DESIGN AND OPERATION STRATEGY FOR A GRID-CONNECTED MICRO-GRID SYSTEM

By

IBHARUNUJELE, Solomon Obhenbhen
AAU/SPS/FET/ELE/M.Eng/15/09966

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING,
FACULTY OF ENGINEERING AND TECHNOLOGY,
AMBROSE ALLI UNIVERSITY,
EKPOMA, NIGERIA.

MAY, 2018

DESIGN AND OPERATION STRATEGY FOR A GRID-CONNECTED MICRO-GRID SYSTEM

By

IBHARUNUJELE, Solomon Obhenbhen
AAU/SPS/FET/ELE/M.Eng/15/09966
B.Eng. (Benin), MNSE.

A THESIS IN THE DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING, SUBMITTED TO THE SCHOOL OF POSTGRADUATE STUDIES, IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF MASTERS DEGREE (M.Eng) IN ELECTRONICS/TELECOMMUNICATION, FACULTY OF ENGINEERING AND TECHNOLOGY, AMBROSE ALLI UNIVERSITY, EKPOMA, NIGERIA.

MAY, 2018

DECLARATION

I hereby declare that this research work was done by IBHARUNUJELE, Solomon Obhenbhen and to the best of my knowledge, this research work has not been submitted elsewhere for the award of Masters of Engineering or any other degree or diploma.

…….…………………………………..   ………………………………..

IBHARUNUJELE Solomon Obhenbhen   **Date**

AAU/SPS/FET/ELE/M.Eng/15/09966

CERTIFICATION

This is to certify that this study was carried out by IBHARUNUJELE, Solomon Obhenbhen with Matriculation number AAU/SPS/FET/ELE/M.Eng/15/09966, in the Department of Electrical and Electronics Engineering, Faculty of Engineering and Technology, School of Postgraduate Studies, Ambrose Alli University, Ekpoma.

…………………………….. …………………………

Engr. Dr. Okundamiya, M. S. **Date**

Supervisor
Department of Electrical and Electronics Engineering,
Faculty of Engineering and Technology,
Ambrose Alli University,
Ekpoma, Nigeria.

…………………………….. …………………………

Engr. Dr. Okundamiya, M. S. **Date**

Head of Department
Department of Electrical and Electronics Engineering,
Faculty of Engineering and Technology,
Ambrose Alli University,
Ekpoma, Nigeria.

.... ………………………

External Examiner **Date**

DEDICATION

This research is dedicated to God Almighty for giving life and strength to come this far in my studies. To Him be all the glory.

ACKNOWLEDGEMENT

I wish to express my profound gratitude and appreciation to God for His unfailing love and care in sustaining my life, to Him be all the glory, honour and adoration forever and ever.

I sincerely thank my supervisor, Engr. Dr. M. S. Okundamiya, for his immerse contribution during this programme. I also thank Engr. Dr. O. Omorogiuwa for his concern, support and encouragement during the programme. Similarly, Dr. A. O. Osahenvemwen was also of great encouragement. God bless you Sir.

Very warm appreciation goes to all staff of the Department of Electrical and Electronics Engineering for their support in one way or the other to the successful completion of this programme.

I also acknowledge my family members – Parents and Siblings for their moral support throughout the programme. My friends and classmates are not left out. I appreciate you all.

ABSTRACT

The economic growth of any country is hinged on reliable and efficient power supply. Many developing countries have not attained sufficiency in energy generation. Hence, there is a need to strategize to meet the ever-rising demand for energy. The micro-grid system can provide a way of escape from this problem as it harnesses the strengths and weaknesses of different energy sources to attain stability in energy provision. The overall aim of this research is the design and operation strategy for a grid-connected micro-grid system for reliable and cost effective energy utilisation. The designed micro-grid, which is made up of three power sources (solar photovoltaic, grid and fossil-fuelled generator), utilises a microcontroller based system to reliably organise the flow of the hybrid power mix from energy sources and battery bank in a cost-effective manner. The microcontroller was programmed to monitor the DC voltage levels of the battery to decide which of the sources powers the load. Results showed that the developed operation strategy proffers appreciable techno-economic benefits especially in areas of energy savings and power supply availability. The developed strategy yielded a grid energy savings of 66.7% and a reliability improvement of 6.5% compared to the conventional strategy. 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 Nigeria.

CONTENTS **Page**

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AC	Alternating current
AESO	Africa Energy Sector Outlook
BLDC	Brushless Direct Current
CMOS	Complementary Metal Oxide Semiconductor
DC	Direct Current
DG	Distributed Generation
ES	Energy Storage
FC	Fuel Cell
HES	Hybrid Energy Systems
IC	Integrated Circuit
JADE	Java Agent Development framework
LCD	Liquid crystal display
LED	Light emitting diode.
MCU	Microcontroller unit
MG	Micro-Grid

MPPT	Maximum power point tracking
PCB	Printed Circuit Board
PIC	Programmable Intelligent Computer
PIV	Peak Inverse Voltage
PMSG	Permanent magnet synchronous generator
PV	Photovoltaic
PWM	Pulse width modulation
SPICE	Simulation Program with Integrated Circuit Emphasis
TTL	Transistor-Transistor Logic
UNDP-GEF	United Nations Development Programme- Global Environment Facility

CHAPTER ONE

INTRODUCTION

1.1 Background to the Study

A major problem hindering the economic growth of most developing countries is unreliable and inefficient power solution. According to the Africa Energy Sector Outlook, an estimate of over 93 million people cannot access electricity in Nigeria; about 80% of these people, who currently lack access to electricity grid, are rural populace (AESO, 2017). In spite of this problem, the electricity supply is not reliable. The reliability fluctuates between 39 and 66 percent and the grid electricity can only be accessed for an average of 6 hours per day (Okundamiya, 2015). If much of the power required to meet the deficit electricity demand was to come from fossil fuels, it could hamper global efforts to reducing the pace of global warming (Okundamiya and Ogujor, 2017). The social and economic impacts associated to these drawbacks could be very alarming.

A micro-grid system can intelligently control distributed power resources and the connected loads while operating independently from or in parallel with the grid. In addition, it can efficiently supply electric power with improved reliability and power quality by integrating and optimising a mix of power sources. It is important that the various energy sources are properly optimised in order to harness its full potentials in terms of its techno-economic implications. The micro-grid design analysis is a pre-requisite for optimum capacity allocation of system components that can guarantee reliable and efficient operation of a micro-power system. Nevertheless, the feasibility of a micro-grid system depends on the mix of energy sources, the allotted power capacity as well as the energy dispatch strategy (Okundamiya and Omorogiuwa, 2016).

Hybrid energy systems are widely utilised as alternative sources of electrical power generation owing to the advances in green energy and power electronics technologies (Chen, Duan, Cai, Liu and Hu, 2011; Okundamiya, 2016; Okundamiya and Ojieabu, 2017). The utilisation of hybrid energy sources could permit improved power system efficiency and reliability as well as a reduction in the energy storage requirements compared to systems with a renewable source. The mixture of different energy sources depends on the enabling technology. Wind and solar are the most promising renewable power sources globally, leading other energy sources in making the surroundings cleaner and more environmentally friendly. However, these sources depend highly on the site meteorology. Hence, the range of economic and technical benefits that can be derived from the hybrid energy systems varies from one place to another (Okundamiya, Akpaida and Omatahunde, 2014). Consequently, the sustainability of hybrid energy systems that include renewable power options should be examined as this could allow potential investors decide on the most suitable design for efficient operation of the micro-grid technology (Okundamiya, Emagbetere and Ogujor, 2014a).

1.2 Statement of the Problem

The rising demand for a sustainable electricity supply is motivating global interests in alternative power technologies. To resolve the problem of inadequate electricity, different hybrid energy systems have been designed and analysed in literatures (Okundamiya, Emagbetere and Ogujor, 2014b; Okundamiya and Omorogiuwa, 2015; Chuachan and Saini, 2016; Han, Chen and Li, 2017; Jurasz and Piasecki, 2017; Kim, Bae, Baek, Nam, Cho and Chang, 2017).

The integration of a hybrid storage/energy system requires the management of energy flow among the different sources (Okundamiya and Nzeako, 2010; Lanre, Mekhilef, Ismail and

Moghavvemi, 2016). An efficient energy management strategy in addition to correct size of the system components is required to reduce the monetary cost of the power system (Han *et al.*, 2017). The operation strategy, which typically depends on the topology of micro-grid system can systematically supervise and guide the flow of energy throughout the power system, thereby minimising the cost of energy drawn to perform a specified function with its requirements (Okundamiya, Emagbetere and Ogujor, 2017). The operation strategy can therefore ensure maximum utilisation of energy sources, integration and optimisation of the combined energy. This will in turn result in cost minimisation, components durability and improvement in power reliability of the system.

This study seeks to integrate various energy sources with a developed strategy not reported in other works. It attempts to minimise the rising cost of grid power supply, high dependence of renewable energy on meteorological factors and the harmful effect of burning fossil fuels on the environment. This was realised by simple electronic components, controlled by a programmed microcontroller.

1.3 Objectives of the Study

The overall aim of the study is the design and operation strategy of a grid-connected micro-grid system for efficient provision of energy.

The specific objectives of this study are to:

(a) design a control switching system that will maximise electrical power from alternative energy sources;

(b) simulate and develop a prototype of the designed control switching system for grid connected micro-grid system; and

(c) evaluate the performance of the developed system.

1.4 Scope of the Study

The grid-connected micro-grid described in this study is limited to three energy sources; solar photovoltaic, grid power supply and fossil-fuelled generator. These are being controlled by a fabricated module made from electronic components and a programmed microcontroller for switching.

1.5 Research Methodology

The set objectives of this study are to be achieved by the following methods:

(a) design of the control switching system is to be realised by the use of hardware electronic components like resistors, capacitors, diodes and microcontroller. The parameters (values) of these components would be determined using the basic circuit theorems – Ohms and Kirchhoff's laws, which are available in literature;

(b) design will be simulated using the "Proteus Design Suite, ISIS Professional V7.7 SP2" software. After simulation, the control switching system will be constructed using components selected; and

(c) two key indices (power supply reliability and energy saving/monetary cost benefits) will be utilised to assess the viability of the developed control switching system compared with that of conventional systems; and these parameters will be determined experimentally.

1.6 Significance of the Study

The presence of sustainable, affordable and reliable energy supply is crucial to a nation's development. The available energy sources have their pros and cons. These include the rising cost of grid power, the high dependence of renewable energy on metrological factors and the harmful effect of the use of fossil-fuel on the environment.

It is imperative that these factors are well harness to meet the ever increasing energy demand. With this designed model, energy will not only be made sustainably available, it would also be cost effective. The model itself is made from cheap electronic components, thus ensuring efficient energy management in an affordable way.

