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Smart Switching Power Supply System for Evaporative Air Coolers

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ABSTRACT

The energy consumption by residential air conditioners could cost about half of the total energy consumption of the building. A combination of conventional and renewable energy is still an emerging technology. Therefore, using solar photovoltaic panels to provide electricity to the air conditioner is a substantial application. This research shows the possibility of using photovoltaic panels as a power source for air conditioners in a sequence exchange with the conventional grid. A smart switching system has been offered to organize the power supply between the grid and solar panels. The photovoltaic panels have been connected to the conditioner across a power inverter module for adopting a reliable and accurate quantity of power supply to the conditioner unit. The smart switching system provides an intelligent connection between the solar power source and the grid, ensuring an uninterrupted electricity supply between the two power sources.

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1. Introduction

The demand for electrical energy has increased exponentially over the past few years. Electrical energy generation is mainly based on fossil fuels which contribute to an increase in greenhouse gases. Nowadays, renewable energy has received more attention, as well as their applications are significantly increased. Renewable energy, such as solar and wind energy sources, could be grid-connected power systems [1, 2]. Hybrid energy systems that generate electricity contain two or more power sources, usually one of them is renewable. Most renewable power generation system needs an energy storage device to guarantee continuous power supply. Ren *et al*. [3] offered a grid-connected hybrid energy supply system that includes a photovoltaic module, a fuel cell, and a storage battery for residential applications. They presented an optimization model to guarantee reliable system operation and to define the optimal running strategies for annual running costs and CO_2 emissions. Therefore, an automated switching mode for multiple power supply systems is essential to provide uninterrupted power to the load. Onipede *et al*. [4] designed and constructed an automatic changeover to switch on a standby generator when the power failure from the mains supply and vice versa when the power is restored. Hassan *et al*. [5] designed and implemented an automatic power supply to control four sources. The authors employed the grid power source to simulate solar, wind, mains, and thermal sources. They used a step-down transformer that converts 230V to 12V AC and a bridge rectifier to convert the alternating current into a direct current. Also, they used four push-button switches to represent a failure of a particular power source. When a push button switch is pressed, that means the absence of this source; the microcontroller sends a signal to take power from another source. Mahesh *et al*. [6] presented a similar idea, showing auto supply switching from four power sources. They offered a design of an embedded circuit to auto-change to another source when the main supply fails.

Krishna *et al*. [7] combined renewable and non-renewable energy sources (such as mains, solar, battery, and adapter) to get a continuous power supply to the load. They used the microcontroller to keep sensing the whole available sources. The microcontroller shifts the load to the other supply source if any source is switched off. This action can be done when the relay driver receives a signal from the microcontroller, and consequently, the relay drive switches on the appropriate load relay. The same switching control technique mentioned previously in Ref. [7] has been followed by Dayana [8] and Ananth *et al*. [9]. They found that the presented auto control power supply system is reliable, effective, and efficient. The same control technique has been repeated by Sampson *et al*. [10] and Muneer *et al*. [11]. Aziz *et al*. presented a dispatch strategy to control switching between different energy sources [12].

Three different control strategies have been proposed in this study for a photovoltaic, diesel, and battery hybrid energy system. They examined the feasibility of load following, cycle charging, and combined dispatch strategies. The study found that minimum battery state of charge, variation of solar radiation, and load growth, affect the system's performance. Soudan and Darya [13] proposed several algorithms for dispatch in a hybrid PV-Diesel-Battery power system. The algorithms use weather forecasts to predict cloud shading at the PV site. A switching schedule has been established to activate the backup of the battery and generator for the continuity of the power supply. The authors concluded that the proposed algorithms reduced generator cycling frequency by an average of 97%.

