Design and Operation Strategy for a Grid-Connected Micro Power System

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Abstract – *The growing demand for a sustainable power system is motivating worldwide interest in alternative technology. The renewable sources are capable of supplying the required energy but are intermittent and location dependent. A micro power system, if optimally designed can be more reliable and cost effective than a single power source. The overall aim of this paper is the design and operation strategy for a grid connected micro power system for reliable and cost effective energy utilisation. The designed micro power system, is made up of three power sources (solar photovoltaic, grid and fossil-fuelled generator), and utilises a microcontroller based system to reliably organise the flow of the hybrid power mix from different sources and battery bank in a cost-effective manner. The microcontroller was programmed to monitor the DC voltage levels of the battery bank to decide which source powers the load. The results showed that the developed strategy yielded grid energy savings of 66.7%, reliability enhancement of 6.1% and reduction of pollutant emission by 36.7% compared to the conventional strategy. The high energy saving as well as improved power supply reliability of the developed strategy has become increasingly necessary especially in the face of exorbitant power supply rates of the various electric power distribution companies in Nigeria. Moreover, the implementation of the developed operation strategy can make the ecosystem more friendly and clean.*

Keywords: *energy saving, operation strategy, power reliability, renewable energy sources, utility grid*

Article History
Received 25 July 2018
Received in revised form 16 September 2018
Accepted 13 November 2018

I. Introduction

The presence of sustainable, affordable and reliable energy supply is crucial to a nation's development. The economic growth of any country is hinged on reliable and efficient power supply. Many developing countries have not attained sufficiency in energy generation. Inefficient and unsatisfactory electric power supply is a major cause of poor economic growth and technological redundancy in Nigeria. This drawback has manifested in the inadequate and erratic nature of its supply [1], [2]. Hence, there is a need to strategize to meet the ever-growing demand for energy.

Various energy sources have their strengths and demerits. The high cost and erratic nature of grid in developing regions [3], dependence of renewable energy on metrological factors [4] and harmful effects of the use of fossil-fuel on the environment [5], [6] are factors that have necessitated an approach that mitigates these drawbacks. The micro power system provides a way of escape from this problem.

A micro power system can intelligently control distributed power resources and the connected loads while operating independently from or in parallel with the grid [4]. It harnesses the strengths and weaknesses of different energy sources to attain stability in energy provision. In addition, it can efficiently supply electric power with improved reliability and power quality by integrating and optimising a mix of power sources. Nevertheless, the feasibility of such system depends on the mix of energy sources, the allotted power capacity as well as the energy dispatch strategy [7].

For a micro power system to efficiently manage its energy sources, it has to operate following a profitable strategy [8]-[13]. This is because the integration of power sources and storage devices requires a cost effective management of energy flow among the different sources [14] - [20]. This paper describes a novel operation strategy that integrates hybrid energy sources with improved power supply reliability at minimal (reduced) cost. It considers the design of a control switching system that will maximise power from alternative energy sources, simulates and evaluates the performance of the developed strategy against the conventional/baseline strategy.

The proposed design is of immerse significance; it optimises the power structure of conventional system, which has multiple sources, since it proffers a more suitable method of connection that maximally utilise all the power sources available to it, ensures energy savings and improves power availability. In addition, pollutant emissions from the use of fossil fuel generator can be reduced.

II. Methods and Materials

A. System Design

Fig. 1 shows the schematics of the component parts of the designed micro power system. The supervisory controller is made up of component blocks that are interconnected via a microcontroller, pre-programmed by the operation strategy. These blocks are powered by a regulated voltage of 5V supplied by the voltage regulator (7805); and comprise of discrete components selected on the basics of design calculations and market availability.

DC Power Monitor: This section consists of sets of op-amps and resistors that detects the voltage and the state of charge (SOC) of the battery bank as shown in Fig. 2. The microcontroller depends on the battery voltage to determine which power source supplies the load requirement of the micro power system. The operation is hinged on the voltage divider principle, which scales down a voltage level as shown in (1). Three reference voltage levels of 12.8V, 12.0V and 11.4V were set with selected values of resistors based on the voltage divider principle.

$$V_{out} = R_2 V_{\text{supply}} / (R_1 + R_2) \qquad (1)$$

Resistors R_1 and R_2 divide the battery supply voltage, V_{supply} by a factor of 10. This brings the battery voltage to a range that the op-amps can compare with the set reference voltage.

