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Rural Household Space Cooling and Lighting through a Solar Power-based Electric Supply System

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Abstract

Quite a number of households in the world still lack electricity, especially in the sub-Saharan African continent. However, the abundance of solar irradiation in tropical Africa can be advantageously exploited to serve the inhabitants in this region, particularly the extremely low-income earners who not only have access to very inadequate power supply but also experience much discomfort in terms of poor ventilation and heat-triggered infections. This paper focuses on developing a small household-sized solar power-based electric energy supply system together with a temperature control circuit to power a direct current (DC) fan, and a light-regulating circuit to control LED lamps—with additional features such as a digital clock, a remote control, and mobile phone charging units. The system also has a provision for power supply through the mains (whenever it is available). The overall intent is to provide the rural dwellers with a cost-effective way of powering essential devices for basic economic living. This affordable solution is designed, simulated, and constructed to have hardware and software sections supported by various components and devices such as Arduino Mega, Lm35 sensor, RF transceivers, diodes, transistors, regulators, batteries, lamps, a DC fan, etc. The sensor senses room temperature, which is compared with the reference temperature of 25°C programmed on the Arduino microcontroller. When the temperature is less than 25°C, the fan remains stationary but when the temperature is higher than the reference value, the fan begins to run. As the temperature rises further, the speed of the fan increases to maintain adequate ventilation.

Keywords: Arduino microcontroller, DC fan, economical living, solar panel, temperature regulation

1. Introduction

Energy poverty is a critical issue in many parts of the world, especially the Sub-Saharan rural areas, with an estimated average of 20% of the World's population not having access to electricity [1-3]. In developing countries, it has been observed that a lot of people are not connected to the national grid—for instance, 50% of Nepal's population is off-grid [4], while 85% of Ethiopia's population do not have access to the national grid [5]. This lack of access occasioned mainly by inadequate generation, weak and limited transmission line, and inefficient power distribution systems [6], has hampered economic growth, particularly at a micro level, and resulted in a poor standard of living [7]. In order to ensure access to clean energy, which is a required component of the sustainable development goal [8], concerted as well as strategic efforts from all stakeholders must be usefully directed towards bridging the gap between demand and supply of electricity to households, especially the off-grid dwellers

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[9]. These should at least help curb fundamental energy issues, such as poor lighting, poor ventilation, and ineffective cooling, which indirectly result in health-related challenges and spread of diseases.

Today renewable energy sources have ushered in new and alternative ways for meeting the various needs of electricity consumers. Thankfully, many of the Sub-Saharan areas with little or no access to electricity also have high solar irradiation that can serve as a source of an environmental-friendly form of energy to them and as motivation for various intervention initiatives for installation of small-sized power supply systems and micro-grids. Various studies have been conducted to investigate and create frameworks for electricity generation based on renewable sources. A micro-grid design for rural areas was considered in [10], with results showing how the integration of renewable energy sources could be harnessed for rural use. Oğuz *et al.* [11] looked at a hybrid wind-photovoltaic system for lighting laboratories in Turkey. In [12], the authors studied the potential of a solar chimney to generate power in rural communities of developing countries, emphasizing the importance of the technology to meet electricity needs. Other variants and investigations are reported in [13-16].

The thrust of this paper is to develop and construct a small household-sized solar power-based electric supply system for powering a temperature-sensitive direct current (DC) fan and LED lamps—with additional features of a digital clock, a remote control, and mobile phone charging units. The system also incorporates a means of power supply from the utility mains. The DC fan, which is self-regulating, has the aim of keeping the room at a standard temperature of 25˚C, which inhibits the spread of disease-causing microorganisms, while the lamps are to provide lighting for adequate illumination.

The overall system, designed to enable rural dwellers have access to electricity to conveniently and economically power basic devices, involves the design of:
(1) a power control circuit to power the fan
(2) a temperature-sensing circuit to regulate the speed of the fan
(3) a dark-detecting circuit to control the states of the lamps, and
(4) a remote-control unit for switching between the several functions of the fan.

2. Materials and Methods

2.1 System Description and Requirements

The system is hybrid-powered, with solar PV as the main power source and utility mains (whenever available) as auxiliary. An additional storage battery is provided to ensure system availability. This arrangement conforms to the standard architecture of having one or more renewable energy inputs with associated power management, storage, and distribution components. Generally, the system should be able to perform the following functions:
(1) generate solar energy
(2) store the generated energy
(3) perform AC – DC conversion and regulation
(4) charge a storage device
(5) sense and monitor the temperature in a room
(6) control the speed of a DC fan

(7) detect light intensity in a room
(7) receive and transmit RF signals
(8) charge mobile phones, and
(9) indicate the day time in hours, minutes, and seconds.

