700. Aby zwiększyć pozyskiwanie energii z panelu słonecznego, ważne jest, aby system fotowoltaiczny działał w punkcie maksymalnej mocy (MPP). Przedstawiamy i omawiamy wyniki eksperymentów układu fotowoltaicznego w rzeczywistych warunkach atmosferycznych, który został zbudowany w Laboratorium Elektrotechnicznym Politechniki Narodowej w Konstantynie.* (Eksperymentalna walidacja jednofazowego, jednostopniowego systemu fotowoltaicznego podłączonego do sieci przy użyciu RT-LAB w rzeczywistych warunkach atmosferycznych***)

Keywords: Maximum power point (MPP), Photovoltaic (PV) system, RT-LAB OP5700 real-time simulator, Single-phase single-stage
Słowa kluczowe: Maksymalny punkt mocy, System fotowoltaiczny (PV), Symulator czasu rzeczywistego RT-LAB OP5700

Introduction

In the last decades, due to industrial evolution and population growth, the world's energy demand has been continuously increasing [1].

Among the vast number of alternative and renewable energy sources, solar energy have gained popularity due to their enormous availability [2]. One of the advantages of this resource is that it is abundant and distributed throughout the earth, making it easily accessible. Additionally, it is pollution-free and recyclable, which makes it an environmentally friendly option [3].

Algeria is located in a region that boasts one of the highest solar energy potentials in the world. The duration of sunshine across nearly all of the country exceeds 2000 hours annually and can even reach 3900 hours in certain areas such as the high plains and Sahara. In general, a horizontal surface spanning an area of 1 square meter yields an energy output of approximately 5 kilowatt-hours per day across most parts of the country. As a result, the northern region receives an estimated annual energy output of around 1700 kilowatt-hours per square meter, while the southern region receives a slightly higher amount of approximately 2263 kilowatt-hours per square meter per year [4]. Due to this abundance of solar radiation, solar energy has significant potential to be developed in Algeria.

In the domain of single-phase PV applications, one-stage and two-stage grid connected PV systems represent prevalent topologies [5]. Employing a single-stage DC–AC inverter can enhance the reliability, compactness, and cost-effectiveness of the PV system. Furthermore, single-phase single-stage grid connected PV systems equipped with low-frequency transformers assume a crucial role in ensuring safety by providing galvanic isolation, thereby mitigating leakage current and averting the injection of DC current into the grid [6].

A solar panel produces varying amounts of power, so the duty of the MPPT in a photovoltaic power transformation system is to constantly adjust the system so that it can obtain the maximum power from the solar panel under different weather conditions [7]. In fact, various MPPT techniques have been introduced and discussed in the literature [8]-[12]. However, the P&O method is the most widely used because it is easy to implement, and it provides good efficiency. This method uses the change in voltage and power to determine the direction of the MPP and adjusts the duty cycle of the converter accordingly.

Numerous research papers [5] and [13]-[18] have examined single-phase single-stage grid connected photovoltaic system, although these studies typically do not consider real atmospheric conditions. In the present research, we will verify the performance of the single-phase single-stage grid connected PV system, under real atmospheric conditions, in two topologies: fulfill electrical demands and maximize the power of the PV panel. The complete system will be implemented in Matlab/Simulink and integrated into the real-time interface RT-LAB. Experimental results of the photovoltaic system (as shown in Figure 1), comprising a solar panel, power control components, a DC-AC inverter, a transformer, a load, a grid, and the real-time interface RT-LAB, will be presented and discussed. This experimental setup was constructed at the Electrotechnical Laboratory of the National Polytechnic School of Constantine.

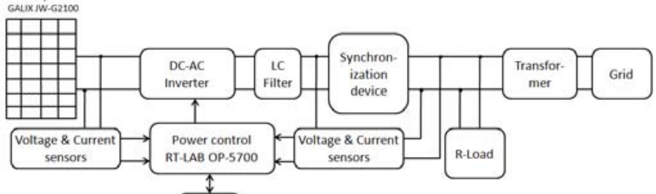

Fig.1. Single-phase single-stage grid connected PV system

This paper is organized as follows. First, the real characteristics of GALIX JW-G2100 solar panel are presented in Section 2. Second, the control of the single-phase single-stage grid connected PV system is provided in Section 3. Finally, the experimental results and discussion are presented in Section 4.