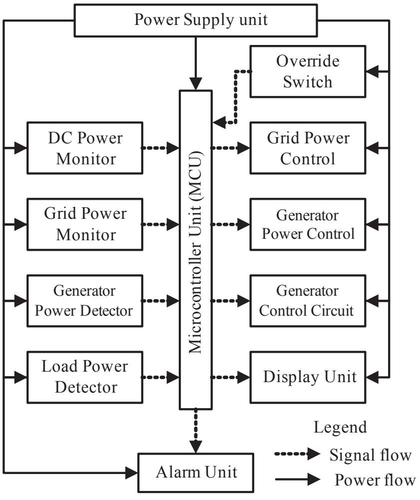


Fig. 1. Schematics of the designed grid connected micro power system

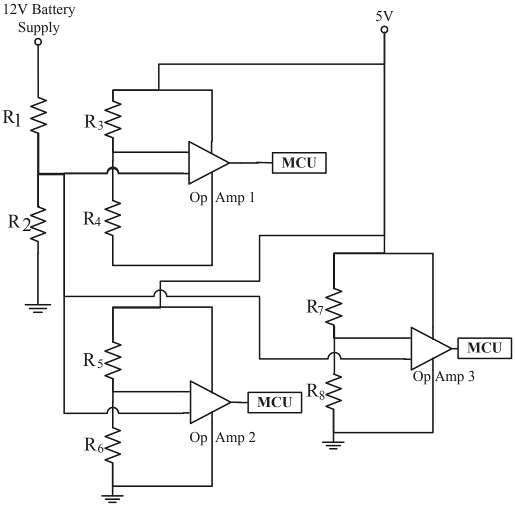


Fig. 2. Equivalent circuitry of the DC power monitor

R_3 to R_8 are used to set the reference voltage values with supply of 5V from the voltage regulator; the values are such that they trigger the microcontroller when the monitored battery voltage gets to 12.8V, 12.0V or 11.4V.

Generator Power Detector: The generator power detector, shown in Fig. 3, senses the availability of power supply from the generator. The microcontroller needs such feedbacks for its operations. When power is available from the generator, the bridge diodes rectifies the AC current to DC. This process switches on the Opto-isolator LED, which saturates the photo-transistor causing a short circuit between the collector and emitter; thereby creating a voltage drop on the emitter resistor. This voltage will be impressed on the input of the NOT gate. The output of the NOT gate constitutes an input to the microcontroller.

The Opto-isolator (4N35) couples the high voltage AC power from the generator to a low voltage DC power to the microprocessor unit (MCU). Its safe operating current as seen in the data sheet is 1mA. Hence, the current limiting resistor R_9 is utilised to reduce the incoming current using Ohms law. A transient capacitor C_2 and a pull resistor R_{10} are also utilised in this block.

Override Switch: The override switch, used to enable or prevent automatic start-up of the generator, is basically a switch connected through a pull resistor.

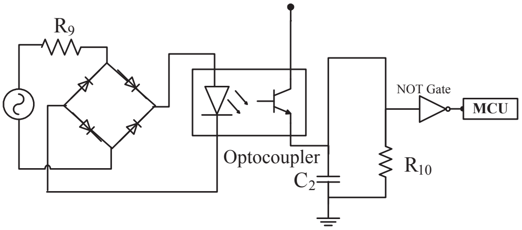


Fig. 3. Equivalent circuitry of the generator power detector unit

Generator Power Control: The generator power control circuitry transfers the load from utility grid to the generator supply. It operates by a TRIAC energising or de-energising the generator contactor coil. The TRIAC is switched on/off by an Opto-coupler, which receives signals from the microcontroller as shown in Fig. 4. The power control unit basically energies or de-energies the coil of the generator contactor, which is actuated by a TRIAC controlled by an Opto-coupler. The input to this unit is received from the MCU through the transistor. R_{12} is a current limiting resistor, R_{13} and R_{15} are pull resistors, and R_{14} is the base resistor to the transistor.

Grid Power Control: The grid power control circuitry, shown in Fig. 5, transfers the load from the DC source to the utility grid. The mechanical contactor opens and closes as it receives signals from the microcontroller unit. Values and analyses of grid power control block are similar to those of the generator power control block.

Generator Control Circuit: The generator control circuit design turns on/off the generator. It consists of relays controlled by the aid of transistors (see Fig. 6). The transistor receives inputs from the MCU and switches through the transistors to energise the relays connected to the start/stop circuitry of the generator. Resistors R_{20} and R_{22} are pull resistors while R_{21} and R_{23} are base resistors for the transistors.

Alarm Unit: The alarm unit alerts the user of a change of power supply or an operation error. It has a buzzer and an LED, which are actuated by a 555 timer connected in an astable mode (Fig. 7). The frequency of the 555 timer is set by (2):

$$F = 1.44/[(2R_{24} + R_{25})C_3] \qquad (2)$$

A frequency of 1Hz is obtained with the values chosen. This drives the buzzer that blare the alarm.