An experimental study has been conducted on a 3.52 kW cooling capacity inverter heat pump connected to a photovoltaic solar power source and a conventional grid source [14]. This study focused on the analysis of heat pump operation. Three PV panels with 230 W power output each have been connected in parallel to deliver electric power at 24V. Measured data were collected to evaluate electrical power consumption from the grid and the photovoltaic panels. The study showed that during summer, the solar contribution of PV power is about 65%. Bulut *et al*. [15] experimentally investigated the off-grid PV power supply system to analyze the performance of a split air conditioner. The power system comprises PV panels, batteries, a charge regulator, and an inverter. They observed that charging time gets longer when solar radiation is low, and discharging time becomes shorter when the outdoor air temperature is high. Tarigan [16] reported the performance of a small split air conditioner (372.85 watts) under a hot tropical climate. The conditioner is powered by a grid-tied photovoltaic system with 1200W max input power. It was found from the study that about 80% of power could be supplied from the PV system. A solar on-grid air conditioning system has also been reported by Aguilar *et al*. [17]. The authors presented a computational model for simulating the behavior of a photovoltaic-assisted heat pump at different operating conditions. They found that the severity of the climatic region increases the costs and the PV power used to drive the AC unit. More recently, a review article has been offered by Alsagri [18] to report a literature survey on PV-powered cooling cycles. This paper demonstrates that the evaluation criteria of PV-powered cooling cycles are based on exergy destruction, efficiency, and coefficient of performance of the cycles. The author showed that using PV technologies has a great potential to supply cooling demand, especially in hot climate conditions.

Most researchers used the grid power line from the above literature to simulate the PV power source. Therefore the variation in solar radiation intensity has been ignored. Also, the control technique used for automatic switching has almost the same. In addition, more information about the switching time from one power source to another must be provided. The main idea of the research is to save the power consumption by the grid during the sunshine period by using solar power without resorting the storage batteries. Thus, this research aims to design and implement a smart automated switching system between solar power and conventional grid for safely running the air conditioning unit. The control strategy has been built on a smart selection of the power source and the swift transition to the source that gives sufficient power.

2. Materials and Components

The main components of the proposed control system can be seen in Fig. (**1**).

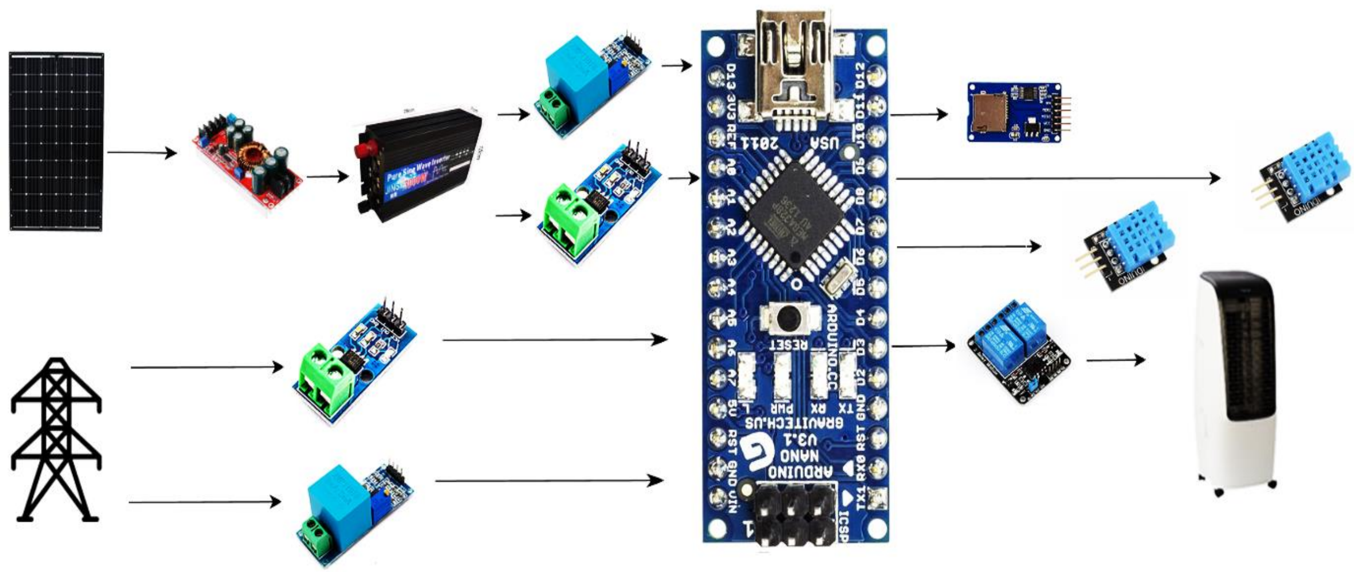

Figure 1: Main components of the control system.