Since Nigeria has a high level of solar radiation, building a system that utilises much of solar power would be cost effective. It will also be an environmentally friendly project, seeing that it reduces both air and noise pollution.

1.7 Arrangement of the Thesis

Chapter one discusses the background to the study, statement of the problem, the objectives, overview of research methods and the significance of the study. Chapter two gives a thorough overview of relevant literature applied in the design, simulation and the fabrication of a grid-connected micro-grid system. Chapter three describes the design methods, analysis and the experimental set-up of the different methods of connection. Chapter four discusses the construction, testing and results while chapter five gives the conclusion and recommendation of the study. Appendix A gives the software programme written using assembly language. Appendix B presents the simulation slides while appendix C gives details experimental measurements for the study. The Bill of Engineering Measurement and Evaluation is presented in appendix D.

.

CHAPTER TWO

LITERATURE REVIEW

2.1 Overview of Micro-grid Systems.

Many nations of the world are making great efforts to decarbonise their energy generation systems. This has resulted in increasing interest in the solution provided by renewable energy. Hybrid energy systems (HES) and micro-grid (MG) amongst other technologies are contributing to sustainable energy development in the society. Hybrid energy systems bring together different renewable power sources and are a major step towards distributed generation (DG).

On the other hand, the micro-grid, represents a group of interconnected DGs, energy storage (ES) systems and loads (Vasquez, Guerrero, Miret, Castilla and Vicuna, 2010). The flexibility of the micro-grid is evident in its modes of connection (Tsikalakis and Hatziargyriou, 2008). The MG can be grid connected or islanded. The grid-linked mode where the micro-grid is joined to the grid, being either partly supplied from the grid or injecting power into the grid (Jiang, Wang, Jin, & Xu, 2011). Conversely, in the islanded mode, the micro-grid operates autonomously when it is disconnected from the grid.

Distributed generation is a vital component for improving the functionality of power grids to form future smart grid. The micro-grid serves as an intermediary between the DGs and the grid. It mitigates the impacts of the uncertainty and irregularity of the DGs on the external grid (Canizares and Palma-Behnke, 2014). Since it coordinates the DGs and energy storage, it can manage a number of DGs efficiently thereby maximise socio-economic gains (Khodayar, Barati and Shahidehpour, 2012). The key to micro-grids is its control and operations strategy (Kong, Bai, Hu, Li and Wang, 2016).

2.2 Components of a Micro-Grid System

The proposed micro-grid system is made up of a solar photovoltaic array, charge controller, batteries, inverter and energy meters. The first components needed are solar panels, which provide energy to charge the batteries. There are three main types of solar panel, they include the mono-crystalline, polycrystalline and the amorphous solar photovoltaic generators. The mono-crystalline is the most efficient and most expensive of the types.

The charge controller prevents overcharging of the batteries. Proper charging can prevent damage and increase the lifespan and energy throughput of the batteries. The power inverter converts the 220V AC from the grid to 12 volts DC for battery storage. Without energy storage the system can only supply power when solar irradiation is adequate or the generator is on. Batteries can be connected either in series or parallel or both (Okundamiya and Nzeako, 2010). Series connection would increase the voltage while keeping the current constant. On the other hand, connecting batteries in parallel increases the current with a constant voltage.

In connecting the components of a micro-grid of this nature, there is need to utilise the correct cable sizes to reduce energy losses. In addition, components overheating and possible damage can be prevented. Most quality charge controller units have a 3-stage charge cycle. The correlation between the voltage and current during the 3 phases of the charge cycle is shown in Figure 2.1.

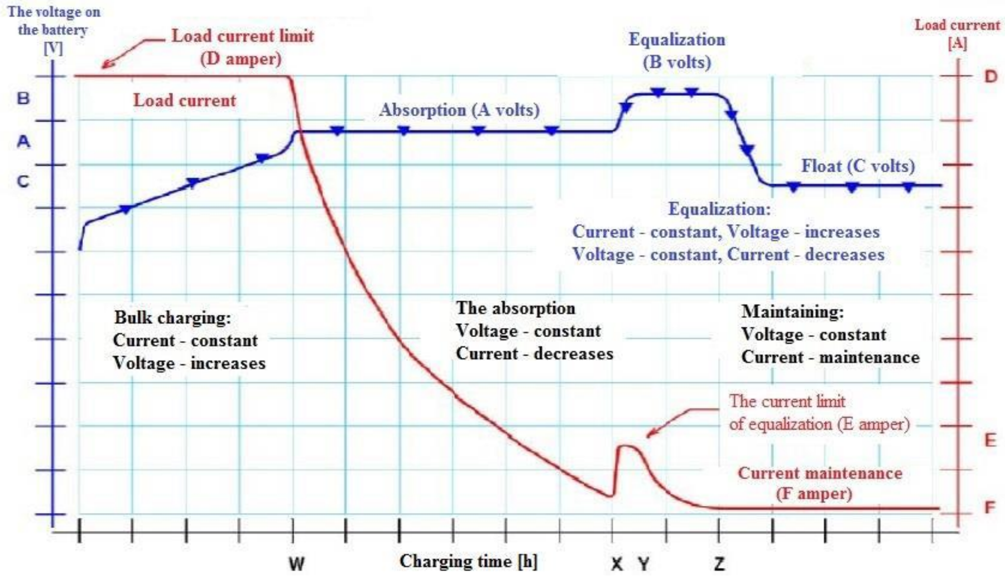

Figure 2.1: Loading characteristics of lead acid accumulator (Dini, Popa and Iagar, 2015)

The state of charge of a battery can be determined from its voltage. The rate of charge and discharge can be determined from its current. Table 2.1 shows the reference values for the state of charge of a 12volts battery and its terminal voltage.

Table 2. 1: State of charge of a battery and voltage

% of Full Charge	Voltage (V)
100	12.7
90	12.6
80	12.5
70	12.3
60	12.2
50	12.1
40	12.0
30	11.9
20	11.8
10	11.7
Completely Discharged	≤ 11.6

2.3 Proteus Simulation Software

The Proteus Design Suite is a simulation tool utilised mainly for the design and automation of electronic systems, to create electronics prints for manufacturing printed circuit boards. Schematic capture in the software can be utilised for designs simulations and for the design phase of a PCB layout project.

A major advantage of the simulator is that it can provide the user with practical feedback when designing real life systems. This can enable the designer to decide the suitability and efficiency of a design before the actual construction. By examining the impacts of definite design decisions throughout the design phase rather than the construction phase, the overall cost of the system can be reduced significantly (Marques, and Pacheco, 2007).

The advantages of using Proteus Design Software for the simulation include the ability to develop and test a design before a physical prototype is fabricated. Moreover, the simulation tool provides extensive debugging facilities including breakpoints, single stepping and variable display for both assembly code and high level language source (Dweikak, Yazori, Aldaraghmeh, 2012). Figure 2.2 shows the interface of the Proteus 7.7 Professional ISIS used in this study.

Fernandez and Paul (2015) implemented a smart micro-grid, which can serve the inter-connected loads each distributed generation (DG) on the basis of cost effectiveness. The developed micro-grid system model was implemented using the Proteus 8 Professional and the program code written in MikroC. From the results obtained, it was deduced that the system operated as required.

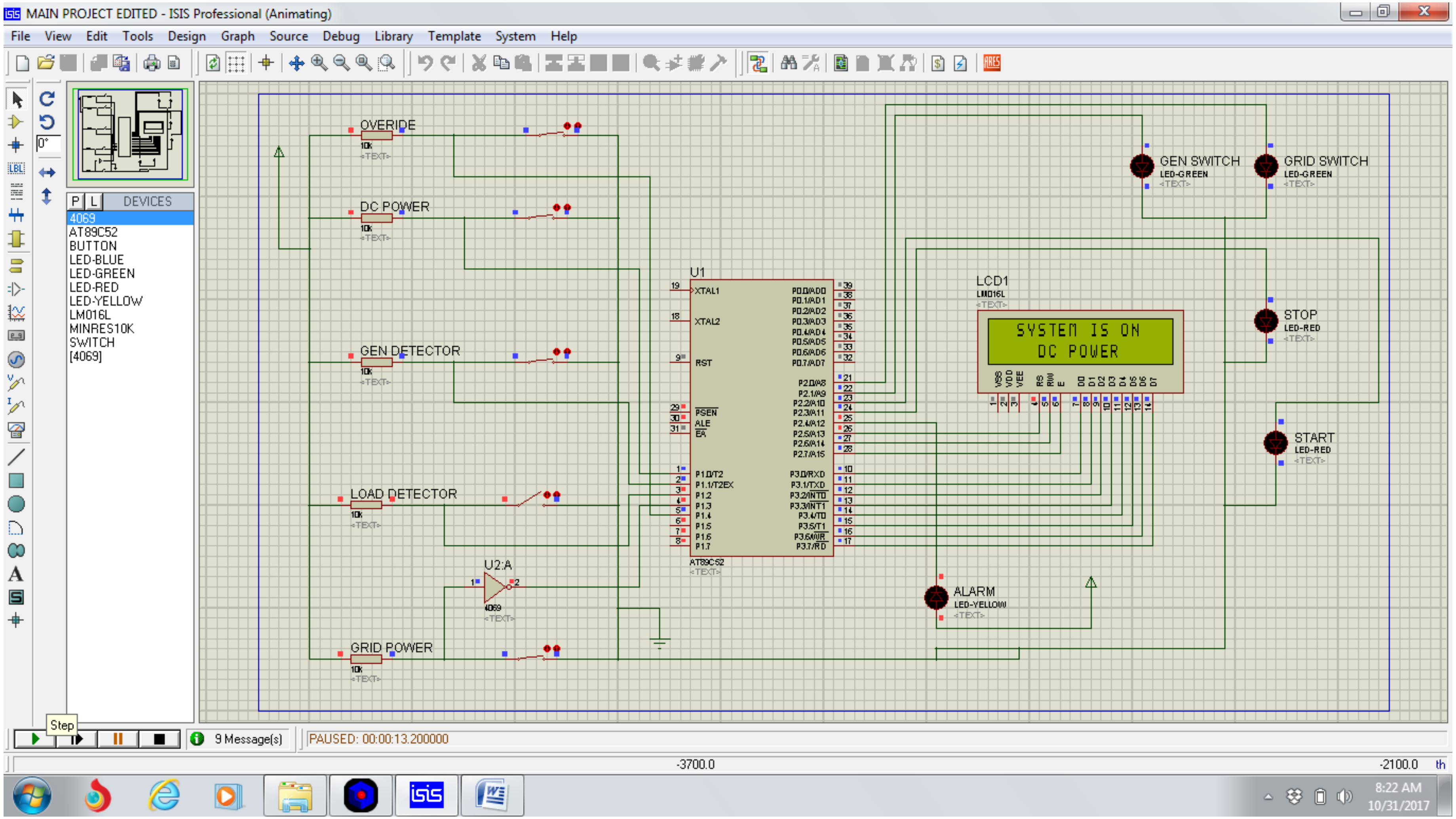

Figure 2.2: The interface of the Proteus ISIS Professional used in this study

Veeramani, Gladson, Sundarabalan and Sanjeevikumar (2016) presented a model that implements a multi-agent based control for micro-grid using an "Arduino" board capable of taking input parameters from the sensors. The design was simulated using Proteus Professional ISIS considering three different types of loads. The result showed that the model can enable the realisation of a low-cost and application-specific architecture as against conventional methods like Java Agent Development framework (JADE).