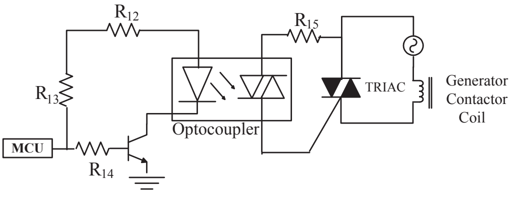


Fig. 4. Generator power control circuitry

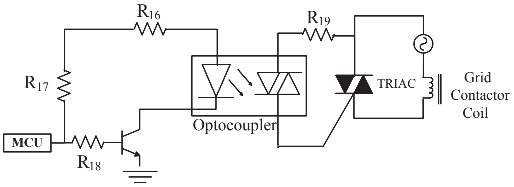


Fig. 5. Grid power control circuitry

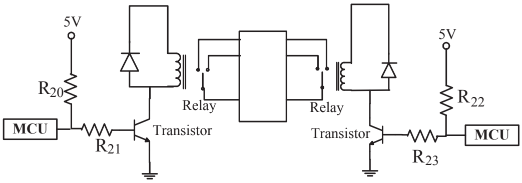


Fig. 6. Circuit diagram of generator control unit

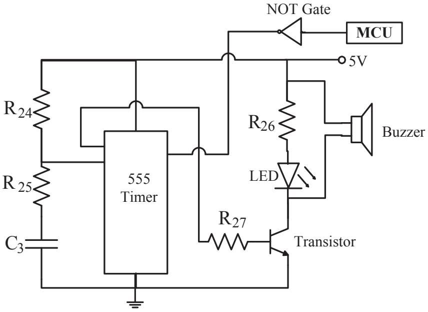


Fig. 7. Alarm circuitry

Grid Power Monitor: This unit (Fig. 8) detects and scrutinises the power supply from the utility grid. Firstly, the microcontroller would require the knowledge of the availability of grid power for its operation. Also, the system is designed to allow utility grid only when its voltage is within acceptable range (between 180V and 240V). The components: R_{31}, R_{32}, R_{33}, R_{34}, Op-amp 4 and Op-amp 5; are used to set the upper and lower voltage limits using the voltage divider principle. When the supply voltage is within the range, the AND gate sends a high to the microcontroller signifying the availability of grid power supply.

Load Power Detector: This is a feedback unit for the microcontroller, which enables the microcontroller ascertains that power is delivered to the load especially after a change over operation (Fig. 9). Its components, ratings and operations are similar to that of the generator power detector. The AC supply from the grid is stepped down by the transformer. The rectifying diodes convert the AC to DC power. Capacitor C_4 filters the issuing currents of ripples. The LED indicates the presence of power reaching the circuit. Resistors R_{29} and R_{30} scale the voltage received by a factor of 0.1 to make it comparable with the voltage from the voltage regulator. Resistors R_{31} and R_{32} set the upper voltage limit of 240V using the voltage divider technique, likewise R_{33} and R_{34} for the lower voltage limit of 180V.

Microcontroller Unit: The microcontroller is the central control IC. The operation strategy of the developed model is burnt into the ROM of the microcontroller. Fig. 10 shows the schematics of the microcontroller. With 32 pins I/O ports, it communicates with other components either directly or indirectly. Its clocking pulse of 12MHz is set by a crystal oscillator and capacitors C_6 and C_7.

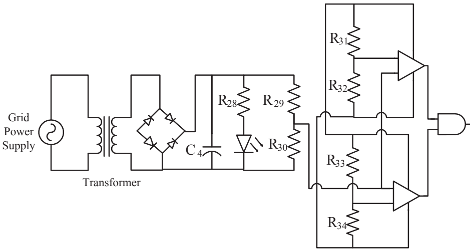


Fig. 8. Grid power monitor circuitry

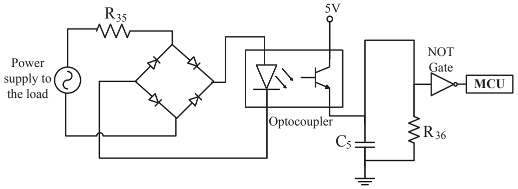


Fig. 9. Load power detector circuitry

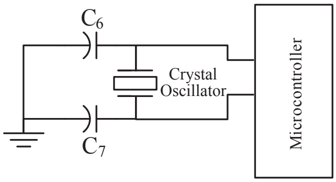


Fig. 10. Schematics of the microcontroller unit

The component units are connected to the microcontroller, which monitor and controls the entire circuit in accordance to the pre-programmed operation strategy. Fig. 11 illustrates the complete designed circuitry with components values.

