Chapter 6
Experimental Work

6.1 Introduction

Energy storage systems used in renewable energy system for storing the energy when renewable power is generated and releasing power when renewable power is not sufficient. BESs provide immediate energy storage in a rechargeable battery. High-performance batteries and battery chargers are necessary for high-efficiency, fast-response, high-power, and high-energy density. In this chapter, the experimental setup along with its components is implemented in renewable energy laboratory, Faculty of Industrial Education, Suez University, Suez, Egypt. This chapter includes two parts; the first part presents the experimental setup of an off-grid PV system, and the second part contains the experimental results and discussion. The experimental study focuses on the effects of using BES with variable irradiation and load profile on the off-grid PV system.

6.2 Experimental Setup of Off-Grid PV System

The main purpose of this research is to develop and investigate the performance of the PV stand-alone systems with energy storage systems. Figure 6.1 illustrates an experimental setup of stand-alone PV system with BES and different loads. In this figure, the PV array is consisting of three modules which are connected to solar charge controller MPPT; the DC/DC converter is controlled with MPPT to maximize the output power with the appropriate output voltage and current of the PV. The battery charger is responsible for charging the battery when the PV is providing power. When the renewable power is not sufficient, the battery releases power to the DC/DC converter for providing a DC link voltage of the DC/AC off-grid inverter. The inverter converter injects the AC power to the AC loads. The components specifications of the experimental setup are listed in Table 6.1.

A. A. Elbaset et al., *Performance Analysis of Photovoltaic Systems with Energy Storage Systems*, https://doi.org/10.1007/978-3-030-20896-7_6

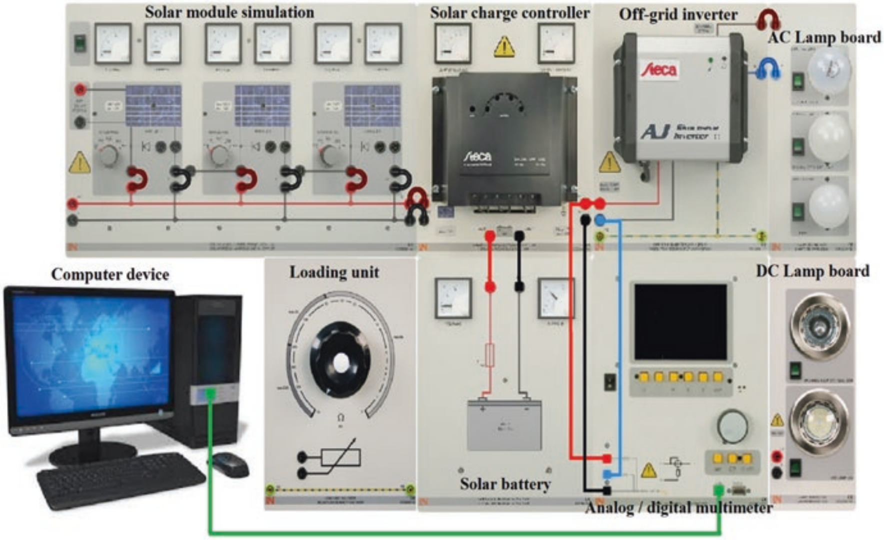


Fig. 6.1 Experimental setup for stand-alone PV system with AC load

Table 6.1 The specification of the experimental stand-alone PV system elements

Component	Rating	
PV modules	Power	3 × 38 W
Solar battery	Type	Lead acid
	Voltage	12 V
	Capacity	12 Ah
Off-grid inverter	Voltage	12 V/230 V
	Frequency	50 Hz
Load unit	Power	500 W
Solar charge controller-MPPT	Voltage	12–24 V
	Current	10 A
DC Lamp board	Voltage	12 V
AC Lamp board	Voltage	230 V

6.2.1 Elements of the Experimental Setup

6.2.1.1 Solar Modules Simulation

Training panel CO3208-1A titled “Solar modules simulation” comprises three independent solar modules as shown in Fig. 6.2. The electrical specifications are as follows:

- Three separate solar modules.
- Each solar module has an adjustable irradiance.