The various components which can be employed to realize the above-mentioned functions are listed as follows:

i. Solar panel
ii. Solar charge controller
iii. Battery
iv. Transformer strip
v. Rectifier
vi. Voltage regulator
vii. LM 35
viii. DC motor
ix. Motor speed regulator
x. Diodes (fly-back)
xi. Arduino Mega
xii. Arduino Uno
xiii. 433Mhz transceiver
xiv. LCD
xv. LED lamps
xvi. Accessories, such as transistors, resistors, jumper wires, push and stay buttons, and UART converter
xvii. Wooden structure to enclose the motor

The system is required to operate in either automatic or remote-control mode. In automatic control, the intent is to ensure that the system can supply a DC fan that is regulated based on the room temperature around it. There are four gradations for the fan speed, i.e., Level 0: when the temperature of the room is less than 25˚C; Level 1: when the temperature is above or equal to 25˚C but less than 30˚C; Level 3: when the temperature is above or equal to 30˚C but less than 35˚C; and Level 4: when the temperature of the room is greater or equal to 35˚C.

The Arduino microcontroller is programmed such that a reference temperature of 25˚C is maintained while the input is set to zero in a closed-loop control system, as shown in figure 4. The sensor senses room temperature values and compares with the reference value, and the fan responds to changes in temperature based on the flow-chat shown in figure 5. The fan is programmed to stop at a temperature less than 25˚C and run at a temperature equal to or above it.

On the other hand, in the remote control, the speed of the fan is regulated to suit the user's preference. Meanwhile, the lamps are automatically controlled, depending on the intensity of light in the room. Besides, the phone-charging point and the timepiece are normally activated as long as the system is powered on. The available fan motor, which is rated 12v, 6.8A, and the available battery, which is rated 12v, 19A, and 18AH, accordingly guide the design of the entire system. The power and control blocks of the system are shown in Fig.1 and Fig.2, respectively, while the remote-control block is depicted in Fig. 3.