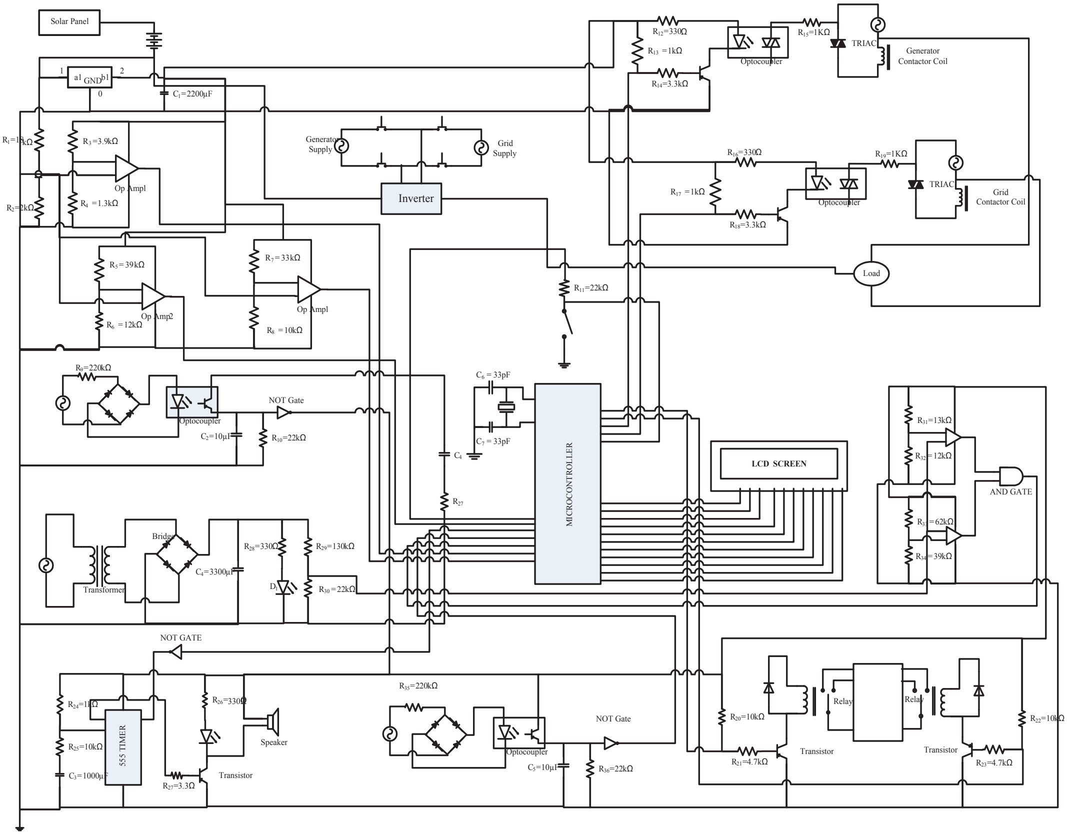


Fig. 11. Complete designed circuitry of the grid connected micro power system

B. Operation Strategy

The developed grid connected micro power system has three power sources, namely solar photovoltaic (PV), utility grid supply and a fossil fuel generator. A battery bank serves as reserve energy storage. Typical 12V Deep cycle batteries are considered 100% charged when their voltage is 12.8V and above. The mid reference of 12V corresponds to a 25% state of charge (SOC). A battery usage range of 12.0V to 12.8V is considered safe operating range of the battery.

The micro power system proposed in this paper does not consider any of the power sources as primary. Rather, it monitors the battery voltage and determines based on a pre-programmed protocol, which source is the priority. Three voltage reference levels are used in the decision making. The upper reference level is set to 12.8V. The middle reference voltage was set to 12.0V and the lower reference level to 11.4V. The lower reference level of 11.4V was chosen to ensure that the designed controller transfers the load to the generator before the inverter shuts down. The shutdown voltage of the inverter used was found experimentally to be 11.3V. These voltage reference levels are sensed by the DC level detectors.

When the battery voltage is above 12.8V, the battery is regarded as being charged; hence, it powers the load, irrespective of whether grid power is available or not. The entire load requirement of the system is satisfied by the battery till the middle reference point of 12.0V is attained. At 12.0V, the system checks for availability of the utility grid supply. If available, the load requirement is transferred to the grid supply. While the load is being powered by the grid, it also charges the battery bank. The batteries get charged from 12.0V to its upper reference voltage of 12.8V before it is considered optimum to provide the load requirement. In the event that the battery gets drained to 12.0V and the utility grid supply is unavailable, the battery keeps on supplying the load requirement till lower reference level of 11.4V.