Solar panel model

The fundamental component for converting sunlight into direct electrical energy is the photovoltaic cell. A solar panel is composed of several photovoltaic cells connected in either a series or parallel configuration, and can be represented mathematically by the following equation [19]:

(1) $$I_{PV} = N_p I_{ph} - N_p I_o \left[e^{\frac{N_s V_{pv} + (N_s / N_p) R_{spv} I_{pv}}{a N_s V_t}} - 1 \right] - \frac{N_s V_{pv} + (N_s / N_p) R_{spv} I_{pv}}{(Ns/Np) R_{shpv}}$$

where: Iph : Photocurrent; Io: Reverse saturation current of the diode; Rs_{PV} and Rsh_{PV}: Series and parallel resistances of the photovoltaic cell, respectively; Vt: Thermal voltage of the solar panel; a: Diode ideality factor; Ns and Np: Numbers of photovoltaic cells in series and in parallel, respectively.

The GALIX JW-G2100 solar panel (Figures 2 and 3) was chosen for the photovoltaic system. It has a maximum power output of 210 W and consists of 72 monocrystalline silicon cells connected in series. Its specifications are presented in Figure 3.

Fig. 2. Solar panel GALIX JW-G2100

Fig. 3. Electrical Characteristics of GALIX JW-G2100

To obtain an accurate representation of the performance of a solar panel under specific environmental conditions, it is necessary to analyze its I-V and P-V characteristics. In the case of this panel, which is subjected to a temperature of 40°C and a solar irradiance of 574W/m2, the real I-V and P-V characteristics are provided in Figures 4 and 5, respectively.

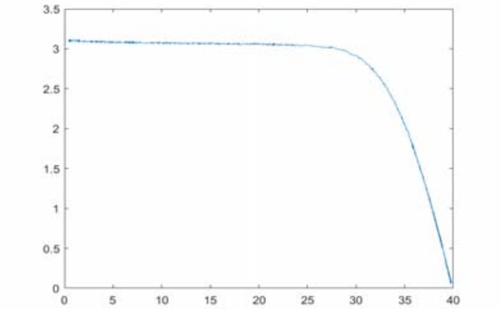

Fig. 4. Experimental I-V characteristic for a temperature of 40°C and a solar irradiance of 574W/m2

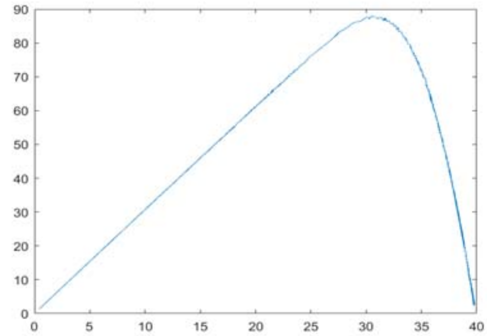

Fig. 5. Experimental P-V characteristic for a temperature of 40°C and a solar irradiance of 574W/m2

Control strategy of single-phase single-stage grid connected PV system

The control objectives of a single-phase single-stage grid connected PV system can be divided into two parts: fulfill electrical demands or maximize the power output of the PV panel as shown in Figure 6.

The DC-AC inverter connected to the grid across the LC filter injects sinusoidal current into the grid to control the power factor. Consequently, the inverter converts the DC power from the PV panel into AC power for grid injection. An essential aspect of the PV system connected to the grid is its control, which can be divided into the synchronization algorithm based on the Phase-Locked Loop (PLL), the maximum power point tracking algorithm and the control of injected current into the grid.