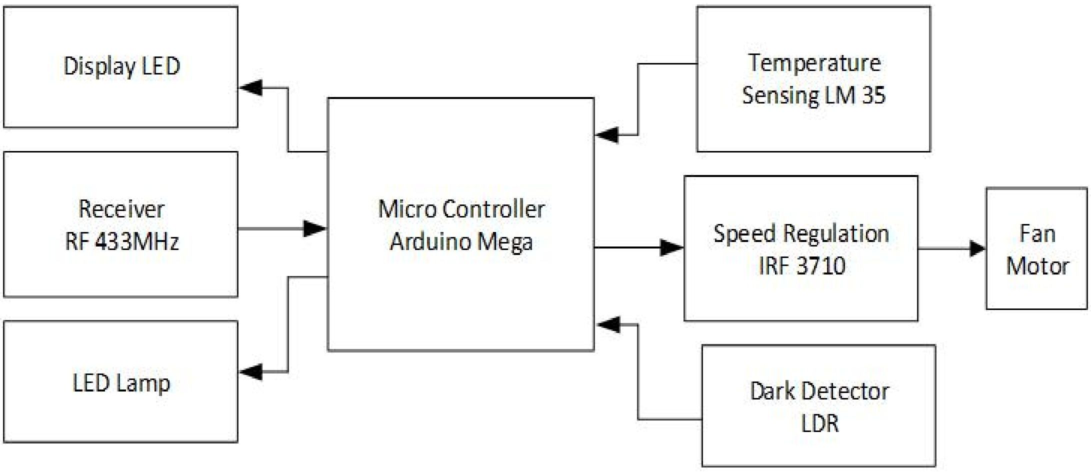

Fig. 1: System control block

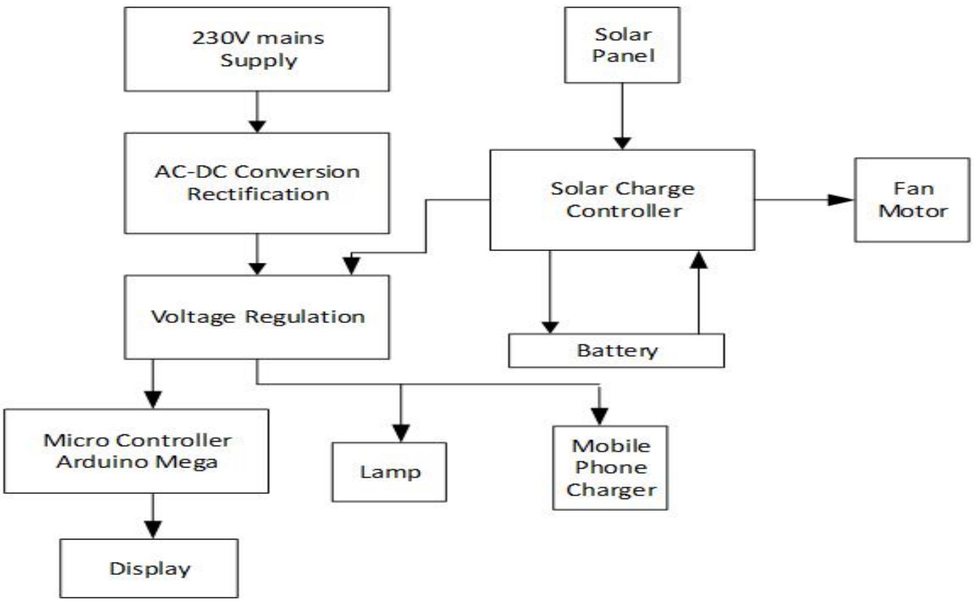

Fig. 2: System power block

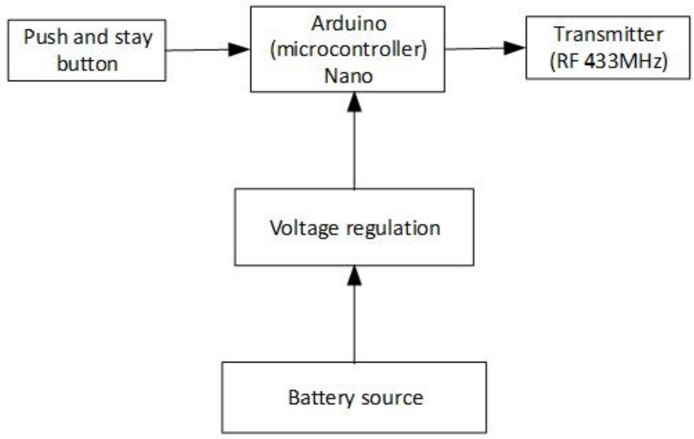

Fig. 3: Remote control block

2.1.1 System Description and Requirements

The DC fan is made to operate in a closed-loop system, as shown in Fig. 4. This arrangement represents a regulator system with the initial temperature of the room, acting as the only input. As previously mentioned, the essence of this closed-loop system is to ensure that the standard room temperature of 25˚C is attained. The room temperature is measured using the LM35 temperature sensor, which is an integrated circuit that has very high precision and an output voltage linearly proportional to the Centigrade temperature. This integrated circuit does not require an external calibration and has high accuracies of ± 0.25°C and ±0.75°C over a full temperature range of -55°C to 150°C [17]. The controller is the Arduino mega, while IRF3710 MOSFET is employed as the switching component to perform pulse width modulation for the purpose of speed regulation.

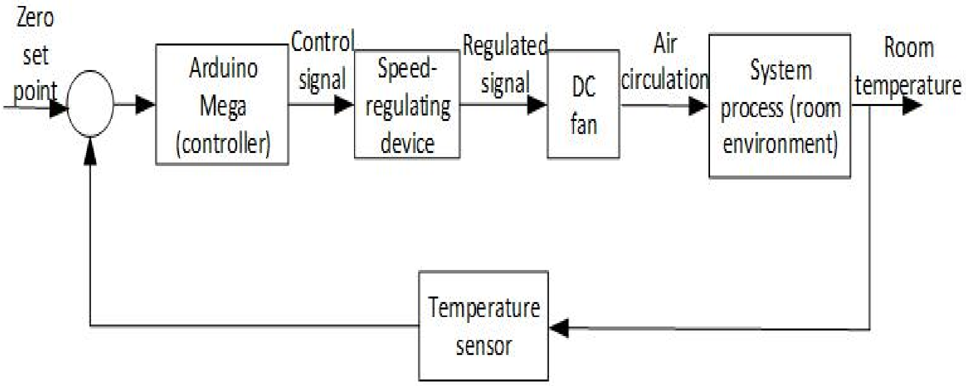

Fig. 4: Closed-loop control system of the temperature-controlled fan

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2.1.2 Lighting, Timing, and Phone Charging Circuits