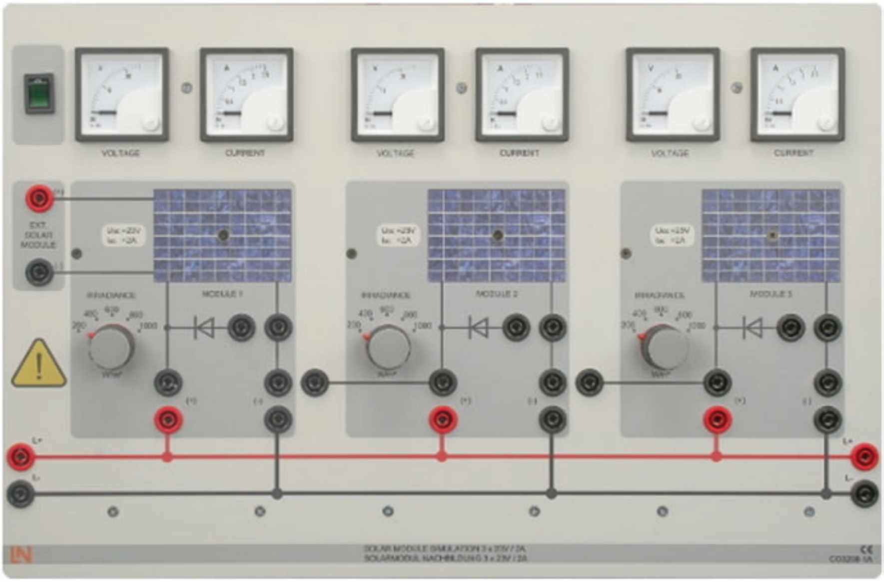


Fig. 6.2 Solar modules simulation

- Each solar module's outputs are protected against short circuit.
- Open-circuit voltage: approximately 23 V
- Short-circuit current: Up to 2A
- Integrated displays of voltage and current
- Operating voltage: 100–240 V and 50/60 Hz

The PV array is composed of three modules that are connected in parallel as shown in Fig. 6.3. For a constant temperature and different solar irradiations (200:1000 W/m^2), the I-V and P-V characteristics of the three PV modules are shown in Figs. 6.4 and 6.5. From Fig. 6.5, it can be easily realized that as the solar irradiation increases, the maximum power generation increases. Similarly, in Fig. 6.4, it is observed that as the solar irradiation increases, the PV module output current increases.

6.2.1.2 Solar Charge Controller-MPPT

Training panel CO3208-1 M titled "Solar charge controller" can be used to charge lead-acid batteries using solar power as illustrated in Fig. 6.6. The electrical specifications are as follows:

- Colored LEDs for indicating operating states.
- Integrated displays for the load connection's voltage and current.
- Deep-discharge protection for the connected battery.

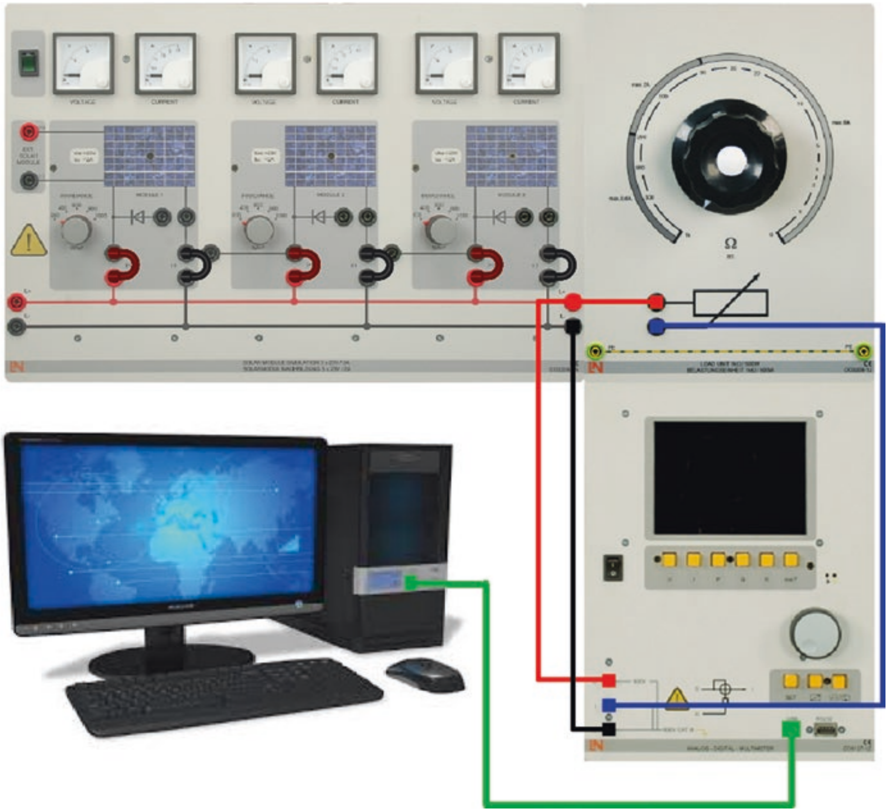


Fig. 6.3 Experimental work for characteristic of PV array (one series and three parallel strings)