If the battery voltage is less than 12.0V and the utility grid gets restored (becomes available), the load demand switches to the grid while the battery is being charged. When the battery gets drained to 11.4V and grid is unavailable, the supervisory controller automatically activates the fossil fuel generator to power the load and charge the battery. This happens before the inverter cuts off the battery supply.

When the generator is being started, different scenarios may play out. It is possible that the generator may not start for many obvious reasons like insufficient fuel or mechanical fault. The system monitors whether the generator supplies power and it reports same to the user/consumer through the LCD screen. The consumer can ascertain if the operation is not successful from the screen and then attend to the problem manually. Once the generator is being switched on, it powers the load and charges the battery. The generator will be automatically switched off when the grid power is restored or when the battery voltage gets charged up to 12.8V by either the solar panels, the generator or both.

It is worth mentioning that during the day, power is being supplied by the sun through the solar panels, which will not be available at night. The availability of grid power is unpredictable in most cases. The generator serves as the last resort when grid power and solar power are unavailable. The battery bank serves as a reserve to smoothen the inconsistencies presented by the alternative energy sources [11]. Conversely, the utility grid supply is taken as the primary source of power for the load irrespective of the availability of other sources of power in the convectional scenario. Hence, solar radiance is underutilised. The controller developed in this paper switches between alternative sources depending on sources availability; thus, maximising the sources and minimising their drawbacks. The flowchart of the operation strategy is shown in Fig. 12

C. Simulation and Fabrication

The process simulation of the developed strategy was done using Proteus ISIS Professional Design suite. Fig. 13 shows the screenshot of the Proteus ISIS interface. At the centre of the simulation process is the programmed microcontroller with inputs from the battery source (DC power source), generator detector, load detector and grid power source. Each of these sources have switches that help ensure the availability of these sources.

At the output of the microcontroller are LEDs, which indicate when the generator and grid supplies power to the load. LEDs also indicate when the generator is being started or stopped automatically. An LCD screen displays the operation and error messages of the microcontroller.

The designed operation strategy was realised by discrete electronic components. The components used in the fabrication include resistors, electrolytic capacitors, 5mm LED, buzzer, 7805 voltage regulator IC, LM 324 operational amplifier, CD 469 Not gate, IN 4007 rectifier diodes, 4N35 Opto-transistor based coupler, NE555 timer, BC 547 NPN transistor, 12 MHz crystal oscillator piezoelectric device, 16 X 2 LCD, BT136 TRIAC, CD481 AND gate, TRIAC Pre-driver, 8089C52 8-bit microcontroller, and 5kV, 25A contactors.

The prototype control system was constructed using wooden material cut to size with the top covered with Perspex. The electronic circuit is soldered on the Vero board, which was fixed firmly to the wooden case by means of screws. Fig. 14 shows the fabricated design with the internal and the finished/cased circuitries.