LED lamps, used for lighting the room, are controlled by a light-dependent resistor (LDR), which operates such that its resistance decreases when the visibility of the room decreases and vice versa. An NPN transistor (BC547), whose base is connected to the Arduino Mega, is used to switch on and switch off the lamps. The combination of a microcontroller and a counter is employed to realize a timepiece that counts and adjusts time appropriately. The hour is counted from zero to twenty-three, while the minute and second are counted from zero to fifty-nine. The time adjustment process is performed by using three different buttons: set, increment, and decrement buttons.
As well, the L1705 voltage regulator is used to adjust the system voltage in order to obtain a suitable voltage level for phone charging purposes.

2.2 Methodological Steps

The methods for realising the overall system are as follows:

i. Hardware design: This involves the design of the various circuits and the selection of the right combination of components. This is aided by an electronic design package (Proteus) used to check for the validity and compatibility of the components, and to correct circuit design errors.
ii. Software design and programming: This involves developing algorithms/flowcharts and writing codes to enable all system control functions. Arduino microcontrollers are employed to create and support necessary control signals for activating proper system operation.
iii. Implementation and testing: After proper simulation to ascertain circuit functionality, the various components and devices are appropriately soldered and coupled together to give an overall working system. Basic tests are carried out on the system to ensure full compliance with operational specifications.
iv. Packaging: All subsystems are assembled together and compactly encased in a suitable package in readiness for deployment.

3. System Design

3.1 Hardware Design and Component Selection

For the entire system, the motor of the fan available is rated 12v and 6.8A, the available battery is rated 12v, 19A, and 18AH, the LED lamp is rated 9v and 0.44A, and the microcontroller consumes 50mA.

3.1.1 Overall System Sizing

Given that the amp-hour of the battery is 18, and choosing the duration for charging the battery to be 10 hours, then the amp per unit hour gives

$$\frac{18}{10} = 1.8A \quad (1)$$

Therefore, the total current required by the system is found as

$$1.8 + 7 + 0.44 + 0.05 = 9.29 \cong 10\text{A} \quad (2)$$

Based on this total current, the circuit requirement for charging would be 12V and 10A, resulting in a power requirement of 120W.

3.1.2 Solar Panel Sizing

The panel is also selected based on the rating obtained from the above calculation. Thus, two 60-W, 12-V parallel-connected panels are used. The solar charge controller is sized accordingly with respect to this output voltage and power. The solar charge controller employed in this paper is a pulse width modulation (PWM) solar charge controller.

3.1.3 Lamp Switching Circuit

The lamp is controlled by a light-dependent resistor and a transistor. Since the current gain (hfe) of the transistor is 150, the current rating of the lamp is 0.44A, and the Arduino voltage is 5V, the base resistance of the transistor is calculated as follows:

$$\text{Base voltage } \mathrm{V_b} = 5 - 0.7 = 4.3\text{V} \quad (3)$$

$$\text{Base current } \mathrm{I_b} = \frac{I_c}{hfe} = \frac{0.44}{150} = 2.933\text{mA} \quad (4)$$

$$\text{Base resistance } \mathrm{R_b} = \frac{4.3}{0.2933} \cong 1.5\text{k}\Omega \quad (5)$$

3.1.4 Fly-back Diode

This diode prevents arcing across the motor switch (when opened) by allowing the stored charge to flow out of the motor to the ground. The current rating of the fly-back diode is selected based on the current rating of the fan motor, which is 6.8A. A readily available 7-A diode is used.

3.2 Software Design

Arduino microcontrollers are used to support the functionality of the system. Programs are written in C language (using Arduino 1.8.5 software) to enable, among others, the room temperature-based fan speed regulation, LED lamp switching, and remote-control operation. The flowchart of the fan speed regulation is shown in Fig. 5, while that of the lamp switching is depicted in Fig. 6.