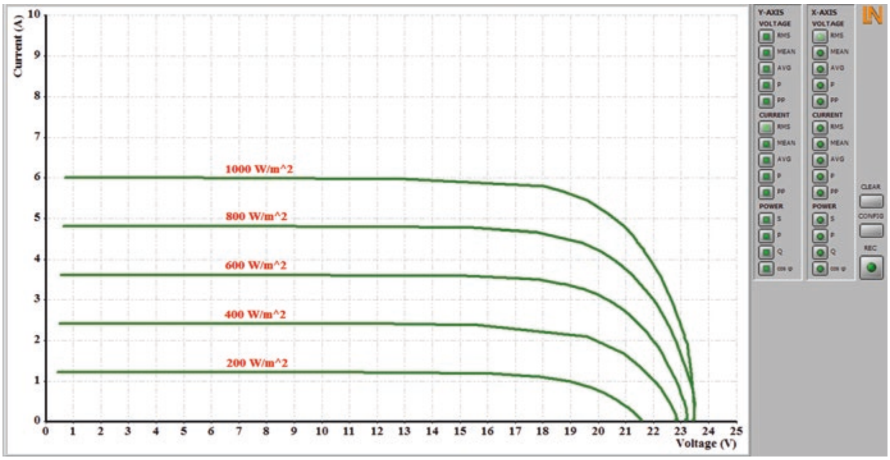


Fig. 6.4 I-V curves of PV array with different solar irradiations

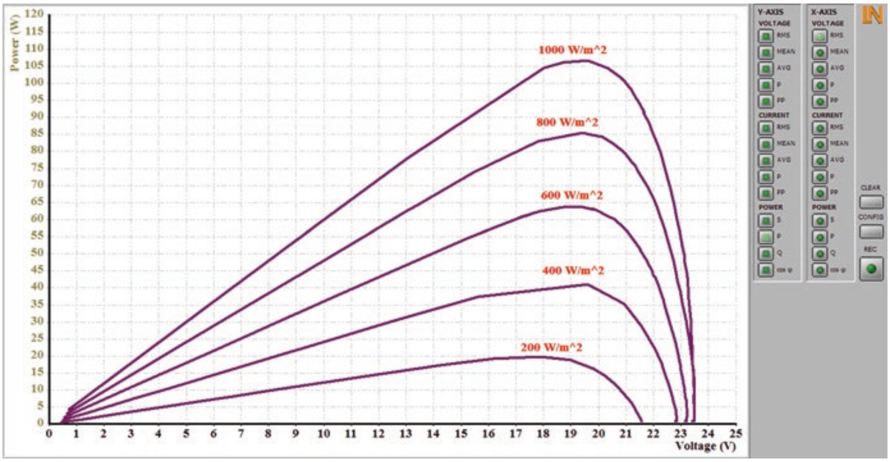


Fig. 6.5 P-V curves of PV array with different solar irradiations

Fig. 6.6 Solar charge controller MPPT

- Overload protection for the connected battery.
- Connect the battery to the charge controller. During start-up, always connect the battery before the solar generator.
- Connect the PV generator to the charge controller. The generator's voltage must not exceed 75 V.
- Connect the load to the charge controller.

6.2.1.3 Off-Grid Inverter

Training panel CO3208-1F titled “Off-grid inverter” contains an inverter for operating a PV system in stand-alone mode as illustrated in Fig. 6.7. The electrical specifications are as follows:

- Inverter (12 V/230 V, 50 Hz)
- Sinusoidal output voltage
- Reverse polarity protection on the DC side
- Deep-discharge protection for batteries

6.2.1.4 Solar Battery

Training panel CO3208-1E titled “Solar battery” contains a lead-acid battery as shown in Fig. 6.8. The electrical specifications are as follows:

- Maintenance-free lead-acid battery (12 V/12 Ah)
- Integrated displays for voltage and current
- Resettable fuse

Fig. 6.7 Off-grid inverter

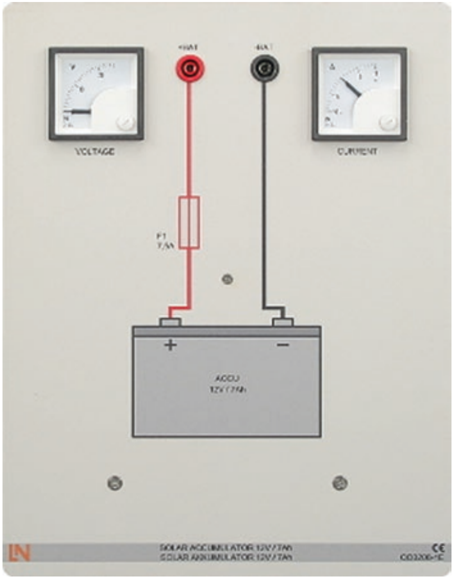


Fig. 6.8 Lead-acid battery

Fig. 6.9 Load unit – 500 W

6.2.1.5 Load Unit: 500 W

Figure 6.9 shows Training panel CO3208-1 J titled "Load unit – 500 W" is used to set various operating points and record characteristics. The electrical specifications are as follows:

- Potentiometer's current-carrying capacity
  - 0 Ω–30 Ω: 6A
  - 30 Ω–200 Ω: 2A
  - 200 Ω–1kΩ: 0.6A
  - Duty cycle 40%

6.2.1.6 Analog-Digital Multimeter

Figure 6.10 shows the analog-digital multimeter possesses USB interfaces for connecting to a PC. The technical data are as follows:

- Supply voltage: 230 V/50 Hz
- Measurement variables: voltage, current, active power, apparent power, reactive power, and cosine φ
- Interfaces: USB

6.2.1.7 DC Lamp Board

Figure 6.11 shows training panel CO3208-1 K titled "Lamp board – 12V" incorporates two 12 V consumers comprising lamps. The electrical specifications are follows:

- Halogen lamp 12 V and Max. 25 W
- LED spotlight 12 V

Fig. 6.10 Analog-digital multimeter

Fig. 6.11 DC lamp board

6.2.1.8 AC Lamp Board

Figure 6.12 illustrated training panel CO3208-1 L that provides three 230 V consumers in the form of lamps. The electrical specifications are as follows:

- LED lamp 230 V and 9 W
- LED lamp 230 V and 6 W
- Energy-saving lamp 230 V and 10 W

6.3 Experimental Results and Discussion

In this section, the experimental results are presented, where the results are divided into three parts as follows: Model 1(without battery)results of the operation of the system without a battery connected with it; Model 2(with battery) results of the operation of the system with a battery connected with it and clarification of the difference between the operating results of the system with and without battery. In the two previous operating cases, the results are obtained with the installation of solar irradiation at 1000 W/m^2; in Model 3 (with battery and changing solar irradiation), the operating results of the system connected to the battery are explained with the change of the solar irradiation and the electrical loads.