2.1. Air Cooler

The air conditioning unit is a Homix multi-functional evaporative air cooler. It produces a comfortable, cool breeze with the natural process of water evaporation fabricated in a compact package. The unit has an adjustable humidification knob for faster cooling and a high four-speed blower. The power needed for running the unit is 110W at 220V-240V with a frequency of 60Hz.

2.2. Solar Panels

As shown in Fig. (**2**), High-Quality Monocrystalline Solar Panels with a max capacity of 150W have been utilized. The technical specifications of solar panels are presented in Table **1**. Two panels have been connected in series to supply sufficient power to the air cooler.

Figure 2: Solar panel.

Table 1: Specifications of solar panels.

Maximum Power (P_{max})	150 W
Voltage at Pmax (V_{mp})	18.62 V
Current at Pmax (I_{mp})	8.06 A
Open circuit voltage (V_{oc})	22.33 V
Short circuit current (I_{sc})	8.53 A
Nominal Operating Cell Temp	45±2 °C
Weight	12 kg
Dimensions	1480X670X35 mm

2.2.1. Sizing of PV Array

The sizing of PV system can be performed as [19]:

I. Load Estimation:

The total energy required for the system (E_{total}) = No. of units × rating of equipment

Total daily energy in Watt-hours (E_{daily}) = Total energy required (watts) × Operating hours per day

The total daily energy could be divided by the efficiencies of the system components ($\eta_{overall}$) to avoid under-sizing the system. The required daily energy from the solar array ($E_{required}$) is:

$$E_{required} = \frac{E_{daily}}{\eta_{overall}} \tag{1}$$

The peak power (P_{eak}) can be calculated as:

$$P_{peak} = \frac{E_{required}}{daily\ peak\ sunshine\ hours} \tag{2}$$

The date for the Khobar region of daily peak sunshine hours is given as 5.32 peak sun hours.

II. The Total Current Needed (I_{DC}) can be Calculated as:

$$I_{DC} = \frac{P_{peak}}{V_{DC}} \tag{3}$$

Where: V_{DC} is the system DC voltage

III. For series connection, the number of solar panels required (N_s) is:

$$N_s = \frac{V_{DC}}{V_{rated}} \tag{4}$$

Where: V_{rated} is the rated voltage of each module.

2.3. DC-DC Boost Converter (Step-up Converter)

The PV module has been joined to a DC/DC boost converter regulator, shown in Fig. (**3**). The boost converter is used to "step up" the input voltage to some higher value required by a load. This capability is achieved by storing energy in an inductor and releasing it to the load at a higher voltage. It can be adjusted to a desired voltage through the output voltage terminal, which in our case, is adjusted to be 48V as the output voltage. The specifications of the boost converter are presented in Table **2**.

Figure 3: Boost converter.

Table 2: Specifications of boost converter.

Input voltage DC	8-60V
Input current	0.5-20A
Output voltage DC	12-80V continuously adjustable
Output current	20A MAX
Conversion efficiency	92%~97%
Module dimensions	116x52x15mm (L x W x H).

2.4. DC-AC Inverter

A high-efficiency pure sinewave power inverter has been used to transmit the direct input current from the solar module into an output alternating current. The inverter has multiple protection functions, such as input low/high voltage shutdown protection, overload protection, and reverse input protection. Also, the AC output frequency from the inverter is more accurate and stable. The specifications of the inverter can be found in Table **3**.

Table 3: Specifications of DC-AC power inverter.