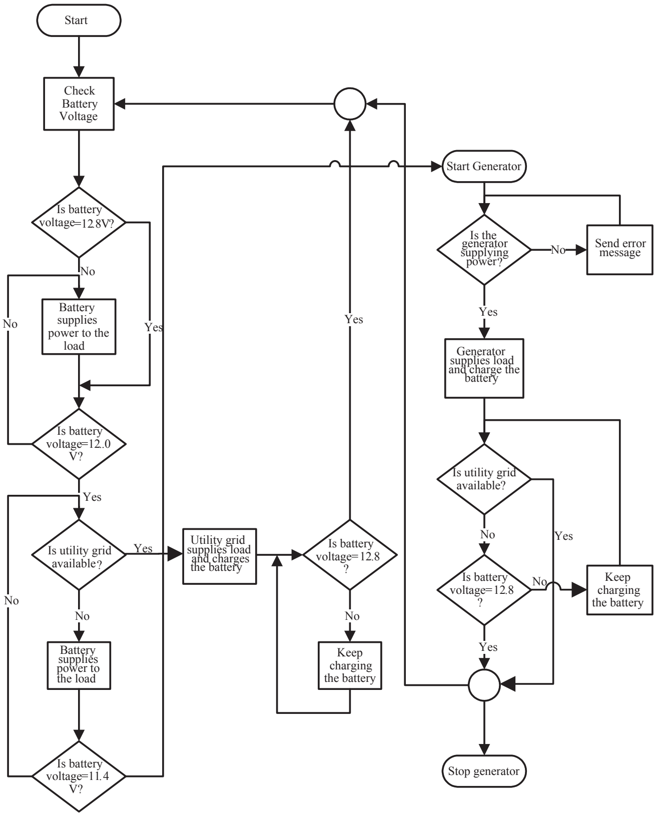


Fig. 12. Operation strategy of the grid connected micro power system

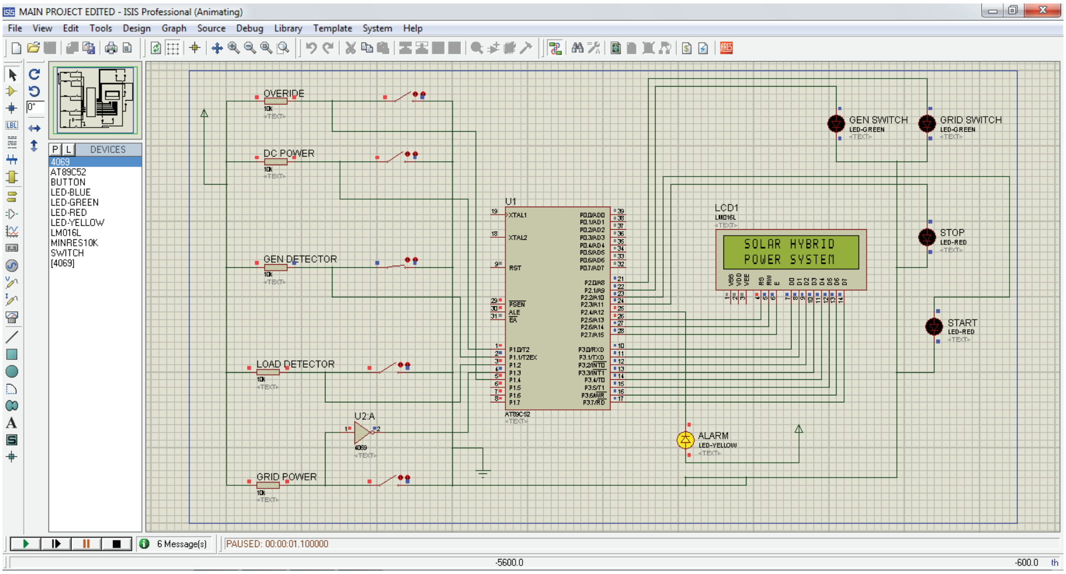
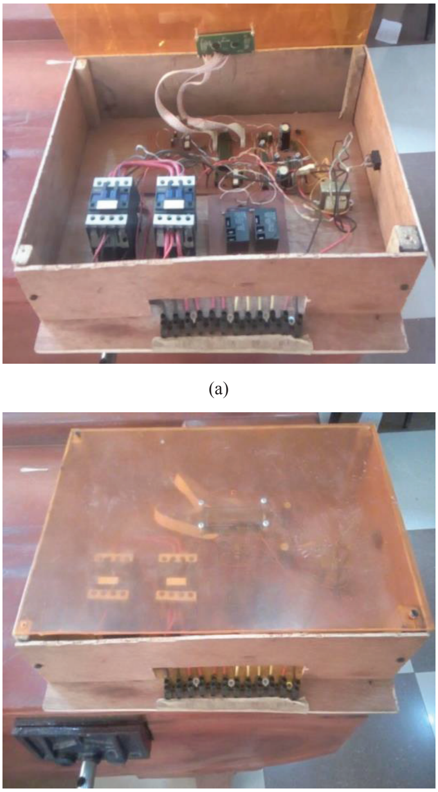


Fig. 13. Screenshot of the Proteus ISIS professional interface



(a)

(b)

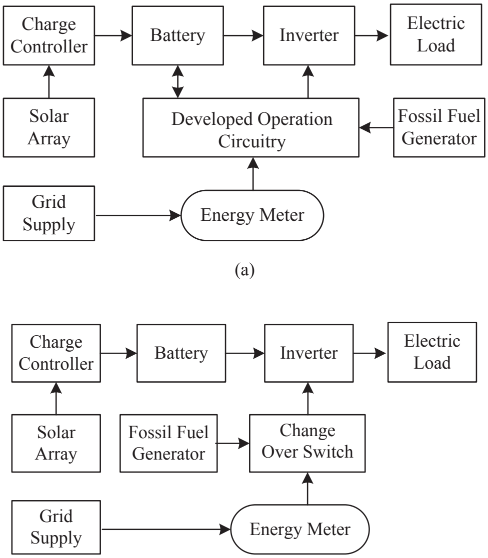
Fig. 14. Fabricated design (a) internal circuitry (b) finished/cased circuitry

D. Experimental Setup

Fig. 15 shows the experimental setups of the developed strategy and the baseline (conventional) strategy, which considers the grid supply as primary. The experiment was conducted in Benin City, Nigeria (Lat. 6˚18.6′N, Long. 5˚32.8′E) for two typical days (February 18 and February 19, 2018), within a 9 hour cycle (9:00 – 18:00 hours) each day.