Ruban, Selvakumar, Hemavathi and Rajeswari (2017) proposed a two level fuzzy based Energy Management System. The proposed scheme was validated using hardware. The temperature, relative humidity, wind direction and wind velocity were sensed using respective sensors and the rest of the parameters were taken based on the literature. In the initial implementation of the work, the system was simulated with the Proteus software before the realisation of the hardware Wireless Sensor Network and the results exhibit proximity with the simulation results.

Ramdas (2017) presented the scope of using Brushless Direct Current (BLDC) motors for elevator systems suitable for operating with DC micro-grid on high rise buildings. A PROTEUS 8 Professional simulation model was developed utilising the different electrical and mechanical components accessible in Simulink library for the elevator system. The effective working of the proposed system was ascertained with the help of a three floor prototype laboratory model which consisted of mechanical components (such as pulley and worm gear); set of sensors for detecting the floor position and rotor position of the motor; user command buttons; LED indicators and BLDC motor along with power and programmable intelligent controller (PIC) control circuits.

2.4 State-of-the-Art Assessment of Micro-grid System Technology

A micro-grid is an arrangement that combines two or more renewable power resources with a facility for energy storage or utility grid. The following paragraphs give a discussion of various works about the configurations and control strategies used to operate such systems.

Chen, Cheng and Wu (2006) proposed a system which comprised of wind and solar photovoltaic (PV) connected to grid. The maximum power point tracking (MPPT) was implemented by a multiple input DC-DC converter. If a source is unable to generate power, the DC-DC converter can still transfer the maximum power from the other source. The DC power is converted to the AC power by a full bridge converter. The operation strategy is implemented using a microcontroller. Li, Zhang, Li and Xu (2012) proposed a similar HES approach, but a single phase current hysteresis pulse width modulation (PWM) control strategy was recommended for the three-phase DC-AC inverter. The hysteresis control provided a fast and accurate response (Prutianu and Popescu, 2010). Nevertheless, it produces a variable switching frequency in the converter (Almi and Marrouf, 2010)

Dali, Belhadj and Roboam (2010) presented a HES system that comprised of a DC and AC linked solar- wind sources. The different modes, either standalone or grid connected were implemented by a dSPACE based controller. All the sources were connected in parallel through their various DC – DC converters to a common DC bus, and a MPPT algorithm was applied. However, the battery storage was not controlled. It was connected directly to the DC bus bar.

Ahmed, Al-Othman and Al-Rashidi (2011) presented a HES which comprised of wind and solar sources with fuel cell as the storage device. The DC-DC converters of the PV array and wind sources are integrated with voltage-based MPPT control technique to extract the maximum power from the energy sources. The system can be connected to the utility grid. A voltage controller is installed at each source to control the output voltages from the sources. The inverter, which connects the DC and AC buses is single phase and it is current controlled. It also controls the current infused into the grid and regulates the DC bus voltage.

A similar DC and AC linked HES approach was proposed by Das, Esmaili, Xu and Nichols (2005). In this setup, the current control voltage source inverter is connected to the utility grid. Its control strategy is such that, the DC bus voltage is controlled to ensure sufficient injection of the active power into the grid (Esmaili, Xu and Nichols, 2005). This controller generates reference active power for inverter control. The components of the inverter output currents are generated using rotating reference frame. The active and reactive power injected into the utility are controlled by the inner current control loops by independently controlling the current components. This control approach is more appropriate for three-phase load.

Bo, Li and Zheng (2010) presented a micro-grid system comprised of wind, solar, battery and super-capacitor. A speed control based on field orientation is realised by fixing one current component reference to 0 and uses the other component current to control the rotational speed of the permanent magnet synchronous generator (PMSG) in accordance with the variation in the speed of the wind. The control strategy controls the converter of the storage unit. The configuration uses a DC bus control strategy similar to the proposal of Esmaili *et al*. (2005) to regulate the active and reactive power flow. The proposed system also works with three-phase load.

A standalone micro-grid model that combines three renewable energy resources was presented in Jiang and Yu (2009). The single three-phase inverter utilises an active power and voltage control scheme. The control strategy is made up of two cascade loops to maintain the active power injection and the amplitude of the AC bus. The inner current control loops also regulates the components of the inverter output current in the rotating frame. The compensated outputs of the current controllers are utilised to generate gate control signals for the inverter switches (Arul, Ramachandaramurthy and Rajkumar, 2015).

The control strategy for a standalone three-phase voltage source inverter proposed by Nie, Wei and Shao (2011) is based on fuzzy logic. For this controller, the parameters of a proportional-integral (PI) controller is set by fuzzy logic rules to yield a greater response.

Li and Kao (2009) proposed three renewable energy resources coupled with energy storage and an inverter that interfaces with the grid. From the control strategy, the virtual inductance efficiently decouples and precisely controls the real and reactive power in both the standalone and the grid-connected mode. However, in virtual inductance, the differentiation of line current can result in high frequency noise amplification. In turn, this may destabilise the voltage control scheme especially during transient events. To mitigate the effect of noise amplification, a low pass filter is included by Matas, Castilla, De Vicuña, Miret and Vasquez (2010). To overcome the effect of excessive noise, a high pass filter was added (Guerrero, Vicuña, García, Matas, Castilla and Miret, 2005). Nevertheless, the arrangement is the trades off between the stability of the overall control scheme and the accuracy of the virtual inductor.

Ipsakis, Voutetakis, Seferlis, Stergiopoulos, Papadopoulou and Elmasides (2008) evaluated the performance of two power management strategies in operating a hybrid power system, which consists of solar photovoltaic, wind and hydrogen storage. The result showed the effect of variation of the hysteresis band gap on the overall performance of the system as a basis for the development of power management strategies.

Liao and Ruan (2009) introduced a control strategy for an isolated solar photovoltaic/battery power system. The objective was to control the power flow of the converter to operate in suitable modes based on the battery state-of-charge and prevailing weather conditions. The strategy claimed to coordinate the solar source and the battery storage to ensure high power system efficiency with a good dynamic performance. The validation results showed a good performance.

Dursun and Kilic (2012) studied the performance of different operation strategies for off-grid hybrid energy system made up of solar photovoltaic, wind and fuel cell. The aim was to increase the operation of the fuel cell membrane to guarantee continuous flow of energy in the hybrid system. The operation strategy in which the fuel cell operates to supply the load and charge the battery when the battery's state of charge reduces below the pre-defined limit, was found to produce the best results in terms of battery efficiency with an efficiency rating of about 85%.

Ismail, Moghavvemi and Mahlia (2013) performed a techno-economic analysis of a hybrid power system made up of a PV array, battery, and fossil generator to provide power for a typical remote village in Malaysia. The operation strategy utilised gave priority to the solar photovoltaic generator and battery system for powering the load. When the battery state of charge is at minimum and the photovoltaic generator supplies deficit power, the fossil generator operates to supply the load and charge the battery.

Dahmane, Bosche, El-Hajjaji and Dafarivar (2013) developed an algorithm for optimum power management of an off-grid hybrid system with PV array, wind, diesel generator, and battery storage. On the other hand, Torreglosa, Garcia-Trivino, Fernandez-Ramirez and Jurado (2016) proposed a strategy for an isolated hybrid power system made of renewable sources and hybrid storage systems. An economic analysis that could affect the choice of selection of energy source/storage device and degradation of components was conducted to determine the lifetimes of the component, hours of operation.

Karami, Moubayed and Outbib (2014) proposed a grid-linked hybrid system with PV panels, a battery, a super-capacitor, and fuel cell. A controller was used to control the flow of energy in the integrated renewable source–grid system. The results showed the capability of the proposed system to supply the load without any interruption. It is worth of mention that the Karami *et al*. (2014) proposal was based on an uninterrupted power supply (grid). However, studies (UNDP-GEF, 2013; Okundamiya, Emagbetere and Ogujor, 2015) have shown that the Nigerian power grid is not reliable. Thus, their approach is not suitable for Nigeria.

The Dursun *et al*. (2012) proposal is built around the fuel cell as a major source of energy. The micro-grid presented in this study integrate common sources of energy adaptable for office or domestic use in the Nigerian environment. It also presents a modification of the baseline line operational strategy of common HES arrangement. In the conventional operations strategy, the utility grid is the primary source. The inverter switches over to the utility grid as soon it becomes available. By this arrangement, the utility grid supply acts as the primary source of power while the solar energy source as a secondary source. Without giving priority to any energy source, the developed strategy switches the load based on a pre-programmed operation strategy. The developed strategy shows an improvement in the techno-economic benefits. The improvement in the benefits in the developed protocol is the research gap this study attempts to fill.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Design and Analysis

In this section, the various block/units and their circuit diagrams, design analysis, criteria and assumptions made for component selection are presented. Figure 3.1 shows the functional blocks of the designed circuit.