Fig. 6.12 AC lamp board

6.3.1 Model 1: Experimental Results of the System Without Battery

The PV array is composed of three modules that are connected in parallel as shown in Fig. 6.3. The following Table 6.2 presents the electrical specification of each module. The operation of Model 1 is based on the three electrical loads (10 W, 6 W, and 9 W) that are connected to the PV system in an increasing manner as shown in Fig. 6.13. In this subsection, the operating results of experimental work for the PV system without a connected battery are reviewed. The solar irradiation value applied to the three models is fixed at (1000 W/m^2). The three PV modules are connected together in parallel to have a maximum output power of 106 W.

The operating results of experimental work for Model 1 are shown in the following figures where the current, voltage, and power values are displayed for the output of the PV modules, solar charge controller, and off-grid inverter. These results were recorded using a single measuring device with a change in its terminals to the places to be measured, so there are some slight differences in the entry and exit of loads due to repeated experiment three times in the same scenario.

Figure 6.14 illustrates the results of Model 1. The PV output of voltage (V_{PV}), current (I_{PV}), and power (P_{PV}) are shown in Fig. 6.14, where the change of loads

Table 6.2 Electrical specification of PV modules

Parameters	Symbol	Value
Rated power for one module	$P_{PV-module}$	35.2 W
Short-circuit current	I_{OC}	2 A
Open-circuit voltage	V_{SC}	23 V
Maximum power for array	P_{max}	106 W
Voltage at maximum power point	V_{mpp}	19.6 V
Current at maximum power point	I_{mpp}	1.8 A

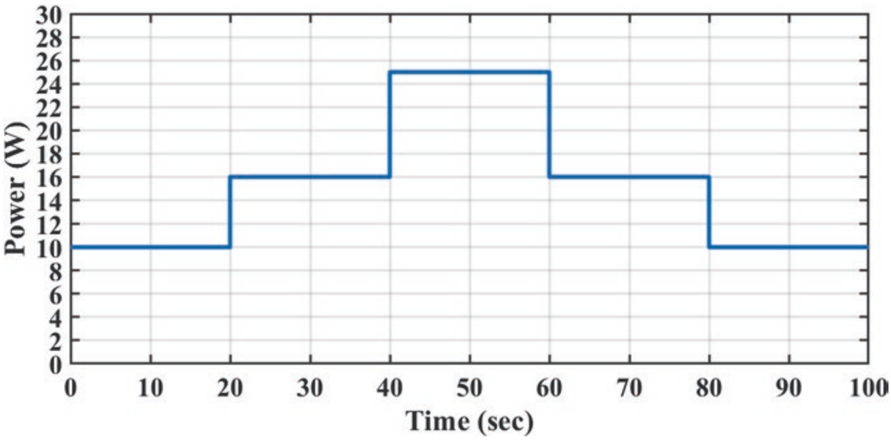


Fig. 6.13 Variable load profile for Model 1

profile is an effect on PV voltage and its value decreases as the load increases. Changes in the PV output voltage did not appear on the output voltage of the charger controller (V_{dc}), to remain stable at 14 V as shown in Fig. 6.15, thus maximizing the required load power (P_{Load}), of only 25 W. Figure 6.16 shows the voltage(V_{ac-rms}), current (I_{ac-rms}), and output power ($S-P-Q$) of the off-grid inverter or the terminals of the electric AC loads. The DC voltage from charge controller was converted from 14 V_{dc} to 225 V_{ac-rms} using the inverter to suit the electrical AC loads.

6.3.2 Model2: Experimental Results of the System with Battery

The operation of Model 2 is based on three electrical AC loads (10 W, 6 W, and 9 W) and one electrical DC load (25 W) that are connected to the PV system in an increasing manner as shown in Fig. 6.17. The difference is that in Model 2 the battery is connected to the system for study its effect on the whole system and to explain differences from Model 1. Figure 6.18 illustrates the results of Model 1. The PV output of voltage (V_{PV}), current (I_{PV}), and power (P_{PV}) is shown in Fig. 6.18. The power generated from the PV modules is greater than the power of the loads demand