The developed strategy was conducted on the first day (February 18) while the baseline scenario was performed on the second day (February 19). Same components: 300W solar panels, 200Ah batteries, 1.2kVA inverter and 200W loads; were used in both cases. For a typical grid supply schedule in Benin City, electricity is available for about 3 hours within a 9 hour cycle. Nevertheless, the grid was available for 90 minutes (1.5h) for each observation (baseline and developed strategies).

The current and voltage profiles of the solar array and battery bank were monitored in both cases. The grid energy drawn (consumed) was also recorded. These parameters were taken at an interval of 3 minutes. The grid energy drawn by the load was measured by analogue watt-hour meters, since it records energy consumption cumulatively.



(a)

(b)

Fig. 15. Schematics of experimental setups for (a) developed strategy (b) baseline strategy

III. Results and Discussion

Fig. 16 illustrates the current profiles of the solar array and battery bank for both strategies observed during the experimental cycle on the 18th and 19th of February, 2018. The corresponding voltage profiles are shown in Fig. 17.

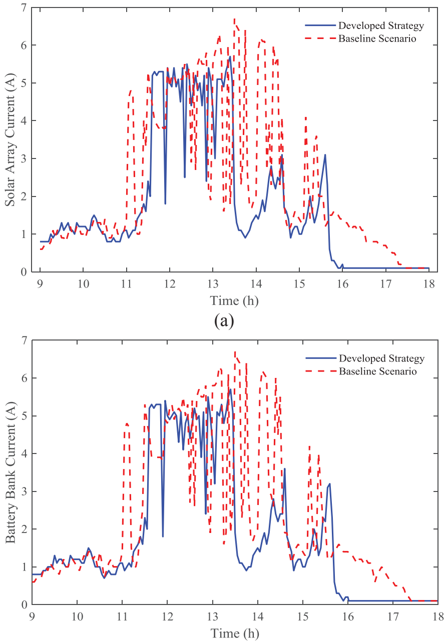
Table I compares the average values of the solar array and battery bank profiles for developed and baseline strategies observed during experimental days. As observed, that the solar array supplied more current (>37%) due to relatively higher solar radiation observed during the baseline scenario compared to solar radiation observed during the developed strategy. Fig. 16(a) and Fig. 17(a) justify that higher current and voltage are delivered by the solar array due to elevated solar irradiance on the 19th of February, 2018. The variation between the average solar array and battery currents could be attributed to losses in the conductor used.

In spite of the higher solar irradiation (hence, higher average current) received, the baseline scenario supplies power for a total of 7 hours 24 minutes (7.40h) switching on the generator at 16.40h as displayed in Fig. 17(b). Conversely, the developed strategy supplies power for a total of 7 hours 57 minutes (7.95h) before switching on generator 16.95h.

TABLE I

COMPARISON OF AVERAGE CURRENT AND VOLTAGE PROFILES OF EXPERIMENTAL SETUPS OBSERVED FOR TWO TYPICAL DAYS

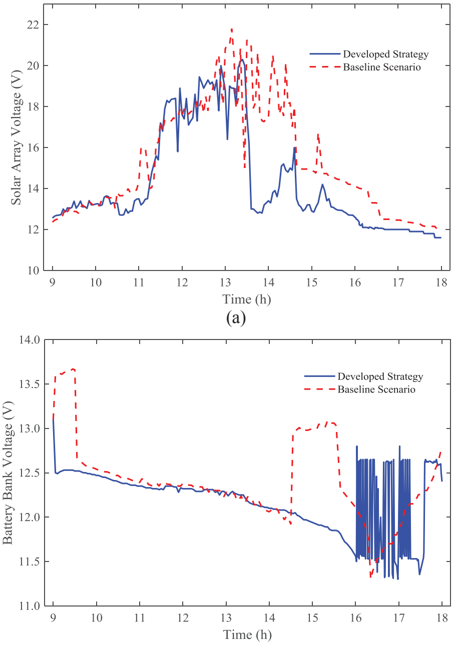
Strategies	Average solar array current (A)	Average battery current (A)	Average solar array voltage (V)	Average battery voltage (V)
Developed strategy (observed Feb. 18, 2018)	1.69	1.66	13.60	12.17
Baseline scenario (observed Feb. 19, 2018)	2.32	2.29	15.30	12.41
% increase	37.28	37.95	12.50	1.97



(a)

(b)

Fig. 16. Comparison of current profiles for two typical experimental days (developed strategy on Feb. 18 and baseline scenario on Feb. 19) for: (a) solar array and (b) battery bank



(a)

(b)

Fig. 17. Comparison of voltage profiles for two typical experimental days (developed strategy on Feb. 18 and baseline scenario on Feb. 19) for: (a) solar array and (b) battery bank

With the developed strategy, the power supply availability of the grid enhanced from 1.5 hours to 7.95 hours, with a corresponding improvement in the power supply reliability of 71.6% (from 16.7% to 88.3%). Conversely, the baseline scenario accounts for power supply reliability improvement of 65.5% (from 16.7% to 82.2%). This result indicates that the developed strategy has power supply reliability improvement of 6.1% compared to the baseline approach. Greater improvement in power supply reliability would have been achieved for the developed strategy if the 37.95% shortfall of solar current observed during February 18, 2018 (see Table I) was supplied.