To capture the maximum power from PV panel, a maximum power point tracking algorithm is essential. The P&O method is the most widely used because it is easy to implement, and it provides good efficiency. The P&O of a solar panel works by adjusting the duty cycle, which perturbs the array terminal voltage. This adjustment is done incrementally or decrementally, and the resulting power and voltage values are compared with the values from the previous cycle. If (DP/DV>0), the perturbation continues in the same direction during the next cycle. However, if there is a decrease (DP/DV<0), the direction of the perturbation is reversed as shown in Figure 7 [20]. The simplicity and the need for only a few measured parameters make P&O algorithm popular in MPPT.

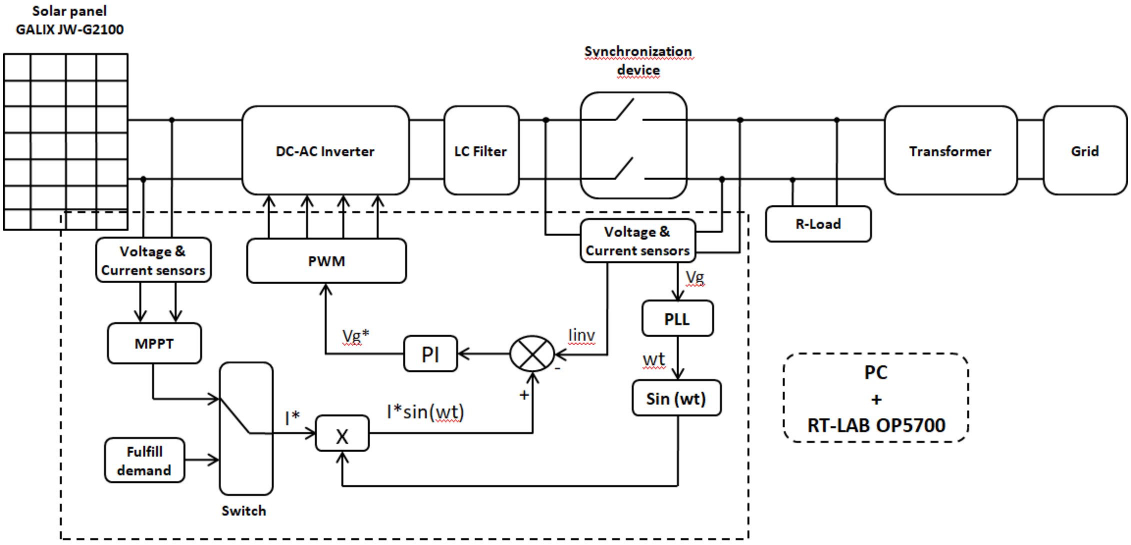

Fig.6. Injected power control of single-phase single stage grid connected PV system

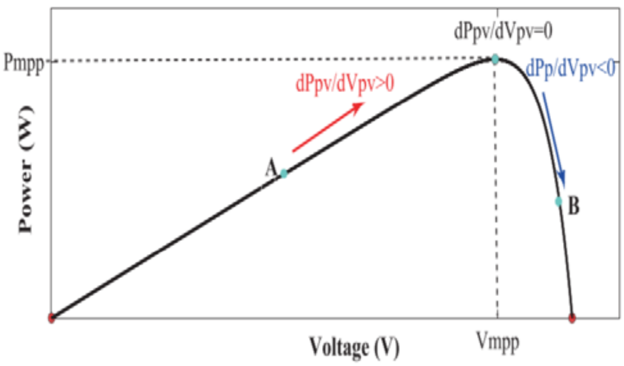

Fig. 7. Basic principle of P&O-MPPT method [20]

Experimental results and discussion

The experimental test bench of a single-phase single-stage grid connected PV system is depicted in Figure 8, which was constructed at the Electrotechnical Laboratory of the National Polytechnic School of Constantine. The prototype consists of several components that are crucial for the verification and validation of the single-phase single stage grid connected PV system, including a solar panel, a power control, a power converter (DC-AC inverter), a transformer, a variable resistive load, a grid and a real-time interface RT-LAB OP5700.

The GALIX JW-G2100 solar panel is the power source for the overall system, with a standard condition power output of 210W.