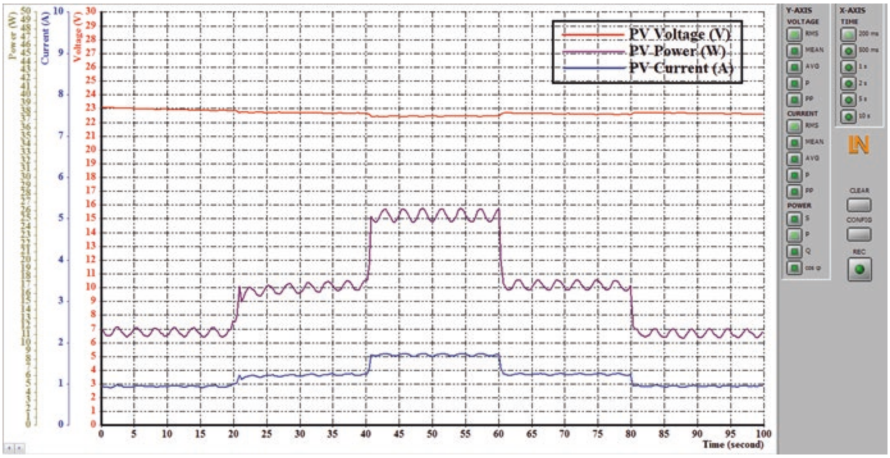


Fig. 6.14 PV output voltage, power, and current without battery

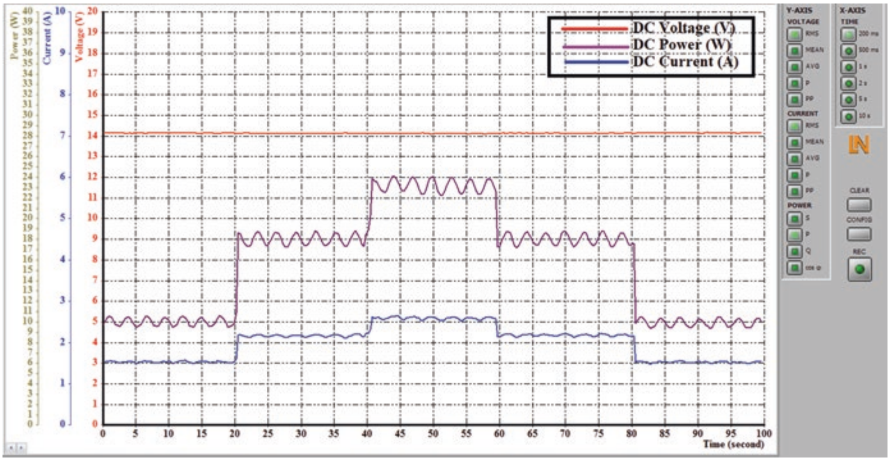


Fig. 6.15 Solar charge controller output voltage, power, and current without battery

because there is a battery connected to the system and is in charge. In Fig. 6.19, changes in DC current (I_{dc}) and DC power (P_{dc}) are consistent with loads changes. Figure 6.20 shows the voltage (V_{ac-rms}), current (I_{ac-rms}), and output power ($S-P-Q$) of the off-grid inverter. When using a battery, it has improved the active power of load as well as reduced the fluctuations in the voltage and current.

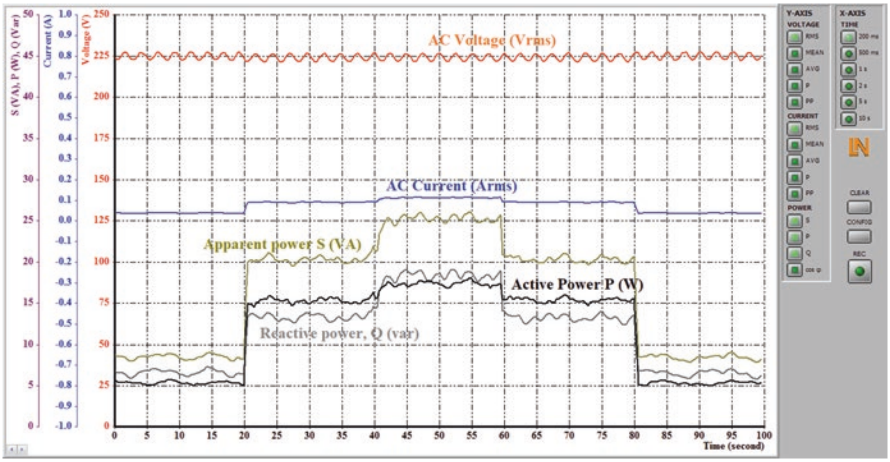


Fig. 6.16 Inverter output voltage, power, and current without battery

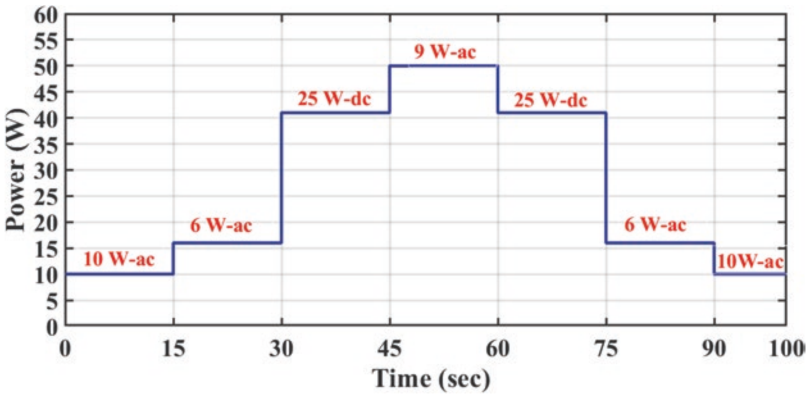


Fig. 6.17 Variable load profile for Model 2

6.3.3 Model 3: Experimental Results of the System Connected to Battery and Changing Solar Irradiation

Model 3 studies the effect of batteries on PV systems in the case of changes in loads profile and solar irradiation that applied to PV modules. Figure 6.21 shows the change in solar irradiation (from 200 to 1000 W/m^2) where it increases by 200 W/m^2 every 15 seconds, until the irradiation reaches 1000 W/m^2 and drops back to 200 W/m^2 in the same time periods. The operation of Model 3 is based on the three electrical AC loads (10 W, 6 W, and 9 W) that are connected to the PV system in an increasing manner as shown in Fig. 6.22.