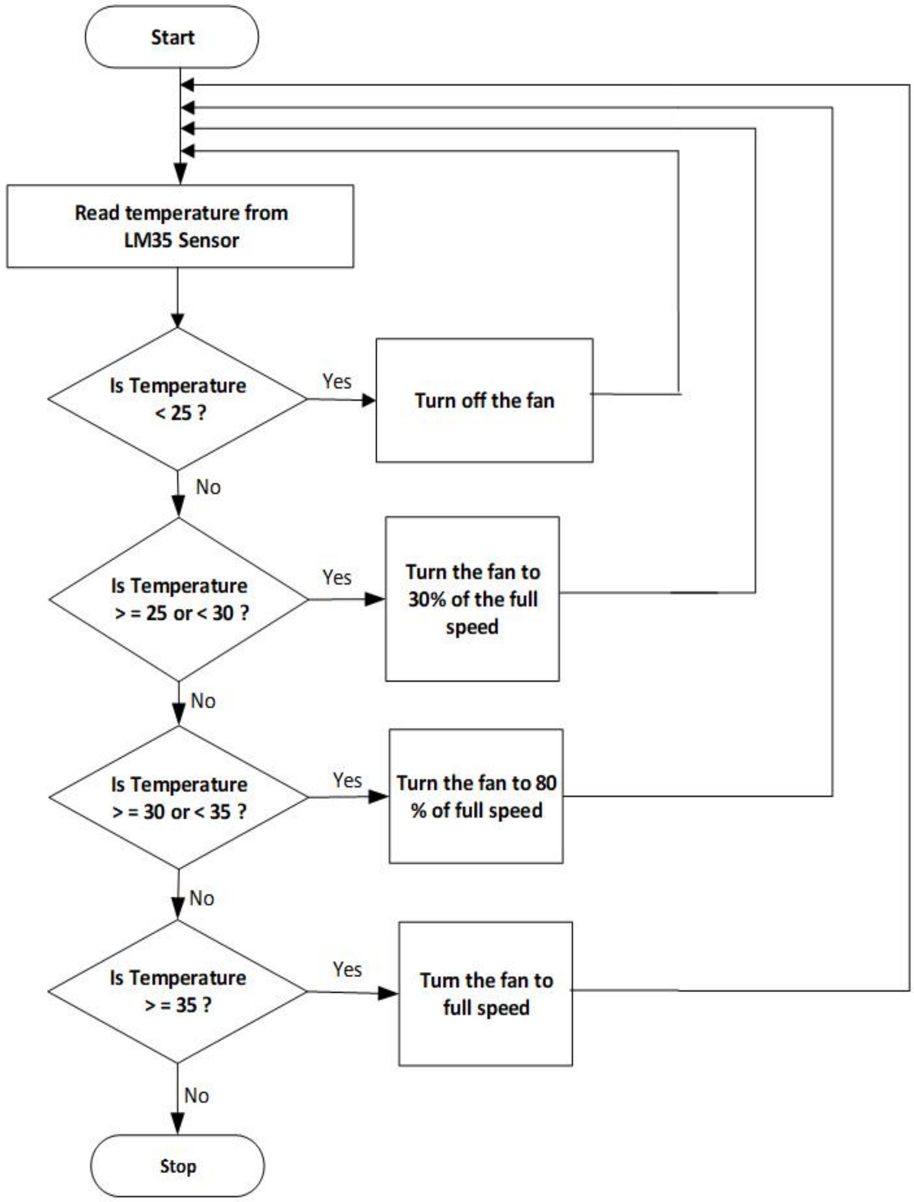

Fig. 5: Flowchart of the automatic room temperature control

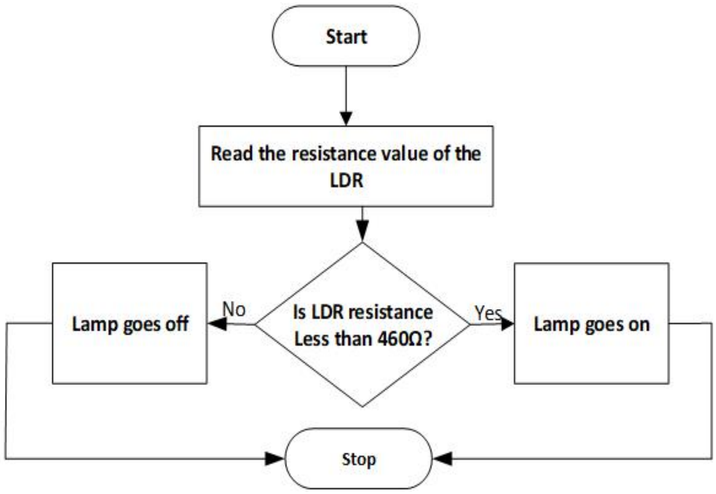

Fig. 6: Flowchart of the automatic lamp switching

The programs are uploaded into the Arduino board, which is the heart of the microcontroller. The microcontroller board used in this paper is Arduino Mega 2560. Based on the ATmega2560 AVR, it has 54 digital input/output pins—15 of these are used for Pulse Width Modulation PMW outputs, and 16 can be used for analog inputs—a 16MHz resonator or a crystal oscillator, a USB connection, a power jack, an In-Circuit System Programming (ICSP) header, and a reset button. The summary of the Arduino Mega 2560 is given in Table 1.

Table 1: Summary of Arduino Mega 2560

Microcontroller Feature	**Description**
Operating Voltage	5V
Input Voltage (Recommended)	7 – 12V
Input Voltage (limits) 6 – 20V	Input Voltage (limits) 6 – 20V
Digital I/O Pins	54 (of which 15 provide PWM output)
Analog Input Pins	16
DC Current per I/O Pin	40mA
DC Current for 3.3V Pin	50mA
Flash Memory	128KB (of which 4KB used by bootloader)
SRAM	8KB
EEPROM	4KB
Clock Speed	16MHz

4. System Implementation

The various subsystems—temperature regulation subsystem, remote control subsystem, lamp subsystem, mobile phone charger unit, and digital clock unit—are integrated and assembled

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into a suitable package to form a functional system. The system circuits are depicted in Fig. 7, and Fig. 8.