Maximum Power (P_{max})	Up to 3000W
Continuous Output Power	1500W
Output voltage	220-240V
Input voltage	48V
Output current	10A
Frequency	60 Hz
Inverter efficiency	Up to 95%

2.4.1. Inverter Sizing

The primary function of the inverter is to convert power from DC to AC power; therefore, the conversion power depends on inverter efficiency (η_{Inv}). Then, the AC power output from the inverter (P_{Inv}) can be calculated as:

$$P_{Inv} = P_{input} \times \eta_{Inv} \tag{5}$$

Where: P_{input} is the DC input power to the inverter

The rating power of an inverter should not be less than the total power consumption by the load, where the delivered power by the inverter (P_{Inv}) could be considered 1.25 times the peak load [19]. Then, the inverter rating power ($P_{Rat-Inv}$) is given as:

$$P_{Rat-Inv} = \frac{P_{Inv}}{PF} \tag{6}$$

Where: *PF* is the power factor taken as 0.8 for home appliances.

2.5. Double Channel Relay Module

A dual-channel relay module has been employed to receive the solar and grid power supply. Each channel of the module consists of 3 terminals which are NO (Normally opened), NC (Normally closed), and COM (Common). The grid power supply line has been connected to the relay module as a default power supply on the startup. In contrast, the solar power supply line is activated when receiving a signal from the microcontroller. The other side of the relay module has been connected to the microcontroller.

2.6. Arduino UNO Microcontroller

Arduino UNO has been used to manage the smart switching control system. The microchips that build into the Arduino are based on an ATmega328p boot loader that can communicate with the devices. The Arduino board has 12 Digital Input/Output pins. Analog input pins can communicate with the devices that send analog signals, such as voltage and current sensors. The program code has been developed in the Arduino IDE software. This code includes the definition of variables used, such as the current and voltages of both sides of power sources and the setup of the switching conditions. The specifications of the Arduino microcontroller are shown in Table **4**.

Table 4: Specifications of Arduino microcontroller.

Operating Voltage	5V
Input voltage	7V-12V
Voltage limit	6V-20V
DC Current per I/O	20mA
DC current for 3.3V	50mA

2.7. AC Current and AC Voltage Sensors

Allegro ACS712 (20A) AC current sensor and ZMPT101B AC voltage sensor have been used to measure each power source's current and voltage. The sensors send the analog signals to the microcontroller since it can decide which of the two power sources gives the required power to run the conditioner. The current sensor has a 5V DC power supply, measuring the alternating current up to 20A, with 100 mV/A output sensitivity. The voltage sensor is a compact single-phase high, accuracy AC voltage sensor module; it can measure within 250V, with a permissible error of ±0.2%, which can be adjusted according to the analog output quantity.

2.8. Temperature and Humidity Sensor

DHT11 Temperature and Humidity sensors have been chosen to measure the condition of air at the inlet and outlet from the air cooler. The sensor contains a capacitive humidity sensor and a thermistor to measure the surrounding air. The working voltage range of the sensor is DC 3.5V-5V with a temperature range of 0-50°C (±1℃ accuracy) and humidity measuring range of 20%-95% with ±4% accuracy.

2.9. Measuring Equipment

The solar radiation intensity has been measured via a SEAWARD Solar Irradiance Meter with an irradiance range of 100-1250 W/m^2 and a resolution of 1 W/m^2. The meter has a built-in inclinometer to measure the pitch, a compass to measure roof orientation (0° to 360°), and a thermometer with 1°C resolution to measure ambient air within the range of -30°C to +125°C.

An EXTECH 380942 AC/DC clamp meter has been used to measure and check the values of AC and DC current and voltage around the control circuit and measure the power delivered from the two sources. The meter has an AC voltage accuracy of ±2% and an AC accuracy is ±1.5%.

2.10. Micro SD Card

A Micro SD card was used to collect and store the data through which high-capacity data can be stored. The SD card has been connected to the Arduino via the Serial Peripheral Interface communication protocol.

3. System Operation

The control strategy of the proposed smart and swift switching system can be offered, as illustrated in Fig. (**4**).