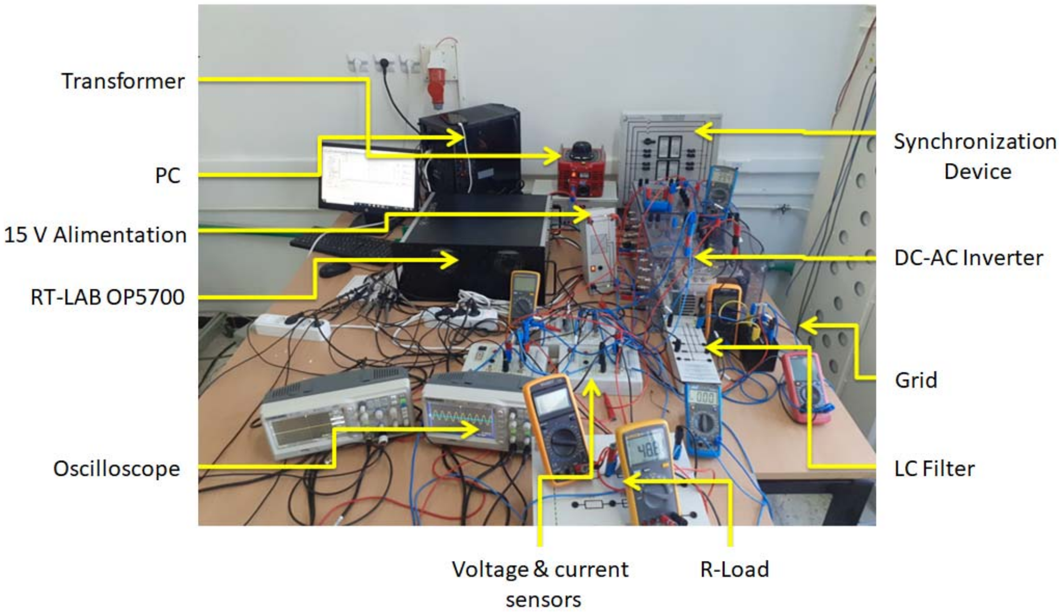

FiG. 8. Experimental test bench of a single-phase single-stage grid connected PV system

The control structure of the single-phase single-stage grid connected PV system have been implemented in Matlab/Simulink and integrated into the real-time interface RT-LAB. The Simulink model is composed of two subsystems: the master subsystem (SM) and the console subsystem (SC). The SM subsystem is responsible for completing the simulation calculation and synchronous communication of the whole control system. On the other hand, the SC subsystem is capable of displaying the voltages, currents, and powers information of the system. The console can be utilized to monitor real-time results, as well as send commands or adjust parameters during the simulation.

Fulfill electrical demands:

Figure 9 contains the current responses of the inverter output due to the change of reference current (fulfill the electrical demands). We notice that when we modify the value of the reference current, the current of the output also varies in the same way. This indicates the efficiency of the current control.