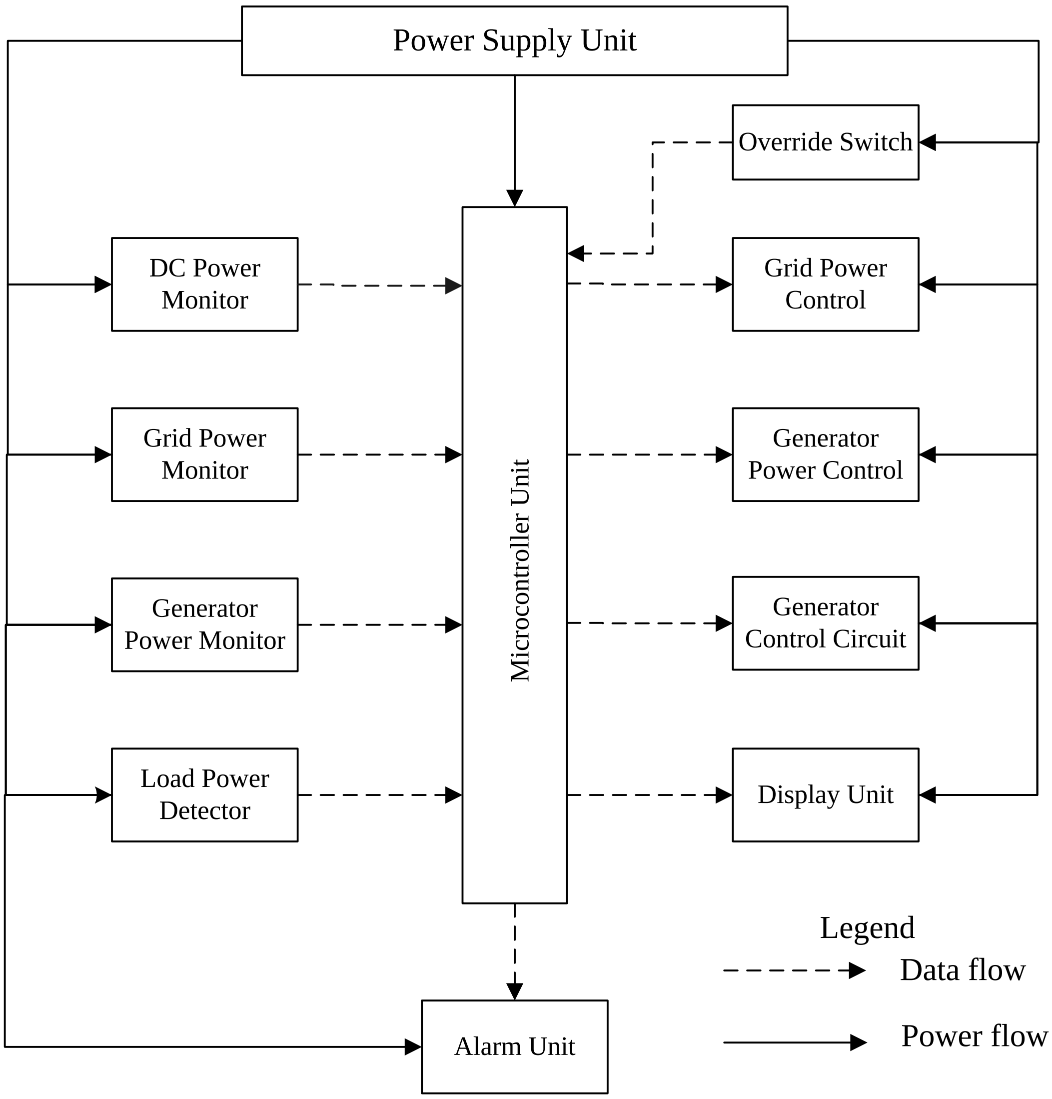

Figure 3.1: Schematics of the designed grid-connected micro-grid system

3.1.1 Power Supply Unit

The Voltage regulator (7805) was employed to supply a constant voltage to the various electronic components in the circuit. It has a maximum input voltage (V_{max}) of 32V.The actual power required is 5 volts for the microcontroller and other discrete components while the DC power required for the relays is 12 volts. The 12 volts power output was used directly from the battery to power the relays. The circuit diagram of the power supply circuit is shown in Figure 3.2.

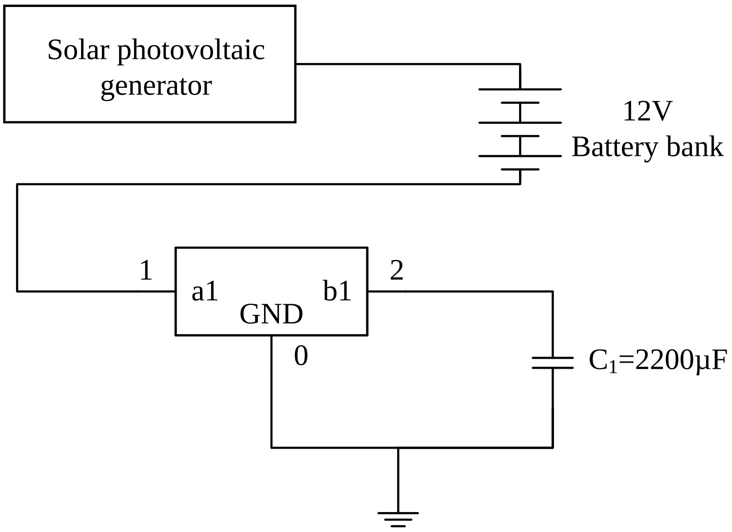

Figure 3.2: Circuit diagram for the power supply unit

Provided the operational input fed into the 7805 is within the range, the output must be 5V. The minimum input voltage of the regulator is given by equation (3.1)

$$V_{\min} = V_{ref} + V_{out}\,. \tag{3.1}$$

V_{ref} is derived from the data sheet as 2V. Hence,

$$V_{\min} = 2V + 5V = 7V\,. \tag{3.2}$$

Therefore, the range of operational input to be fed into the 7805 is from 7V to 32V. Consequently, the Voltage regulator is adequate for the 12V battery bank chosen in this study.

On the other hand, the transient Capacitor (C_1) stores charges that will be used during the brief period of switching. Usually, transient capacitors in excess of 10μF are required, but a 2200μF capacitor was chosen to enable more tolerance.

3.1.2 DC Power Monitor

This unit monitors the combined DC power gotten from the solar charge controller and the battery. If the combined power in the DC bus bar falls below a certain reference value, through this unit, our system detects it and activate an output to the microcontroller which will in turn activate the necessary action. Hence, the function of the DC power monitor is to keep track of the voltage level of the dc bus bar. This unit comprises of biasing resistors, level tracking operational amplifier and modulating logic gates.

The circuit diagram of the DC level monitor is shown in Figure 3.3. The op amps are connected in the comparator mode. It compares between two voltages and produces an output depending on the difference in the input received. An op amp has two inputs, the inverting and non-inverting. If the voltage at the non-inverting is higher than the voltage at the inverting, the output of the op amp is positively saturated and vice versa. For the sake of our system, a reference voltage is set at the inverting input using voltage divider principle. Similarly, an equal voltage is set to the non-inverting input. However, in this case, this set voltage represents the minimum reference voltage of the DC bus bar.

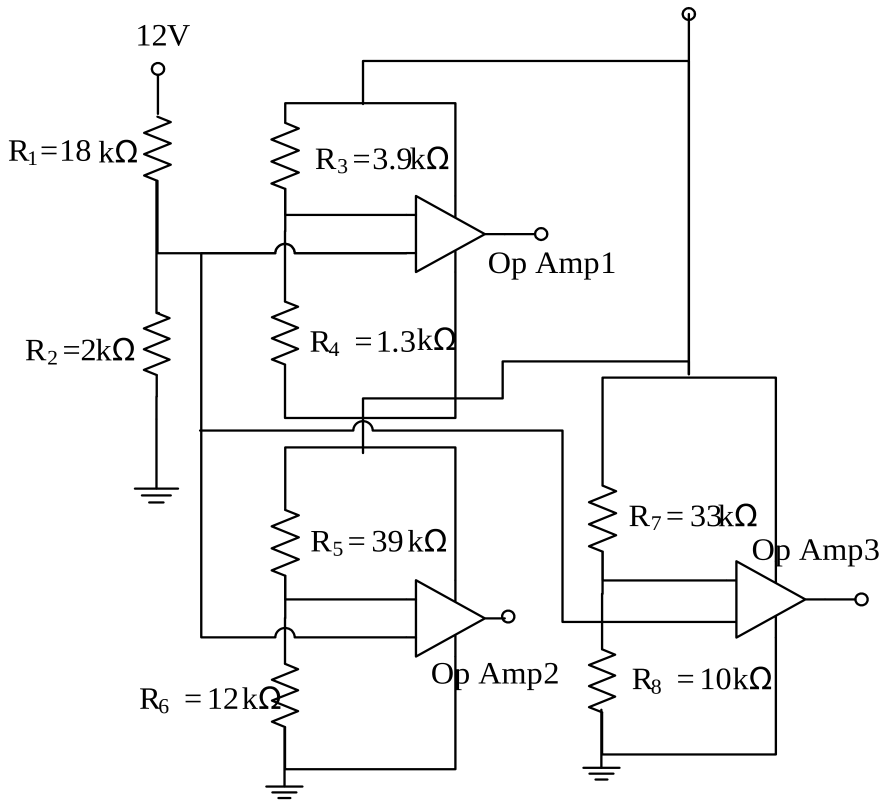

Figure 3.3: Circuit diagram of the DC level monitors

Using a voltage divider formula:

$$V_{out} = \left(\frac{R_2}{R_1 + R_2}\right)V_{supply} \tag{3.3}$$

R_1 and R_2 were used to divide the voltage from the battery by a factor of 10.

$$\frac{V_{out}}{V_{supply}} = \frac{R_2}{R_1 + R_2} = \frac{1}{10} \tag{3.4}$$

$R_2 : R_1$ of 1:9 will serve the purpose. However, R_2 = 2kΩ and R_1 = 18kΩ were used due to the fact that they are commercially available.

Resistors R_3 and R_4 were used to set the upper reference voltage level of 12.8 volts. The op amp is supplied by a 5V DC from the voltage regulator. Since, the battery voltage has been scaled down by a factor of 10 (12.8 V becomes 1.28V), the value of resistors set is given by the equation:

$$\frac{V_{out}}{V_{\sup ply}} = \frac{R_4}{R_3 + R_4} = \frac{1.28}{5} \tag{3.5}$$

A ratio of R_4 : R_3 equivalent to 1.28:3.72 will satisfy the equation. Commercial values of R_3 = 13kΩ and R_4 =3.9kΩ was selected.

Resistors R_5 and R_6 were used to set the middle reference voltage level of 12volts. The values of R_5 and R_6 were deduced by the equation:

$$\frac{V_{out}}{V_{\sup ply}} = \frac{R_6}{R_5 + R_6} = \frac{1.20}{5} \tag{3.6}$$

A ratio of R_5: R_6 equivalent to 1.20 : 3.80 will satisfy the equation. Commercially available values of R_5= 12kΩ and R_6 = 39kΩ were used.

Resistors R_7 and R_8 were used to set the lower reference voltage level of 11.4 volts. The values were deduced from the equation:

$$\frac{V_{out}}{V_{\sup ply}} = \frac{R_8}{R_7 + R_8} = \frac{1.14}{5} \tag{3.7}$$

A ratio of R_7: R_8 equivalent to 1.14: 3.86 will satisfy the equation. Commercially available values of R_7 = 10kΩ and R_8 = 33 kΩwere used.

The resistors were used to create voltage references for the trip point of the operational amplifiers. On the other hand, the operational amplifiers were used to compare the reference voltage with the input voltage.

3.1.3 Generator Power Detector

This unit senses the availability or unavailability of generator power. The system will require knowledge of whether or not the generator supplies power. This unit transmits the information to the microcontroller. It comprises of current limiting resistor, a transistor based Opto-isolator integrated circuit. The circuit diagram of the generator power detector unit is shown in Figure 3.4.