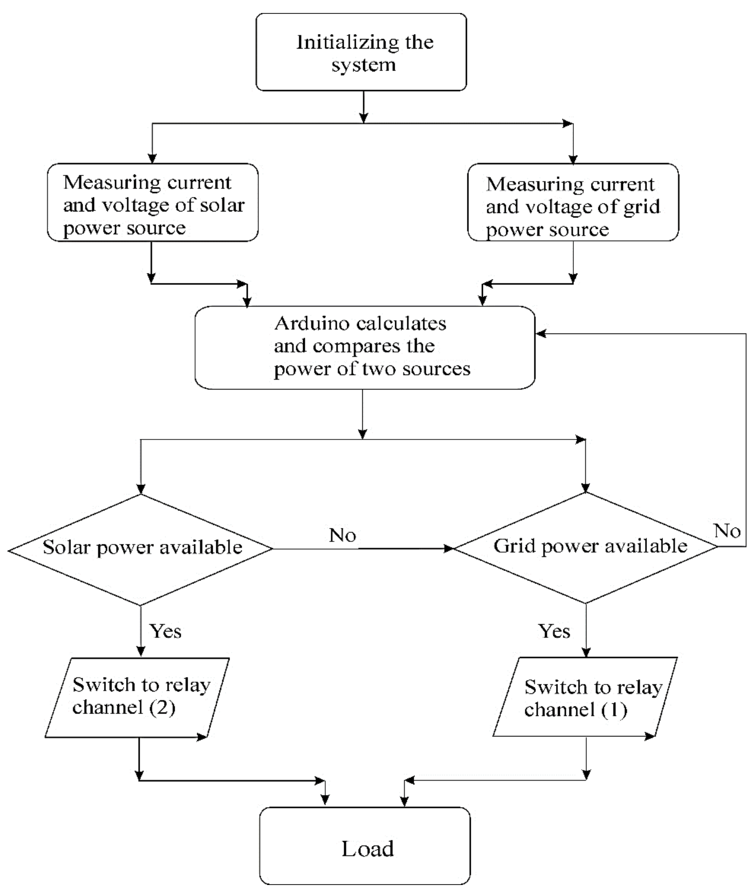

Figure 4: Flow chart of control strategy for switching system.

At the startup of the air conditioner, the grid power supply is always used to accommodate the impact of the startup current. Then the controller monitors the current and voltage values of both PV and grid sources. The controller calculates the power output from both sides and compares their values. Suppose the power delivered by the solar power system is sufficient for running the conditioner. In that case, the microcontroller generates an output signal to the relay driver for switching the solar system's power. In case of a low energy supply from the solar system, the controller will automatically return to the grid power.

4. Circuit Diagram

The proposed control circuit to switch between the PV power source and the grid is shown in Fig. (**5**). The grid source is connected to channel 1 in the dual channel relay module since the alternating current and voltage are measured via current and voltage sensors. The power output from the solar system passes through a boost converter to ensure a steady output of voltage provided to the inverter. The current and voltage delivered by the inverter is measured, and then the PV power source is transmitted to channel 2 in the dual-channel relay, which is normally closed. The microcontroller collects the data and decides which source will be activated. Temperature and humidity sensors have been employed to measure the inlet and outlet air conditions passing through the air cooler to determine its performance.