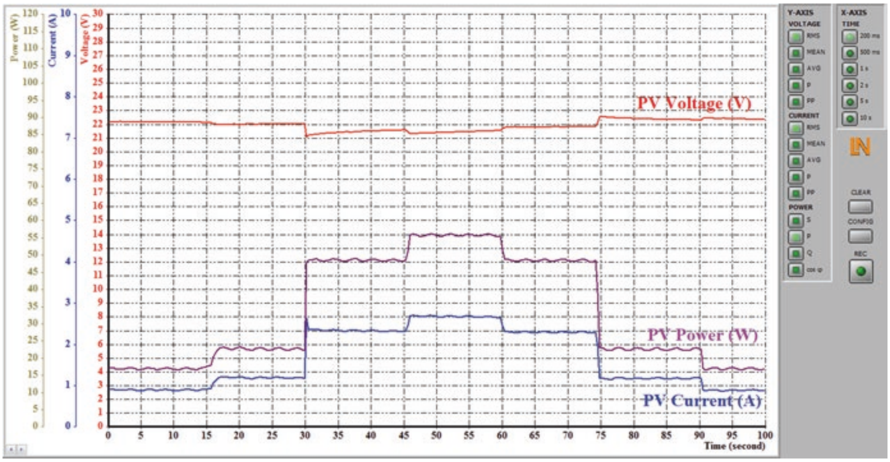


Fig. 6.18 PV output voltage, power, and current with battery

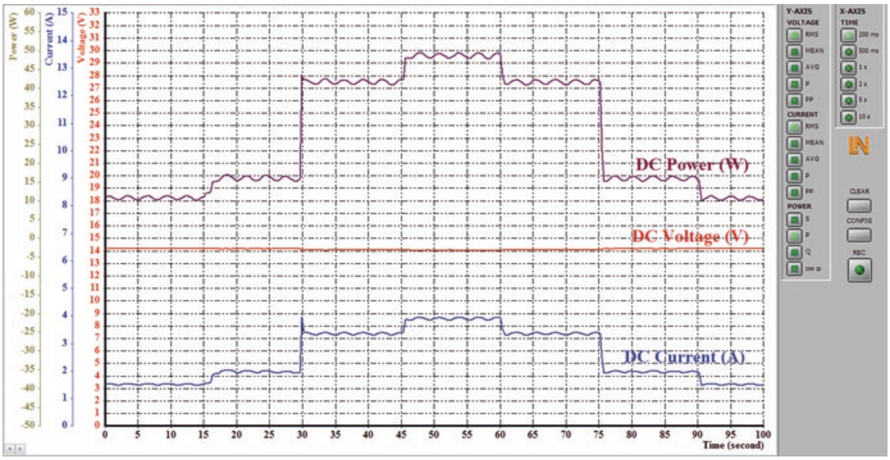


Fig. 6.19 Solar charge controller output voltage, power, and current with battery

Figure 6.23 shows the experimental results of Model 3, which consists of a PV system with a battery connected to it. The results of the experiment are obtained when the solar irradiation was changed and showed an effect on output voltage from PV as shown in Fig. 6.23. The PV output current (I_{PV}), and power (P_{PV}) are changed according to the change of the load profile from entry and exit loads. Figure 6.24 illustrates the output signal from solar charge controller; note that the voltage signal value is stable at 14 V due to battery and charge controller. The current starts at 1.5 A and the power value of 10 W at the start of operation of the experiment, and at the largest electric load, the current increases to 2.5 A and power 25 W. Figure 6.25 shows the signals on the terminals of the electric loads, voltage (V_{ac-rms}), current