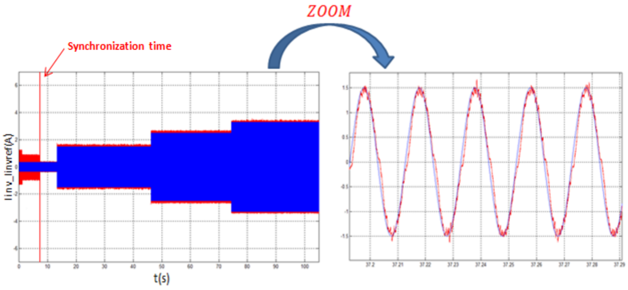

Fig. 9. Inverter current and its reference

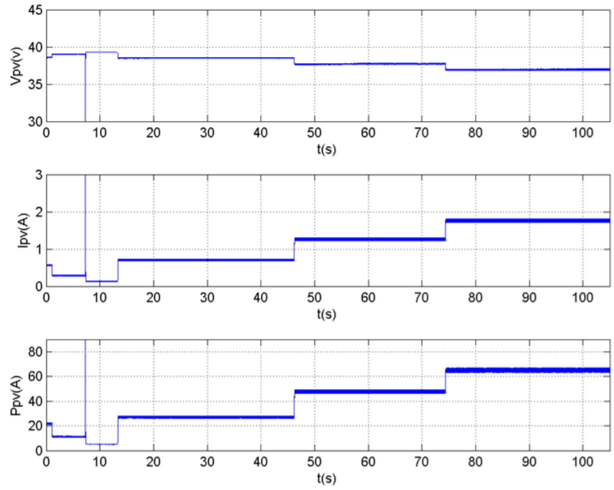

Fig. 10. Voltage, current and power of the PV panel

Figure 10 contains the responses of the current, voltage and power output of the panel due to the change of the reference current. We note that when we modify the value of the reference current, the current of the output panel also changes with the same way.

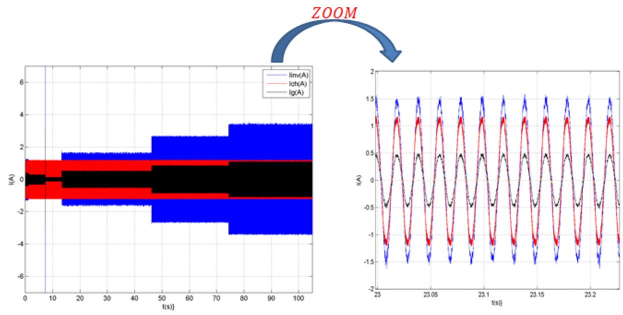

Fig. 11. Inverter, grid and load currents

Figure 11 represents the inverter, grid and load currents. In the case where the inverter current is sufficient for the load, then the excess current is injected into the grid, and from there the inverter current is equal to the sum of the two currents (load and grid currents).

Maximize the power of the PV panel:

Figure 12 shows the change in temperature and irradiation for about 10 minutes and as the duration is short the temperature is almost stable.

Figures 13 and 14 show the variation of PV voltage, current and power during the change of temperature and irradiation.

When the irradiation is 760 w/m2, the voltage is equal to 34.3V and the current 2.95A, so the maximum power is equal to 101.1W (Maximum Power Point), after when the irradiation is reduced to 590 w/ m2 and 350 w/m2 respectively, the optimum PV power is attained in a relatively short time and has a small steady-state oscillation. Figure 15 illustrate the grid voltage after the transformer.

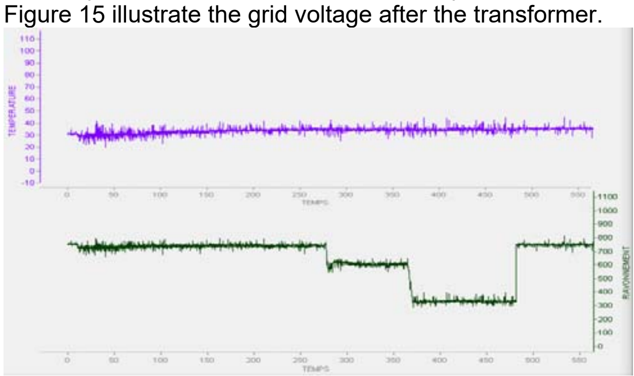

Fig. 12. Temporal evolution of temperature and irradiance levels over a 10-min period