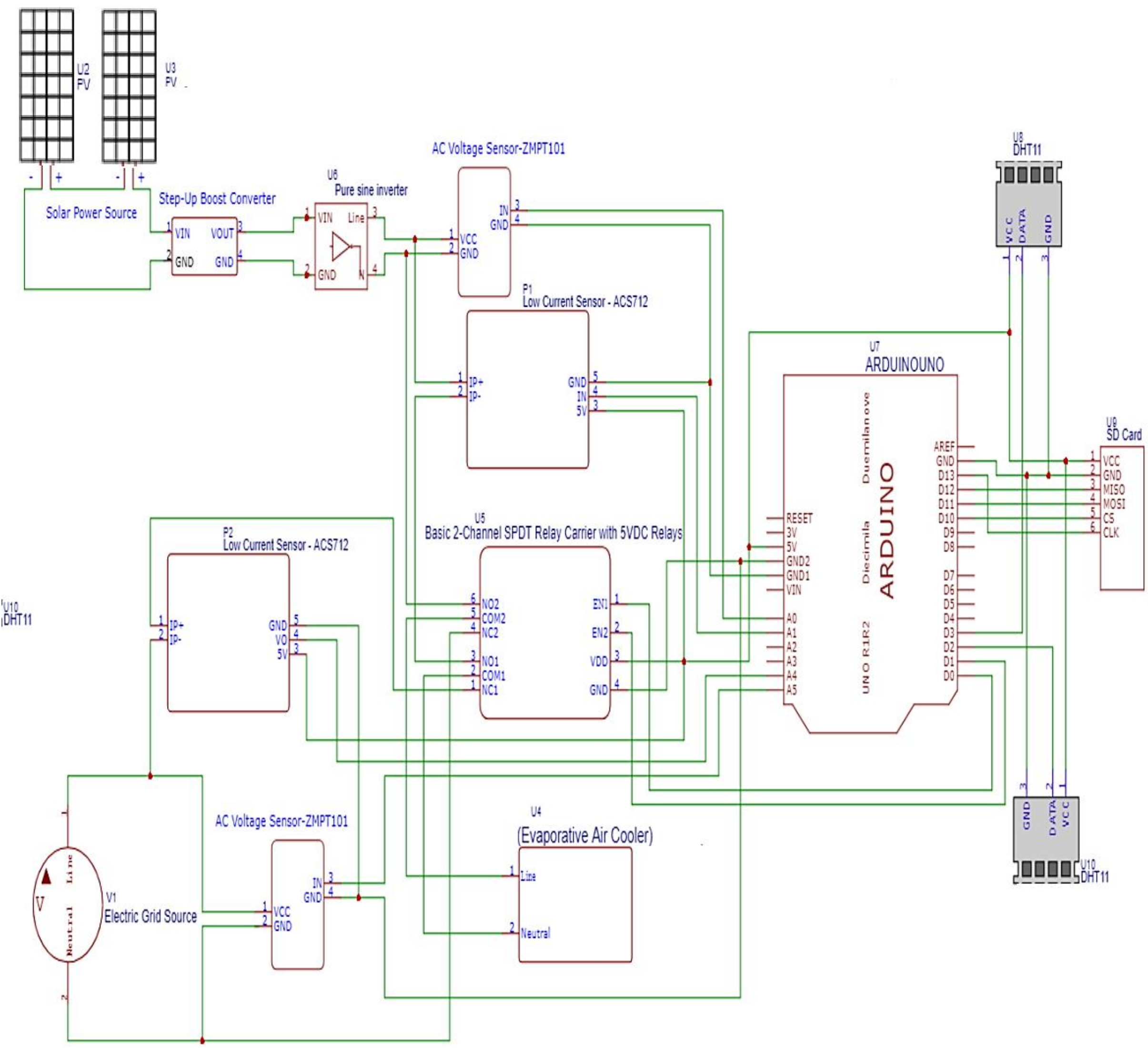

Figure 5: Control circuit diagram for switching system.

5. Results and Discussion

At the beginning of the experiments, the PV solar module was tested to evaluate the productivity of the electrical power. Fig. (**6**) shows the values of electric power the PV module delivers at different solar radiation intensities. It is seen that max power is achieved at 1000 W/m^2 solar irradiance. However, less than 500 W/m^2 of solar irradiance produces insufficient power to run the air conditioner.

The effect of the inverter's transition from DC to AC power has been offered in Fig. (**7**). In this figure, the electric power of the PV module has been plotted versus the power output from the inverter at various times. It is seen in this figure that about 15% of power loss is registered during the transition process.

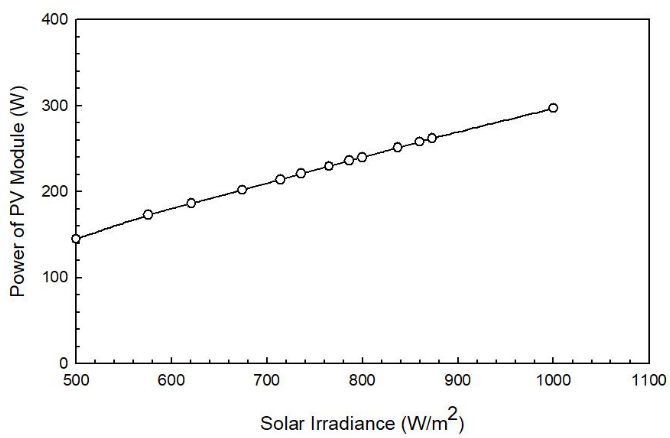

Figure 6: Power delivered by the PV module.