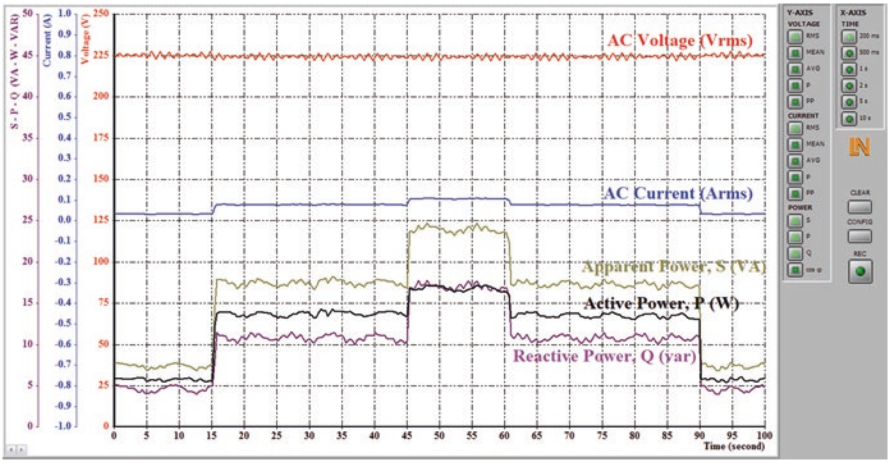


Fig. 6.20 Inverter output voltage, power, and current with battery

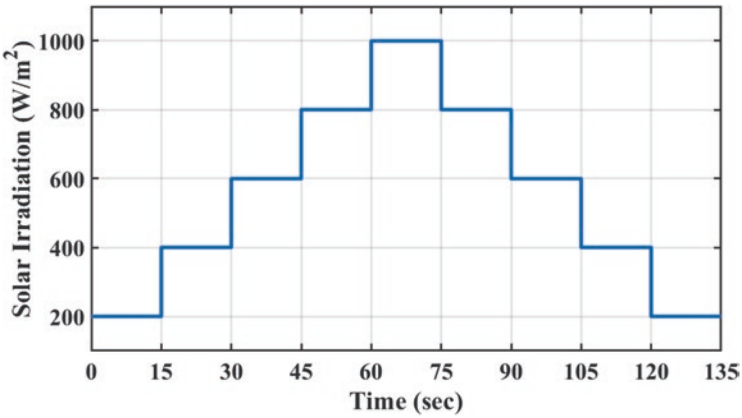


Fig. 6.21 Variable solar irradiation for Model 3

(I_{ac-rms}), apparent power (S), active power (P), and reactive power (Q). Changes in AC current and powers are shown as a result of the enter and exit of electrical loads to adjust the output of the off-grid inverter according to the required load power and to maintain the constant voltage value at 225 V_{rms}.

Figure 6.26 presents the AC voltage and current waveform at enter and exit load. Figure 6.26a shows that when the load power increases, the current increases and the voltage decreases, and voltage then returns to settle again. The reverse occurs in Fig. 6.26b when an electric current is switched off, the current value decreases, and the voltage increases instantaneous value and then returns to settle again.

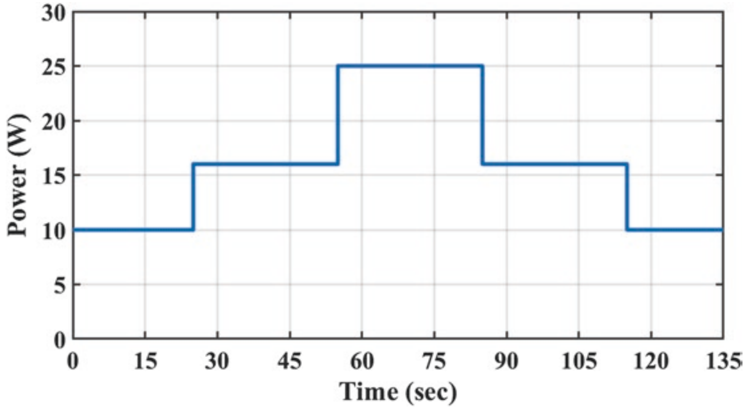


Fig. 6.22 Variable load profile for Model 3

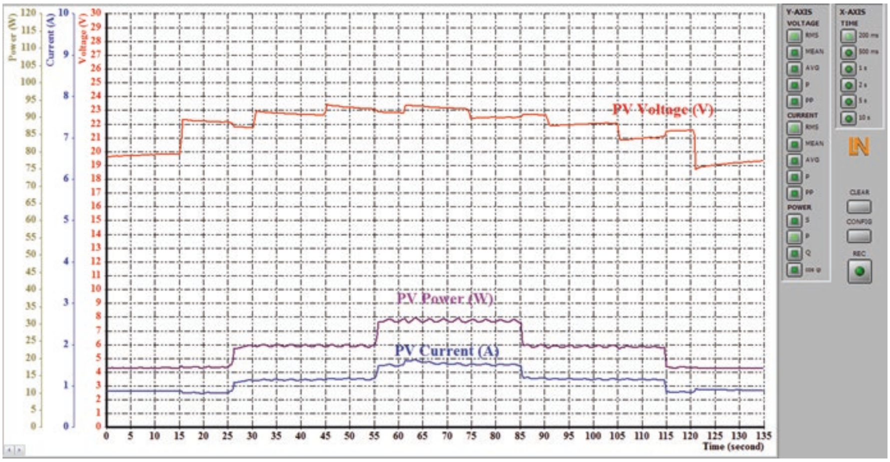


Fig. 6.23 PV output voltage, power, and current with battery and changing solar irradiation