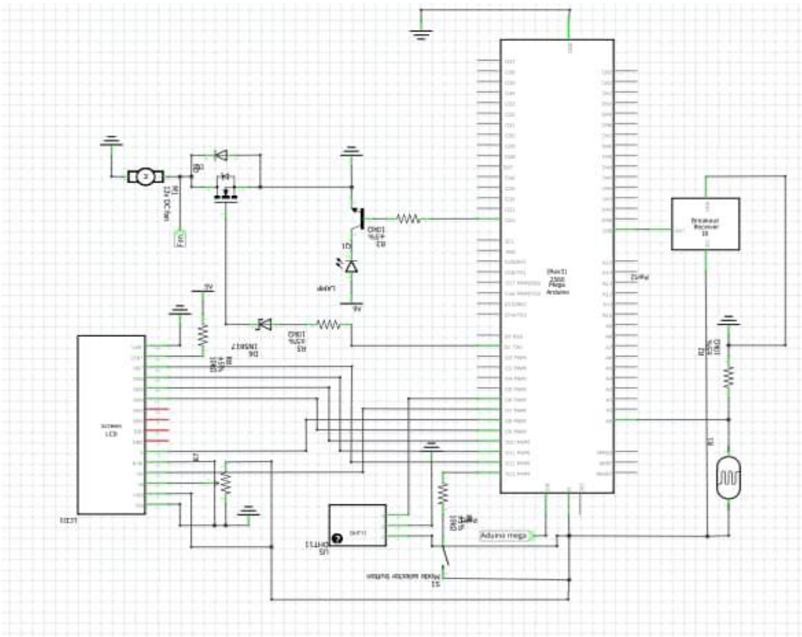

Fig. 7: System control circuit

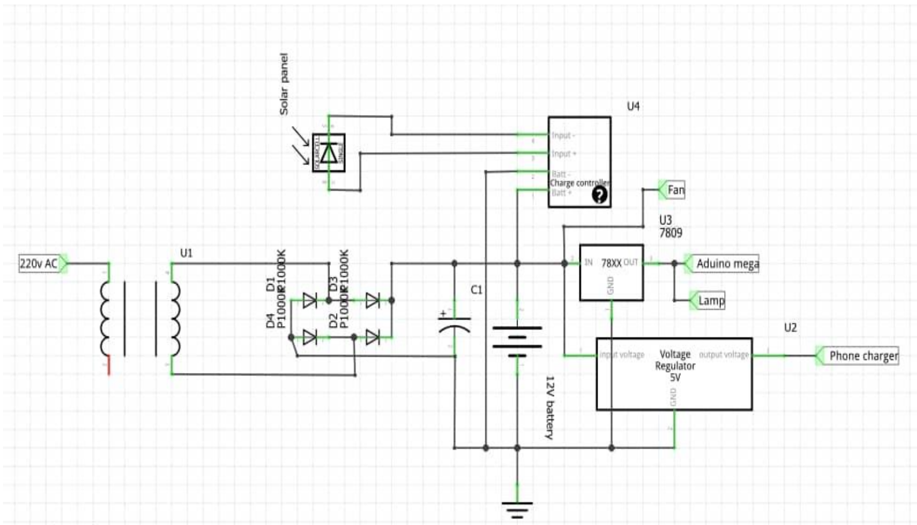

Fig. 8: System power circuit

The solar panels and the charge controller are mounted in appropriate positions, with connections from the charge controller to the loads and battery firmly established. Voltage and current outputs from the solar panels are tested to confirm they are within specifications. The

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temperature sensor (LM35), light-dependent resistor (LDR), and LCD are connected to the Arduino Mega, with the speed of the fan and LDR sensing programmed according to specifications. Similarly, with the help of an Arduino pro mini and RF 433MHz transceiver, the remote-control connection is established and functionally confirmed. The timing operation that yields the digital clock is programmed on the Arduino IDE and read through the LCD. As well, the output of L1705 voltage regulator is extended to an outlet for mobile phone charging purposes. The entire subsystems are housed in a box to provide a secure connection and housing to all the components used in the entire system, as shown in Fig. 9 and Fig. 10.

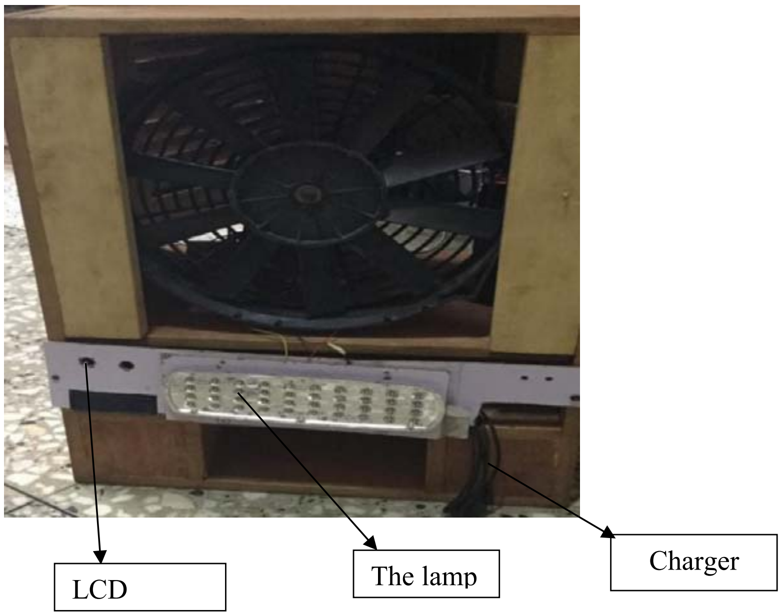

Fig. 9: Image of the overall system

Fig. 10: Image of the overall system with the LED lamps powered on

5. Results and discussion