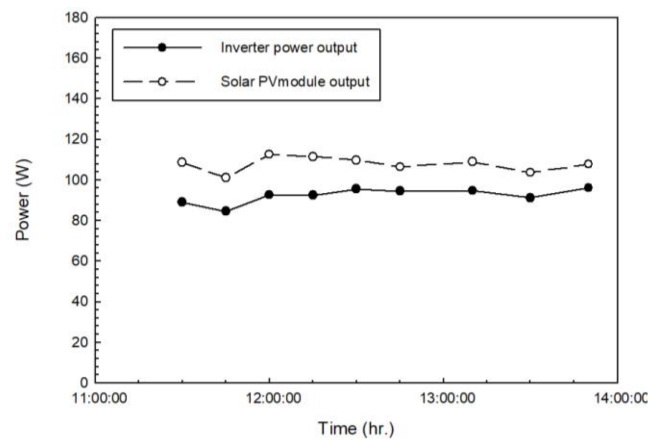

Figure 7: Power output from PV module and inverter.r

To check the validity of the results, the rated power output from the inverter has been compared with the grid power. The comparison, shown in Fig. (**8**), reveals that the discrepancy of solar power is less than 4% compared to the measured grid power. This does not affect an air conditioner's rates or performance.

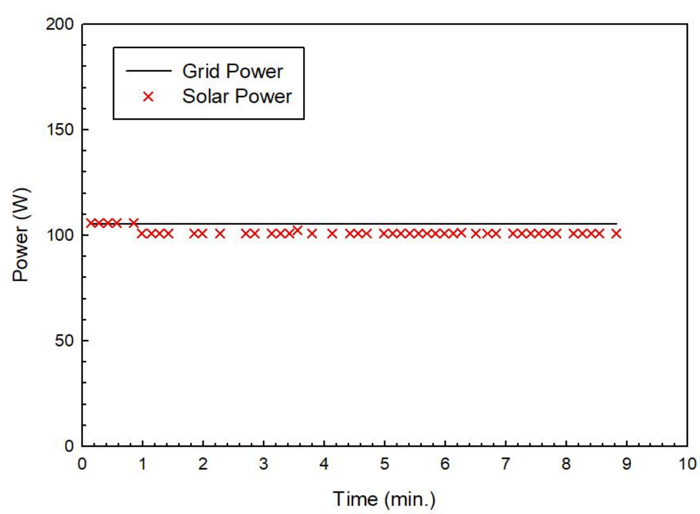

Figure 8: Comparison between inverter-rated power and grid power.

The solar alternative current and voltage and the automatic switching process have been examined and reported in this set of experiments, during which a switching process has often occurred by shading the PV panels. Fig. (**9**) shows the output voltage from the inverter for about two hours. As shown in the figure, the average voltage value is about 220V. It is worth mentioning that when the solar-generated voltage drops less than 200V, the microcontroller cuts off the flow of electricity from the solar panels and switches to the grid power line.

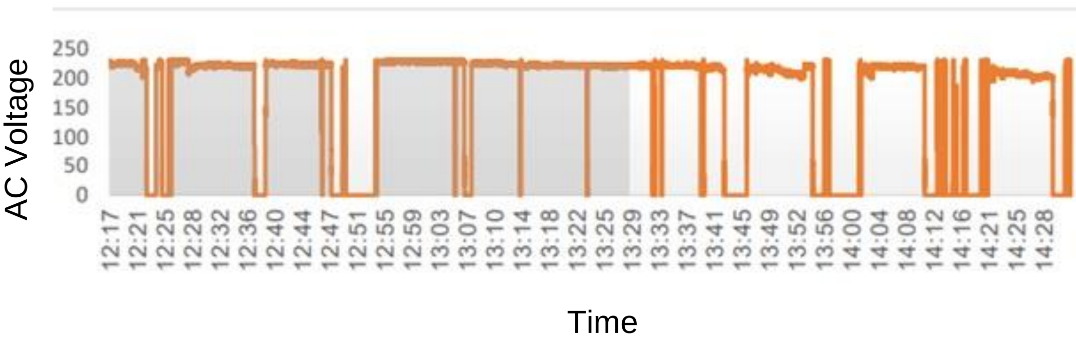

Figure 9: Solar output voltage measured after the inverter.