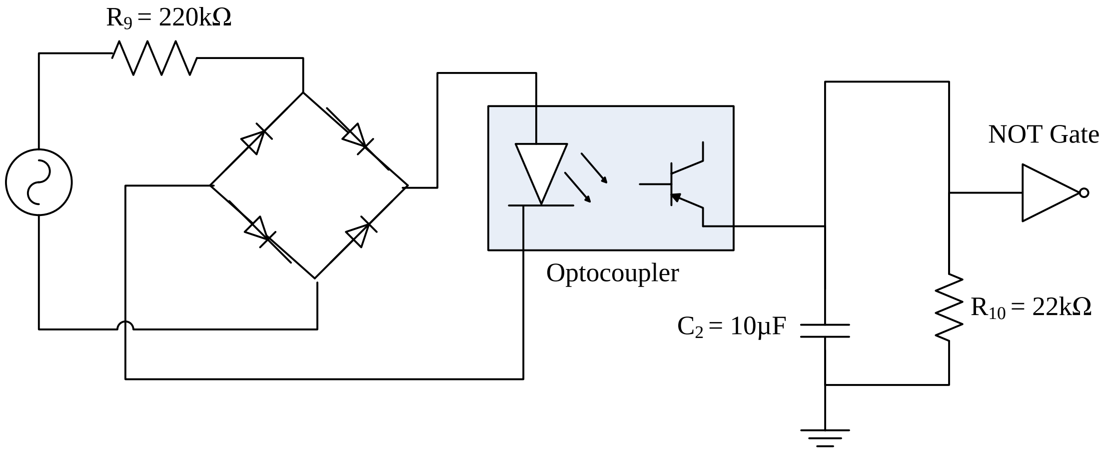

Figure 3.4: Circuit diagram of the generator power detector unit

When power is available, resistorR_9will reduce the current, the bridge will rectifier the voltage which will then lights up the LED and saturates the photo-transistor causing a short circuit between the collector and emitter; thereby creating a voltage drop on the emitter resistor R_{10}. This voltage will be impressed upon the input of the NOT gate. The output of the NOT gate will constitute an input to the microcontroller unit (MCU) to elicit a response. Resistor R_{10}= 22kΩ is a pull down resistor. Arbitrary values of pull down resistors are between 47Ω to 47kΩ. C_2serves as a transient capacitor with a value of 10μF.

The opto-isolator 4N35 was used to couple high voltage power source to low voltage power source. From datasheet, the appropriate safe operating current through the 4N35 is 1mA. The appropriate current limiting resistor value is deduced from the Ohm's law as follows:

$$R_9 = \frac{V}{I} \tag{3.8}$$

$$R_9 = \frac{220}{10^{-3}} = 220k\Omega$$

The bridge diodes rectify the alternating current to direct current which is being utilized by integrated circuit and discreet components. Logic gate links the transistor-transistor logic (TTL) and Complementary Metal Oxide Semiconductor (CMOS) components. Hence, a NOT gate is used.

3.1.4 Override Switch

This is the part the circuit that the system uses to change its mode. The microcontroller is programmed to automatically turn on the fossil fuel generator whenever there is power failure and the battery level is less than the lower reference voltage of 11.4V. The override switch is used to change from this automatic start off mode to manual start off mode and vice versa. This would mean that with the override switch on, the generator does not come on automatically; the user will have to put on the generator manually if so desired. This arrangement will save fuel since it will prevent generator from turning on when it is undesirable. The override switch unit comprises of pull up resistor and a toggle switch. The circuit diagram is as shown in Figure 3.5.

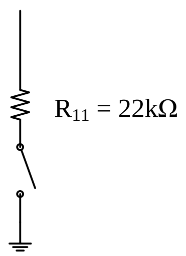

Figure 3.5: Circuit diagram for the override switch

3.1.5 Generator Power Control

This is the unit allows the generator to supply power to the load. The system has the ability to change over source of power supplied to the load, from mains to the fossil-fuel generator. This unit is in charge of this transfer. This unit comprises of biasing resistors, switching transistors, linking TRIACS based opto-isolator, AC power switching TRIACS and electromechanical contactors. The circuit diagram of the generator power control is shown in Figure 3.6.

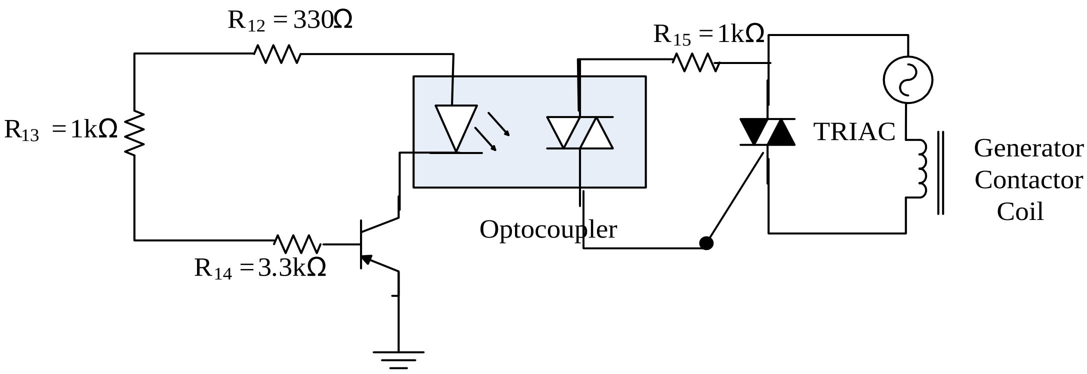

Figure 3.6: Circuit diagram of the generator power control unit

The main duty of this circuit is to energize or de-energize the coil of the generator contactor. The coil of the contactor is controlled using a TRIAC. The TRIAC is controlled by using a pre-TRIAC driver which is sometimes known as a TRIAC-based opto-coupler. This opto-controller is activated via an NPN transistor (BC547).

Every LED has a current limiting resistor, calculated by the equation:

$$R_{12} = \frac{V_s - V_d}{I_d} = \frac{5-2}{10mA} = 300\Omega \qquad (3.9)$$

However, R_{12} = 330Ω was selected because it is the nearest commercially available value.

The data sheet of BT 136 gives R_{13} as 1kΩ. R_{14} is a base resistor, given as 10 XR_{C}. This forces the transistor to saturation. R_{15}can be between 470Ω and 47kΩ. The resistor is for biasing the transistor and for limiting current. The transistor switches on or off the opto-isolator which in turn switches on/off the TRIAC. The TRIAC controls the load.

3.1.6 Grid Power Control

This is the unit that the utility grid to supply power to the load. This unit is in charge of this transfer. This unit comprises of biasing resistors, switching transistors, linking TRIACs based opto-isolator, AC power switching TRIACs and electromechanical contactors. The circuit diagram of the grid power control is shown in Figure 3.7.

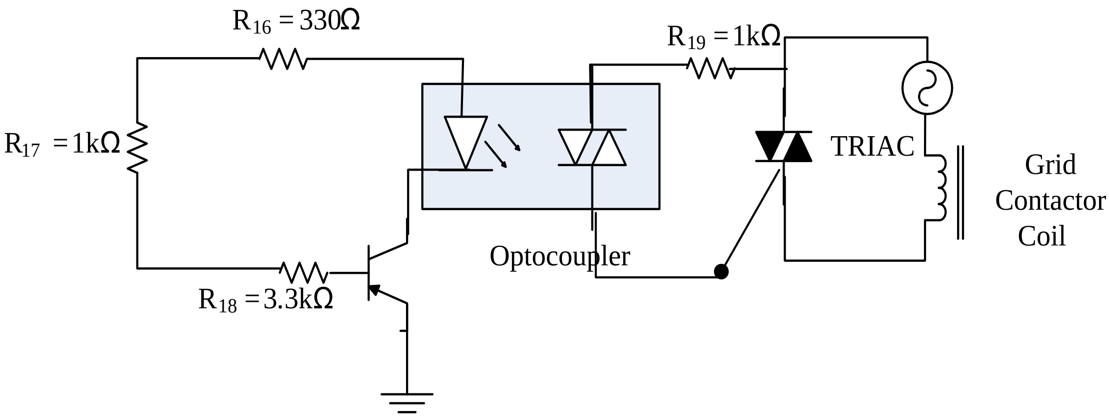

Figure 3.7: Circuit diagram of the grid power control unit

The design calculations are essentially similar to that of the generator power control of section 3.1.5

3.1.7 Generator Control Circuit:

This is the part of the circuit that turns on or off the fossil-fuel generator. This unit comprises of biasing resistors, switching transistors and control relays. The circuit diagram is shown in Figure 3.8.

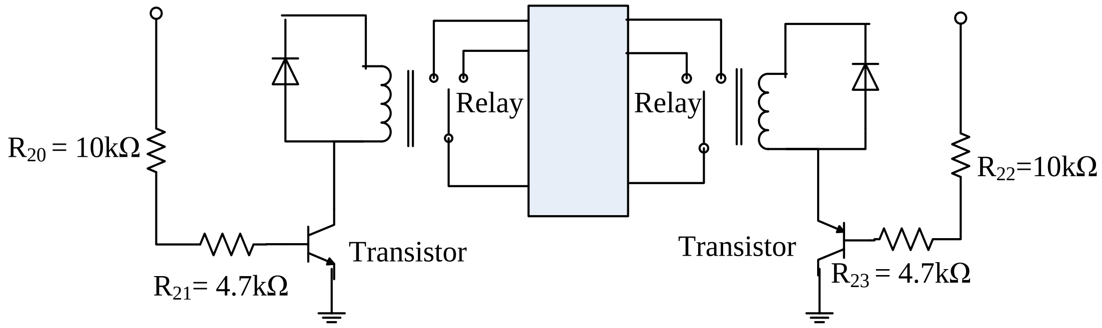

Figure 3.8: Circuit diagram of generator control unit

R_{20} is a pull-up resistor while R_{21} is a base resistor. Its value is usually 10 times the collector resistance. In this case, the collector resistance is the relay coil impedance. This is known experimentally to be 400Ω. Therefore, R_{21} = 10 x 400 = 4kΩ≅ 4.7kΩ (Nearest commercially available value). Resistor R_{21} in the circuit is for biasing the transistor and for limiting current. The transistor switches the relay which makes and breaks the contacts that turns on and off the generator.

3.1.8 Alarm Unit

This is the unit that the system uses to alert the user that a change in the power system is in progress or an error has occurred in the operations of the system. The alerting unit includes an audio alerting feature and a visual alerting one too. It is basically a 555 timer integrated circuit multi-vibrator connected in an astable mode which is designed to produce an output frequency of one hertz. This basically means that the alerting unit, once activated, will be fired every one second. It comprises of a 555 timer multi-vibrator integrated circuit, biasing resistors and capacitors, a piezoelectric buzzer, a light emitting diode and a switching transistor. Figure 3.9 shows the alarm unit circuit diagram.