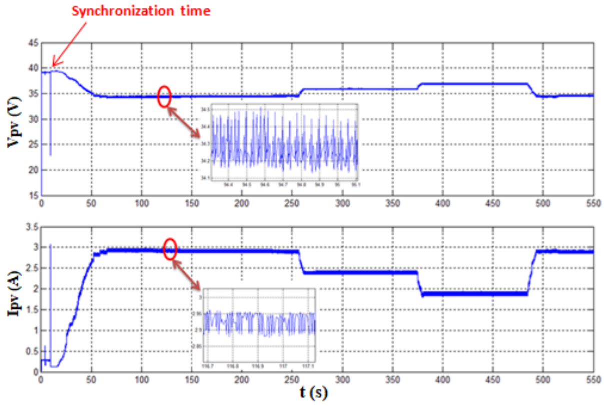

Fig. 13. Voltage and current of the PV panel

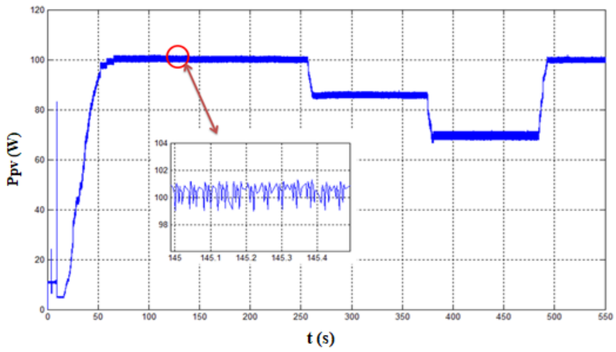

Fig. 14. Power of the PV panel

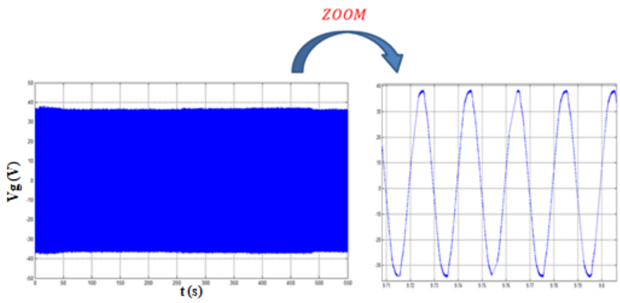

Fig. 15. Grid voltage

Figure 16 represents the inverter, grid and load currents. The Inverter current is greater than the PV current because of the transformer (the power is conserved). In addition, the inverter successfully injects the PV current into the grid.

It has been verified that from experimental results, the whole system is able to track the desired maximum power point under varying irradiation and temperature levels effectively.

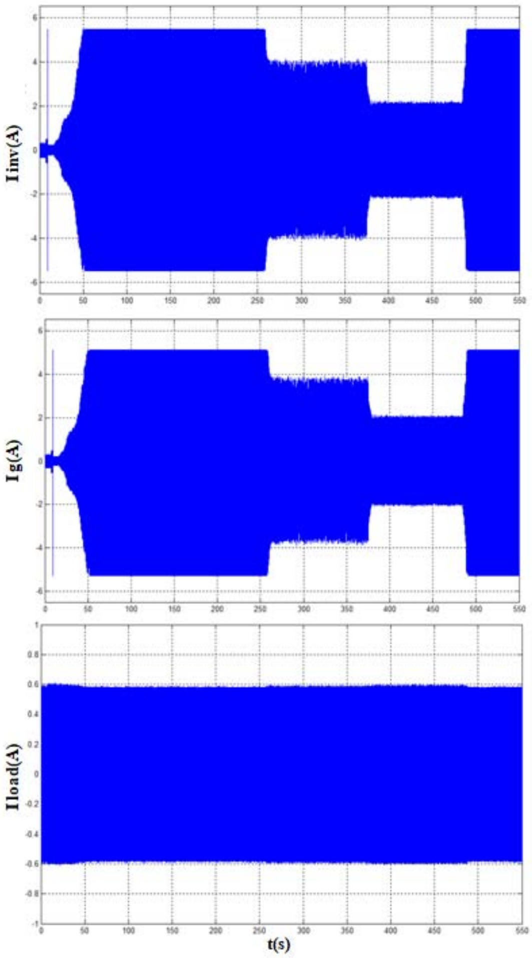

Fig. 16. Inverter, grid and load currents.

Conclusion

The objective of this paper was to validate experimentally a single-phase single-stage grid connected photovoltaic system's performance utilizing the real-time simulator RT-LAB OP5700. The research is structured into two distinct parts: firstly, an introduction to the GALIX JW-G2100 model photovoltaic panel is provided, and secondly, the configuration and implementation of the single-phase single-stage grid-connected PV system in two different topologies are detailed. Experimental results of the photovoltaic system under real atmospheric conditions are presented and discussed. They validate the two cases: fulfill electrical demands and maximize the power output of the PV panel. During about 10 minutes experiment, the power at the PV panel terminals adjusted to changes in temperature and irradiance, and the system converged towards optimal values.

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