The fuel consumption of the generator used to energise the load to prevent downtime is compared in Fig. 18. The comparison of the grid power consumption profile for both strategies is shown in Fig. 19.

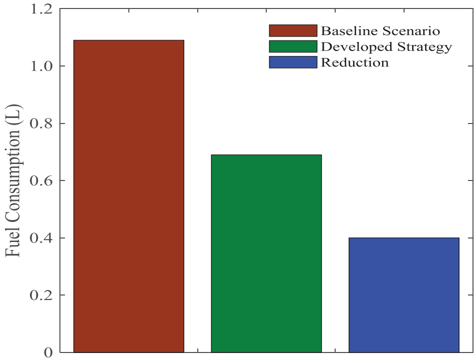


Fig. 18. Comparison of fuel consumption for developed strategy and baseline scenario

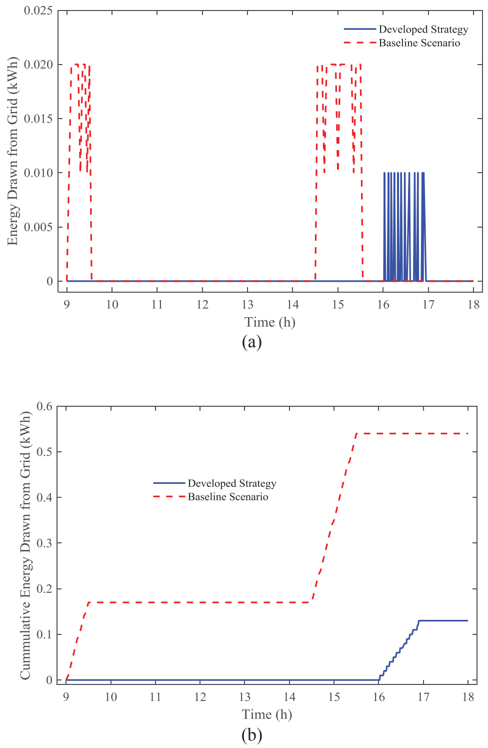


Fig. 19. Comparison of energy drawn from the grid for two typical experimental days (developed strategy on Feb. 18 and baseline scenario on Feb. 19) for: (a) energy drawn (b) cumulative energy drawn

The developed strategy is advantageous in terms of CO_2 emission. As shown in Fig, 18, pollutant emission released into the atmosphere as a result of fossil fuel combustion can be reduced by 36.7%.

As observed (Fig. 19), the grid energy drawn by the 200W load for the baseline scenario is considerably higher (0.39kWh) compared to energy drawn (0.13kWh) by the developed strategy. In terms of energy savings, the developed operation strategy gives energy savings of 66.7% (from 0.39kWh to 0.13kWh) compared to the conventional technology. The high energy saving as well as improved power supply reliability of developed strategy has become increasingly necessary especially in the face of exorbitant power supply rates of the various electric power distribution companies in the Nigeria.

IV. Conclusion

To ensure the sustainability of electric power, the micro power system can be used to integrate energy sources in an effective way following a functional operation strategy. The traditional (baseline) operation strategy recognises the utility grid as the primary source of power supply. Hence, it takes precedence when available.

In this paper, a control switching system for a micro power system made up of the utility grid, PV array and a fossil fuel generator with a battery bank was designed, simulated and fabricated. The system design was realised through the use of discrete electronics components. The components were soldered on the Vero board and were cased in a wooden and Perspex container. The developed operation strategy controls the energy flow, reduces monetary cost of the energy and ensures maximal utilisation of the micro power system. In addition, the operation strategy monitors the battery voltage and decides which of the energy source can power the load. This essentially can ensure energy sustainability thereby reducing cost.

Upon testing, the device performed in line with the expected results. It was found that the developed strategy reduces the grid power consumption by 66.7% with an improved power supply reliability of 6.1% as well as emission reduction of 36.7% compared to the conventional (baseline) strategy presently used in Nigeria. The high improvement in monetary cost savings of grid power consumption especially in Nigeria can improve the economic wellbeing of the citizens.

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