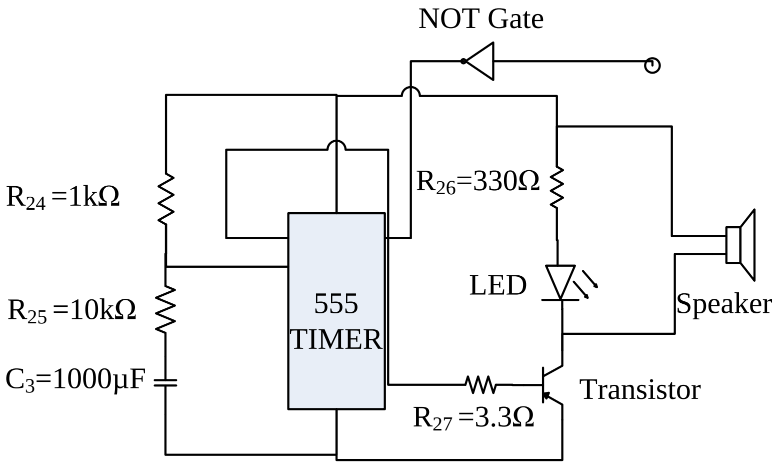

Figure 3.9: Circuit diagram of the alarm unit

The frequency of the pulses is set by R_{24}, R_{25} and C_3, by the equation:

$$F = \frac{1.44}{(2R_{24} + R_{25})C_3} \tag{3.10}$$

With a frequency of 1Hz desired, the values of R_{24}, R_{25} and C_3 chosen are 1kΩ, 10kΩ and 1000µF respectively.

$$R_{26} = \frac{V_S - V_D}{I_D} = \frac{5-2}{10mA} = 300k\Omega \tag{3.11}$$

However, the closest commercially available resistor selected is 330kΩ. The buzzer chosen has an operating range of 3V to 24V.

The 555 timer integrated circuit, connected in the astable mode produces the required pulsating output. The frequency of the output is set by the capacitor. The resistor is for biasing and current limiting. The buzzer which is a piezoelectric device is for audio alerting, while the light emitting diode is a visual alerting device.

3.1.9 Grid Power Monitor

This is the unit that the system uses to monitor the power output from the national grid. This monitoring is essential because when the grid power is not optimum, that is if it falls out of a stipulated voltage range, the system carries out some form of instructions. In other words, if the grid voltage is too high or too low, through this unit the system prevents the inflow of grid power. This unit comprises of biasing resistors, modulating operational amplifiers and logic gates. Figure 3.10 shows the circuit diagram.

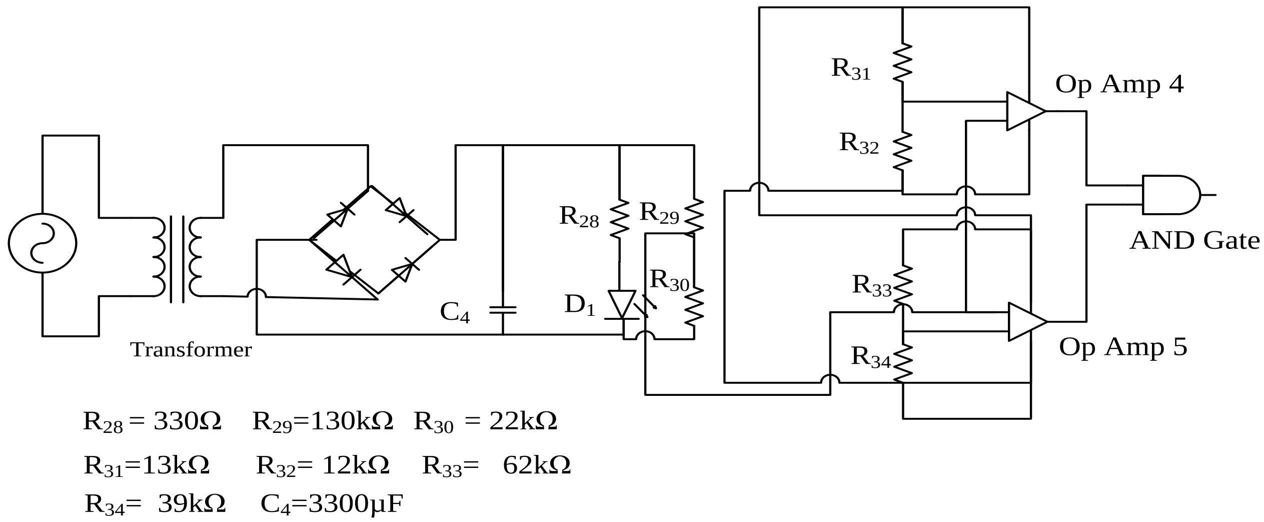

Figure 3.10: Circuit diagram of the grid power monitor

The power from the grid is first of all stepped down by transformer to a lower AC level. The bridge diodes convert the AC current to direct current (DC). The filter capacitor C_4, filters off the ripples to produce a pure DC.

LED D_1, protected by R_{28} indicates the presence of power to the circuit. R_{29} and R_{30} act as a voltage divider that modulates the voltage to a usable level. The combination of op-amps and an AND gate creates a window comparator system that gives upper and lower limits of operating voltage.

In choosing diodes, the peak inverse voltage (PIV) and the forward current I_F of the diodes are considered.

$$PIV \geq 2V_{peak} \tag{3.12}$$

$$V_{peak} = 1.414 \times 12V = 16.97V$$

$$PIV \geq 34V$$

$$I_F \geq 1.5 I_{\max}$$

$$I_F \geq 450mA$$

Considering available market values of diodes, the IN4007 with PIV = 100V and forward current I_F = 1A was chosen. The capacitor C_4 is a filtering capacitor. A capacitor with capacitance of 3300µF was used.

The voltage from the rectifier diodes is deduced by the equation:

$$V_o = V_P - (2 \times V_D) \tag{3.13}$$

$$V_o = 16.9 - (2 \times 0.7) = 15.5V$$

The current limiting resistance for LED 2 is deduced using the equation:

$$R_{28} = \frac{V_{rms} - V_D}{I_{\max}} = \frac{10.96 - 2}{10mA} = 896\Omega \cong 1k\Omega \tag{3.14}$$

The $1k\Omega$ is the nearest commercially available value to what was calculated for.

Transformer steps down the high AC voltage to a lower AC voltage. The diodes rectifies the AC voltage to pulsating DC. The output of which is filtered by the capacitor to remove ripples. The resistor limits current flow to the LED, which indicates the presence of power in the system. The operational amplifier transmits data to the system when appropriate input power is available. The logic gate modulates the output signal to only activate when the power is optimum.

3.1.10 Display Unit

This is the unit that the system uses to interact with the user. All the operations and sequences performed by the circuit is displayed on the screen. All instructions to be carried out by the system are also shown on the screen. Also the status of the system is shown on the screen. This consists of a 16 by 2 data length Liquid Crystal Display screen and its biasing resistors. Figure 3.11 is a schematic diagram of the LCD screen.

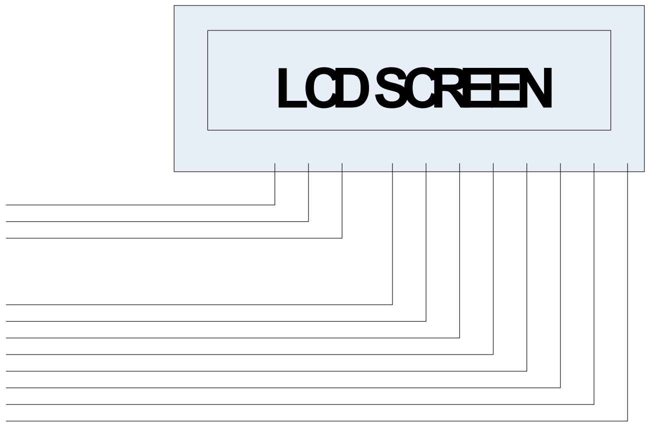

Figure 3.11: Schematic diagram of the LCD screen

3.1.11 Microcontroller Circuit

This is the heart of the whole system. All other components blocks receives signals from or sends signals to the microcontroller. This is where the protocol of operation for the system is written in form of a code and burnt into the ROM of the microcontroller. The microcontroller is an 8 bit data and code length integrated circuit that carries out instructions under the guidance of a program. It has 4 input/output ports each comprising of 8-bits and this makes it a total of 32 input/output terminals. This unit comprise of clocking circuit connected crystal oscillator and capacitors as well as reset capacitor and resistor. Figure 3.12 is the circuit diagram of the micro controller unit.

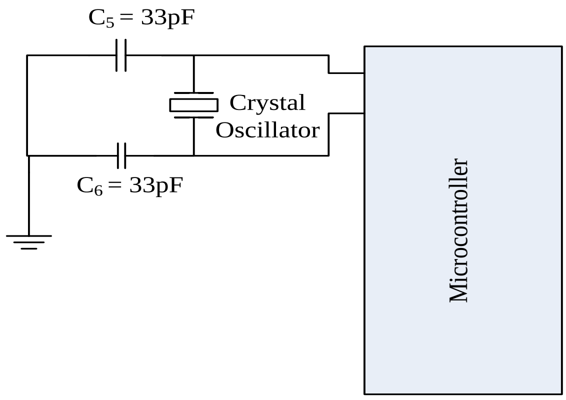

Figure 3.12: The circuit diagram of the micro controller unit

Essentially, the microcontroller is for programming of all the instruction codes that contains the sequence of operation of the system. The clock pulse of the system is set by the crystal oscillator and it associated capacitors. The resistor and capacitors are responsible for resetting the program.

3.1.12 Load Power Detector

This is the unit that the system uses to detect the presence or absence of the load power in the system. When a change over operation needs to the performed, the system requires information as to whether the operation was successful or not by monitoring the power delivered to the load. This unit comprises of current limiting resistor, modulating transistor based opto-isolator integrated circuit and linking logic gates as shown in Figure 3.13. The analysis is similar to that of generator power detector in section 3.1.3.

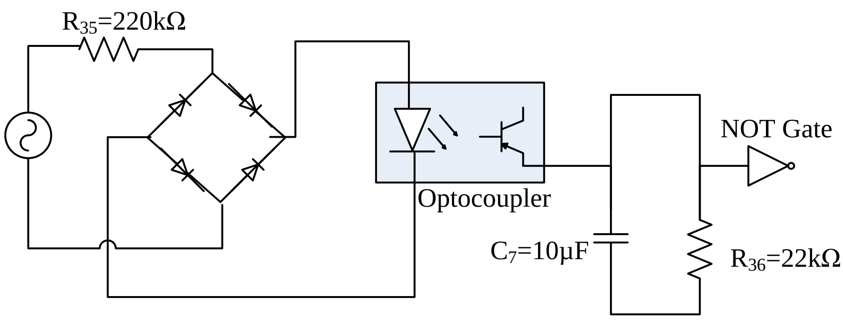

Figure 3.13: Load power detector circuit

The component units of the designed system are integrated to ensure functioning of the overall system. The complete circuit diagram is shown in Figure 3.14.