In Fig. (**10**), the solar current and grid current have been plotted in the same graph to show the automatic switching process between the two power sources. It is seen in this figure that the averaged values of solar-generated current and grid current are 0.390 A and 0.406 A, respectively. Also, it is seen, at zero solar generated current (e.g., at time= 12:48 in Fig. **5** and **4a**), the microcontroller allows for flowing the grid current, which shows a max value of current in Fig. (**10**). At time 12:54 the microcontroller turns again to the solar power line due to sufficient energy delivered by the solar panel module. The switching time between the two power sources was measured using the Arduino code time runs. The average time of the switching process is 498 Milliseconds. This short time does not interrupt the air conditioner's operation since the conditioner's electric motor runs at full speed. The startup of the air conditioner is always occurred by the grid line power.

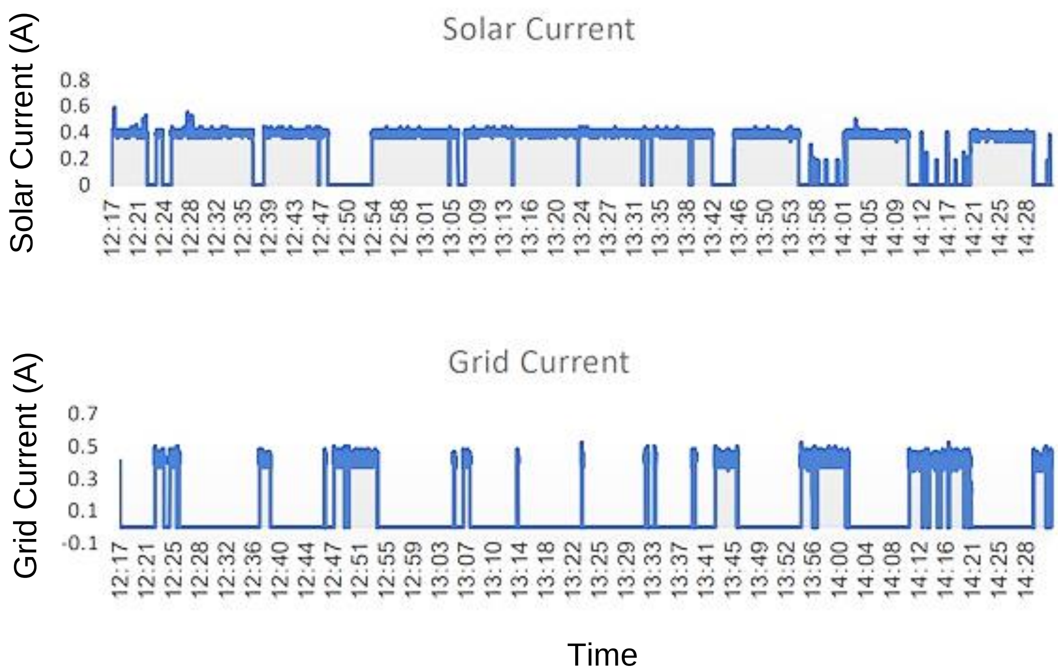

Figure 10: Solar current and grid current presenting the automatic switching.

6. Conclusion

An automated smart switching control system has been designed and implemented to monitor the switching performance between solar and grid power supply for optimal and safe air conditioning unit running. The proposed switching control system provides an intelligent connection between the solar power source and grid source, ensuring uninterrupted electricity supply and the correct quantity of power supply. The significance of this control system is reducing the power consumption from the grid during the sunshine period and guaranteeing a continuous power supply. The Arduino is a capable programming tool for automating smart switching applications. The average time of the switching process has been calculated as 498 Milliseconds, during which the operation of an air conditioner is uninterrupted. The automated smart switching system could be applied for many appliances (e.g., Variable speed air conditioners) implementing a smart home energy management system.

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