It was observed that when the sensor LM35 of the hybrid-powered fan sensed a temperature below 25°C, the fan remained static, indicating that room temperature is good enough. However, when the room temperature was raised to the range between over 25°C and below 30°C, the fan started rotating at about 30% of its full speed as detected by the number of pulses (i.e number of pulses multiplied by 60/2). Then, when the room temperature was over 30°C and less than 35°C, the fan speed increased to about 80% of its full speed.
Lastly, when a temperature of over 35°C was sensed by the sensor of the fan, it rotated at full speed. This showed that the results obtained at each temperature range tracked the reference ambient conditions appropriately. Also, the charging port and the lightning lamp continued to be operational as long as the fan was powered ON. The sensor also triggers illumination whenever darkness was detected.

6. Conclusions

An affordable solution for primarily providing ventilation and lighting for rural households has been developed in this paper, which will invariably enhance the standard of living of low-income earners, farmers, and rural villagers. The fan speed of the device varied with room temperature and remained off at an ambient temperature below 25˚C. That is, it does not come on when the room temperature is usually cool, but as the temperature begins to rise above the preset value, the fan starts to rotate. Thus, the system can be adopted by various users who are not connected to the utility grid network and can also serve as a cost-effective and environmentally friendly alternative to gasoline generators in terms of basic household electrical energy provision.

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