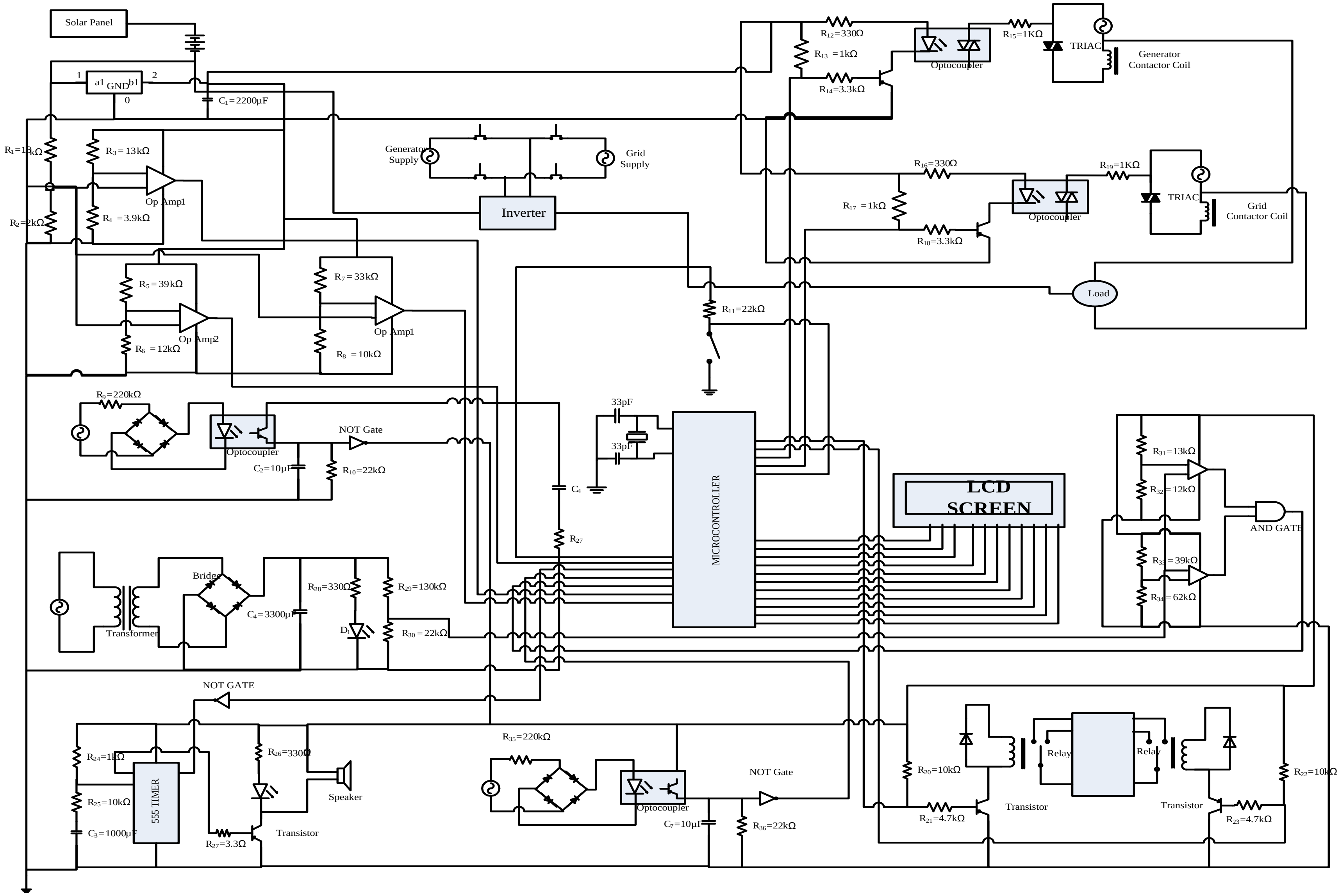

Figure 3.14: Complete circuit diagram of the designed module

The overall system functions as separate blocks that are interconnected via the microcontroller. The program that is written and burnt into the ROM of the microcontroller determines the operational strategy of the system since all the blocks sends signals to or receives signals from the microcontroller. The study is of immerse significance. It optimizes the power structure of a standard domestic or industrial environment. A system that will have multiple sources, the project will produce a more suitable method of connection so as to maximally utilize all the power available to it

3.2 Operational Strategy

The system works in such a way that it receives power from a PV source, a battery for storage, the utility grid and a fossil-fuelled generator. The operation strategy developed in the study did not regard any power source as primary. Its decision of which source powers the load was dependent on the voltage level of the battery. The entire battery voltage range is monitored by the developed supervisory controller. Three voltage reference levels were used in the decision making. The upper reference level of 12.8V; the middle reference voltage of 12.0V and a lower reference voltage of 11.4V. These voltage reference levels were set by DC voltage detectors reviewed in the design session of this work. They were programmed in the microcontroller and the system responds to take decisions when the battery voltage gets to these points.

When the battery voltage is above 12.8V, the battery is regarded as charged and hence 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. Owing to the fact that the batteries were connected to photovoltaic panels, the rate of discharge of the battery was reduced because the battery is being charged by the solar panel even while it is being discharged by the load.

At 12.0V, the system checks for the availability of utility grid supply. If available, the load requirement is transferred to the grid supply. While the load is being powered by the grid supply, it also charges the battery. 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, the load demand switches to the grid while the battery is being charged. When the battery gets drained to 11.4V, the developed supervisory controller automatically activates starting the fossil fuel generator to power the load and charge the battery. This happens before the inverter cuts off the battery supply. This switch to an alternative power supply has a protective value on the inverter. The process of starting and turning off of the generator is an automated process initiated by the microcontroller when the battery voltage has reached the lower voltage reference.

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 observer through the LCD screen. The observer can ascertain if the operation is not successful from the screen and then he will need to attend to the problem manually.

Once the generator is started, it powers the load and charges the battery. The generator will be turned off automatically when the grid power is restored or when the battery voltage gets charged up to 12.8V by the solar panels.

The result of the operation process is a self-monitored micro-grid system which caters for the availability and intermittency of the various sources of power. In the day, power is constantly 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 serves as a reserve to smoothen the inconsistencies presented by the alternative energy sources. Ordinarily, in the conventional connection, the utility grid supply is taken as the primary source of power for the load irrespective of the availability of other sources of power. By that arrangement, solar radiance is underutilized. This developed operations strategy enables switching between alternative sources depending on their availability and meteorological circumstances thus maximising the sources and minimising their drawbacks.

This operation strategy is programmed in the microcontroller using assembly language. Appendix A presents the source codes of the microcontroller. The entire operation strategy is shown in Figure 3.15.

3.3 Simulation

The simulation was done using Proteus ISIS Professional Design suite. At the heart of the simulation 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 helps ensure the availability and otherwise of these sources.

At the output of the microcontroller are LEDs which indicates when the generator and grid powers the load. LEDs also indicate when the generator is being started or stopped automatically. An LCD screen outputs the operations and error messages of the microcontroller. Figure 3.16 shows the screenshot of the Proteus ISIS interface.