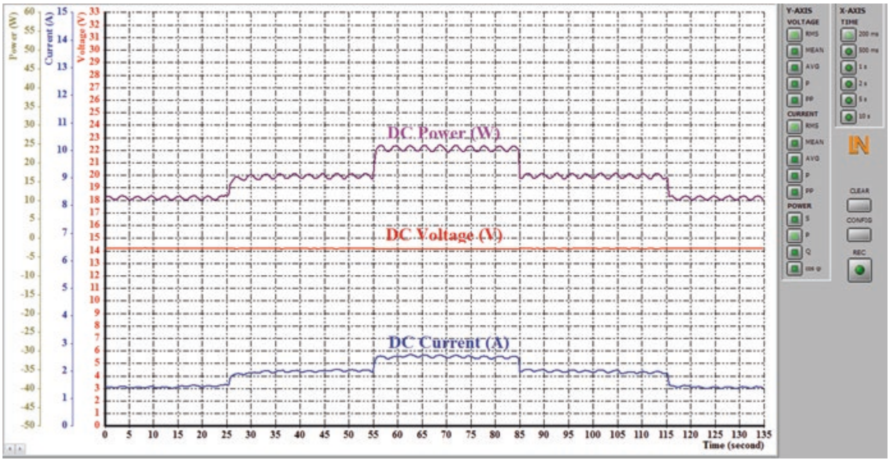


Fig. 6.24 Solar charge controller output voltage, power, and current with battery and changing solar irradiation

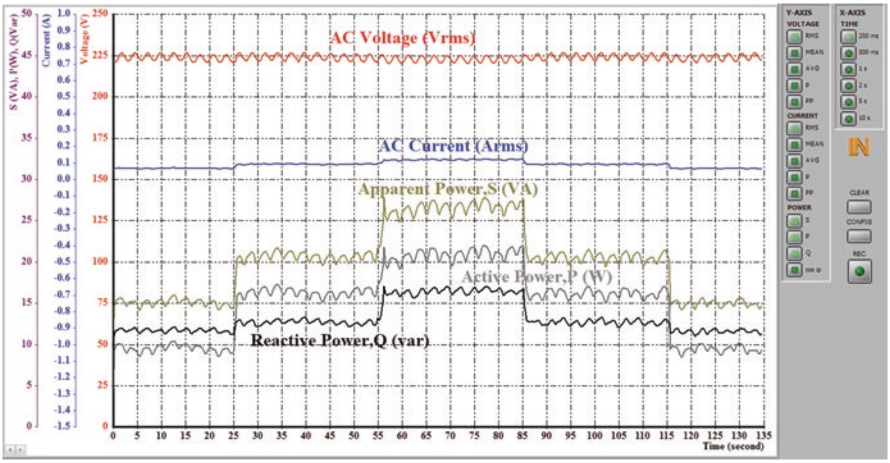
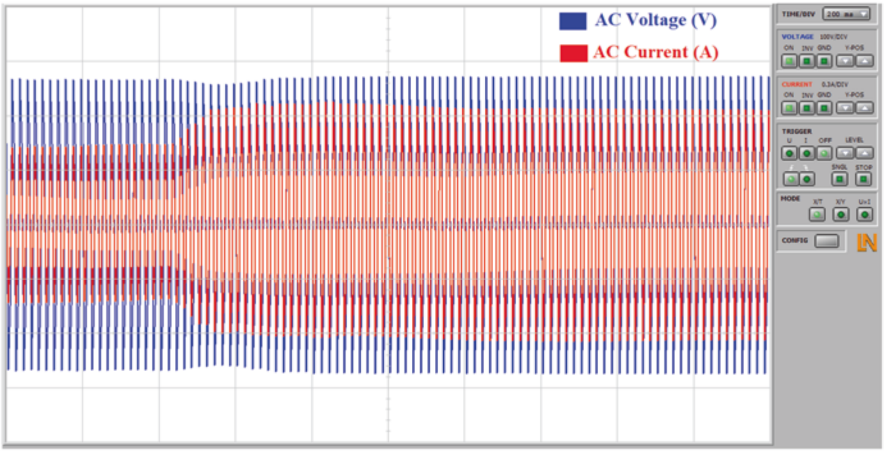
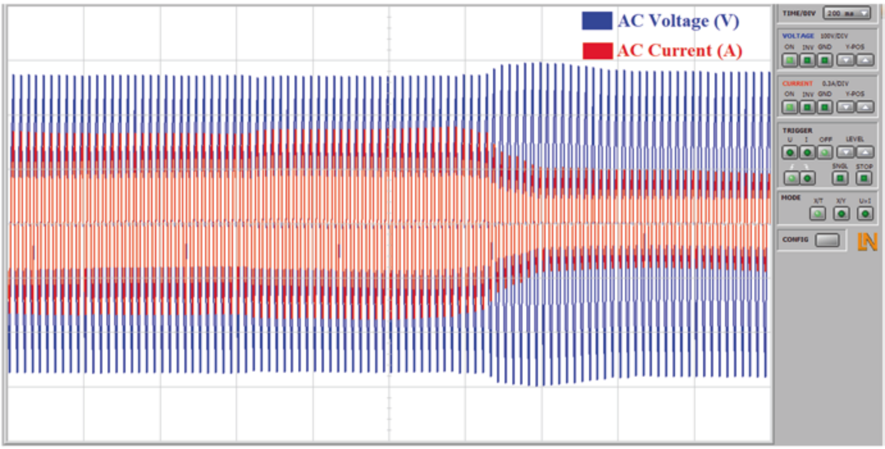


Fig. 6.25 Inverter output voltage, power, and current with battery and changing solar irradiation



(a)



(b)

Fig. 6.26 Oscilloscope measure of AC voltage and current at enter and exit a sudden load. (**a**) AC voltage and current at enter a sudden load. (**b**) AC voltage and current at exit a sudden load