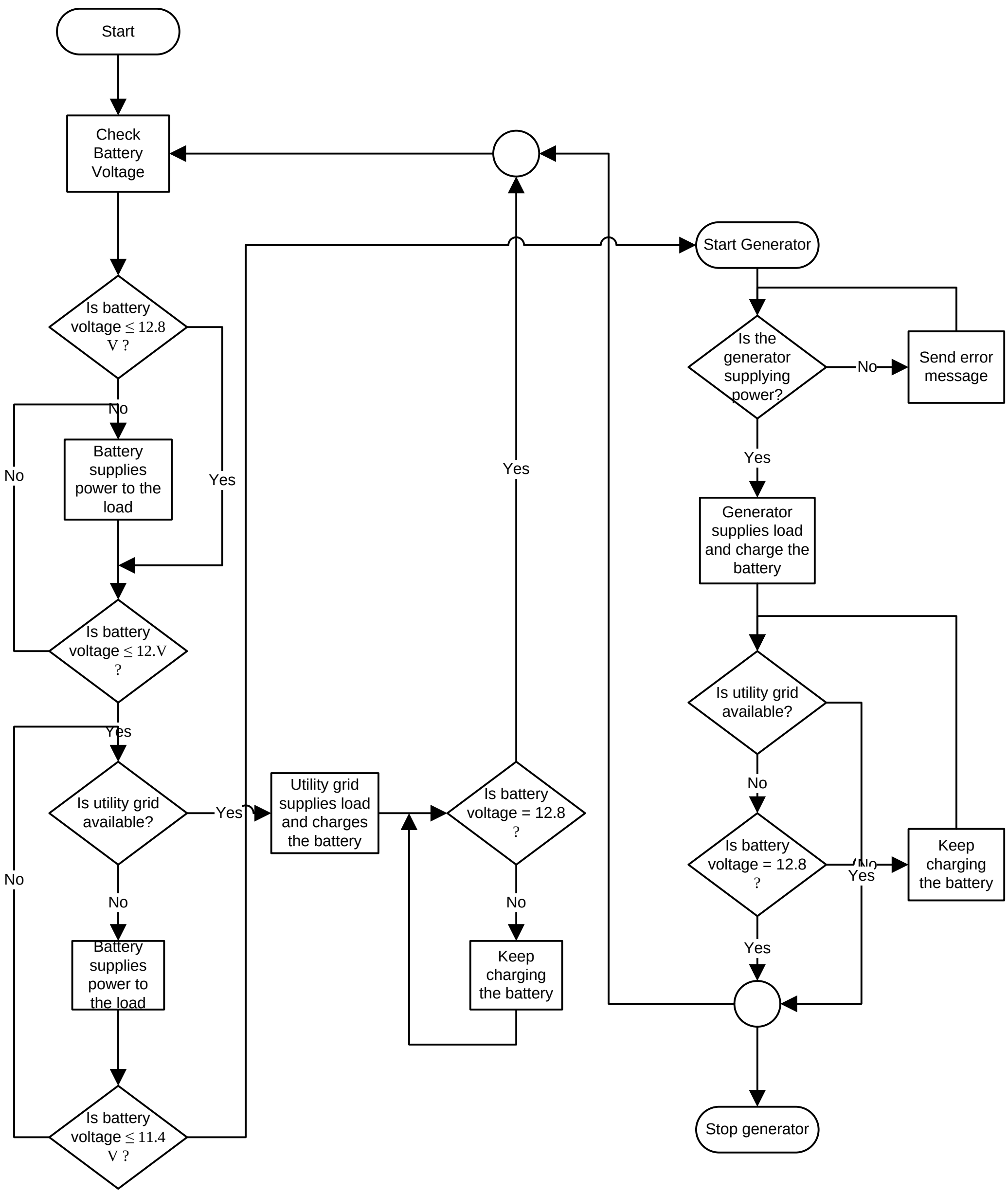

Figure 3.15: Operation strategy of the grid-connected micro-grid

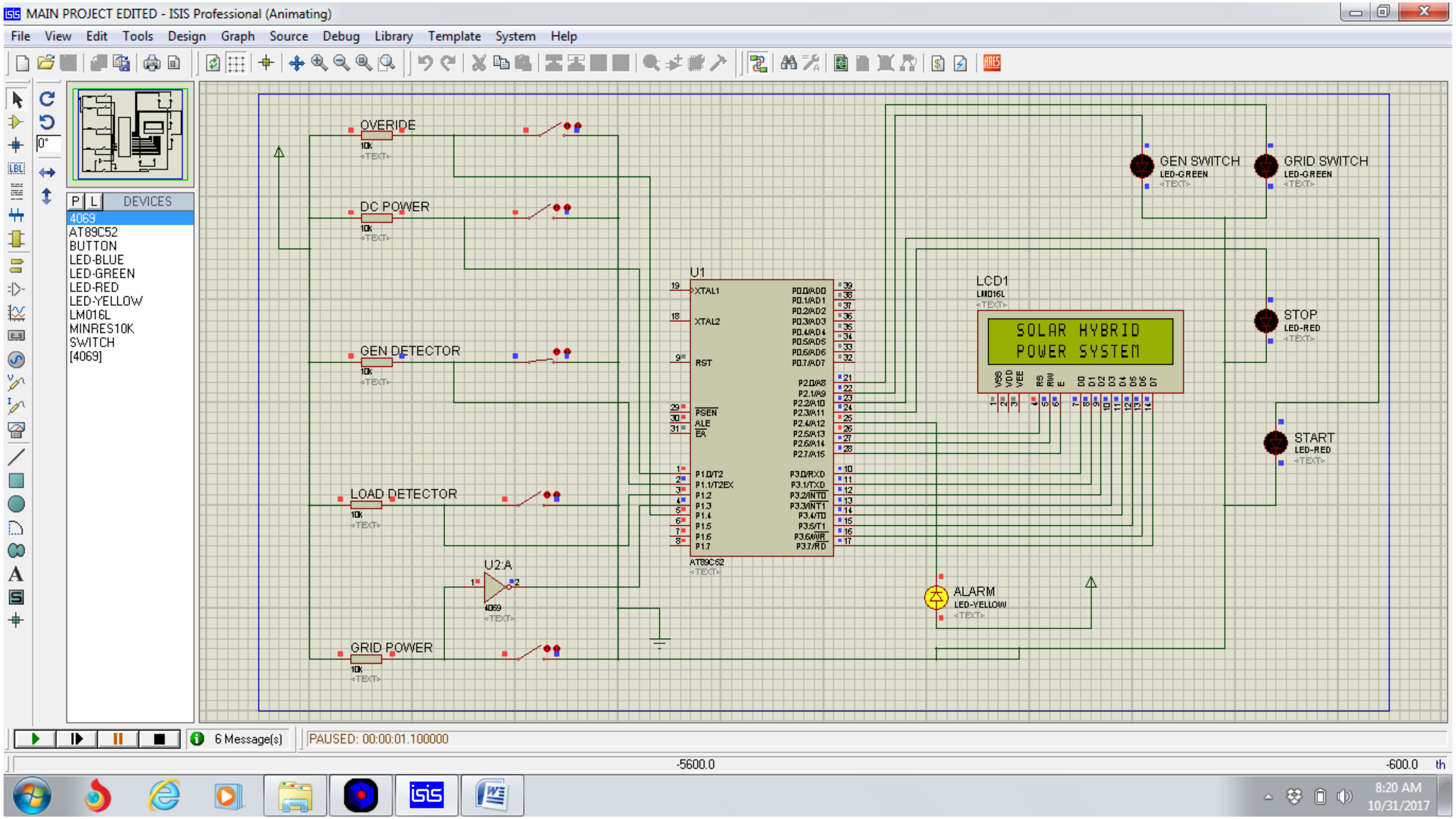

Figure 3.16: Screenshot of the Proteus ISIS professional interface.

At the beginning of the simulation, the microcontroller (Figure 3.16) checks whether the DC power switch is closed? If yes, it displays that the load is on DC power supply. In reality that means the voltage of the battery is above the medium reference level of 12.0 V. If the switch is open, it checks whether the grid power switch is closed. If yes, it displays that the load is on grid power and the grid LED glows. If the switch is open, it checks whether the override switch is closed, if yes, it will display that the system is on override mode, hence the generator cannot be started. If the override switch is open, the system starts the generator and displays the result on the LCD screen. The generator is programmed to switch off when the grid switch is closed or when the DC power switch is closed. These various scenarios typify how the designed system behaved after fabrication.

3.3.1 Simulation Procedures

The Proteus software was to simulate the system design workability. The simulation procedures and the results when different scenarios were inputted are shown in appendix B. The opening scenario or welcome home screen (Appendix B, Figure B1) displays when the system is turned on for the first time and officially activates the system. The second stage checks the voltage level of the battery to determine if it is optimum for supply. The LCD screen displays this process while checking the status of the battery level voltage (Figure B2).When the voltage level is optimum, the load is supplied by the battery and the LCD displays this status to the user; the alarm is activated and sounds as indicated by the light emitting diode (Figures B3 and B4).

When the battery voltage is below the middle reference level, which isnot considered as optimum, the program is activated to start the next process of power supply transfer (Appendix B, Figure B5).The system checks for other sources of power supply that is optimum starting from the grid power, while the screen displays the status of the operation to the user. When the system checks for alternate sources of power, the first thing it checks for is grid power (Figure B6). When grid power is found to be optimum, i.e., not too low or too high, the screen displays that it is optimum and the program jumps to the next course of action (Figure B7). When the grid power is optimum, the system changes the source of power supply to the load, to the utility grid. The screen displays that the system is running on grid power (Figure B8).

However, in the event that the grid power is not optimum, the program launches into the next protocol for the changing of power supplied to the load in the event of grid failure or not being up to the optimum required level (Appendix B, Figure B9). In the event the grid power is not optimum and the DC bus bar voltage level drops below reference, the system tries to activate the generator. However, it first checks the status of the generator to determine which mode is operates on or is set by the user (Figure B10).

The generator status is checked and if it is set to the override mode, the generator does not get turned on automatically, the screen displays this status and the program jumps to the protocol of operation that is done for the generator being in the override state (Appendix B, Figure B11). Usually, this protocol gets involved in the system waiting for one of the alternate power sources to be restored. Either the DC bus bar comes back on or the grid power is restored. When the generator status is checked and the system discovers that the generator is in the operational mode (Figure B12). This mode entails that the generator has been set by the user to operate automatically whenever power failure occurs from all the other alternate sources. The screen displays this status and the program jumps to the protocol set for this operation. The system activates the generator control circuit as indicated by the light emitting diode, the screen display this action being performed and the program monitors the operation to determine if it is successful. If the operation is successful, the screen displays this for the user to acknowledge (Figures B13 and B14).

When the generator is successfully turned on, the system changes over the sources of power supplied to the load from the grid to the generator power (Figure B15). After the operation, the system changes it source of power supply to generator. The screen displays that the system is on generator (Figure B16). The program protocol then awaits the restoration of the grid power or the restoration of the charge to the battery by either the generator or the renewable energy source.

3.4 Fabrication

The components used in the fabrication are 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, NE 555 Timer, BC 547 NPN Transistor, 12 MHz Crystal Oscillator Piezoelectric device, 16 X 2 LCD, BT 136 TRIAC, CD 481 AND gate, TRIAC Pre-driver, 5kV, 25A Contactors and 8089C52 8-bit microcontroller. Appendix D shows the Bill of Engineering Measurement and Evaluation.

The prototype control system was constructed using wooden material cut to sizes. It has a dimension of 60cm by 40cm by 15cm. The top was covered with Perspex. The electronic circuit is soldered on the Vero board which was fixed firmly to the wooden case by means of screws.

The following steps were taken during the construction of the device:

(a) the various components were identified;

(b) components were connected on the breadboard with the aid of a schematic circuit diagram, after which it was tested and was found working accordingly. Its workability was achieved by connecting the terminals of each component on the breadboard and thereafter checking for continuity;

(c) proposed designed was simulated with the Proteus Design Suite to check for its workability before the components are soldered on the Vero board;

(d) components were laid out on a Vero board and soldered. Making sure there was no partial contact, dry solder left on the board and tested before fixing it on the casing. Figure 3.17 shows the layout of the various components of the Vero board; and

(e) the module was cased to give it an appealing look as shown in Figure 3.18 and 3.19. The dimension of the case was determined by the size of the Vero board, transformer, contactors and relays.

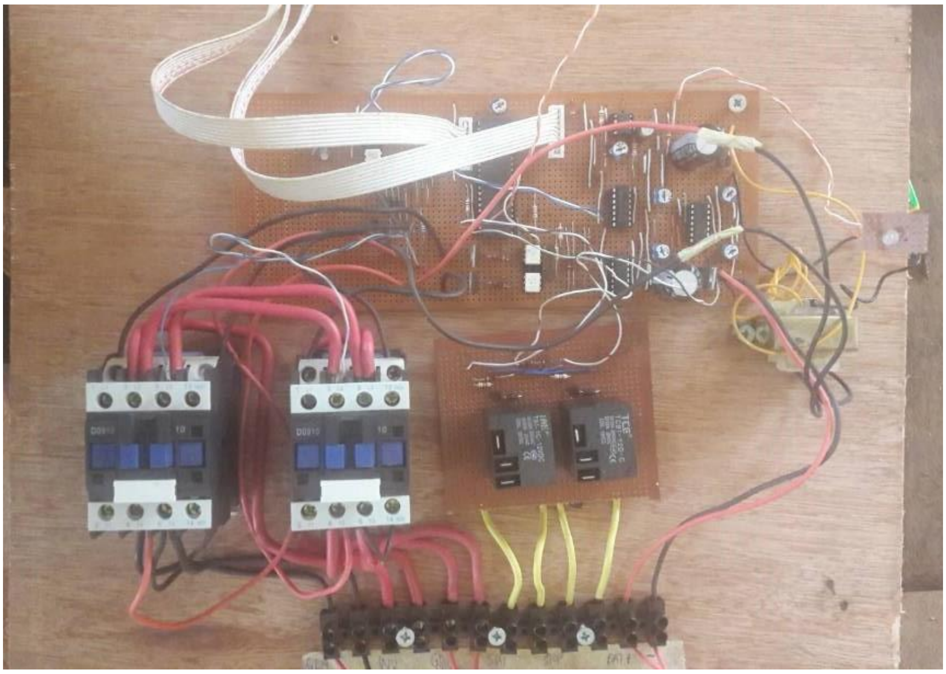

Figure 3.17: Internal circuitry of the fabricated control module on a Vero board

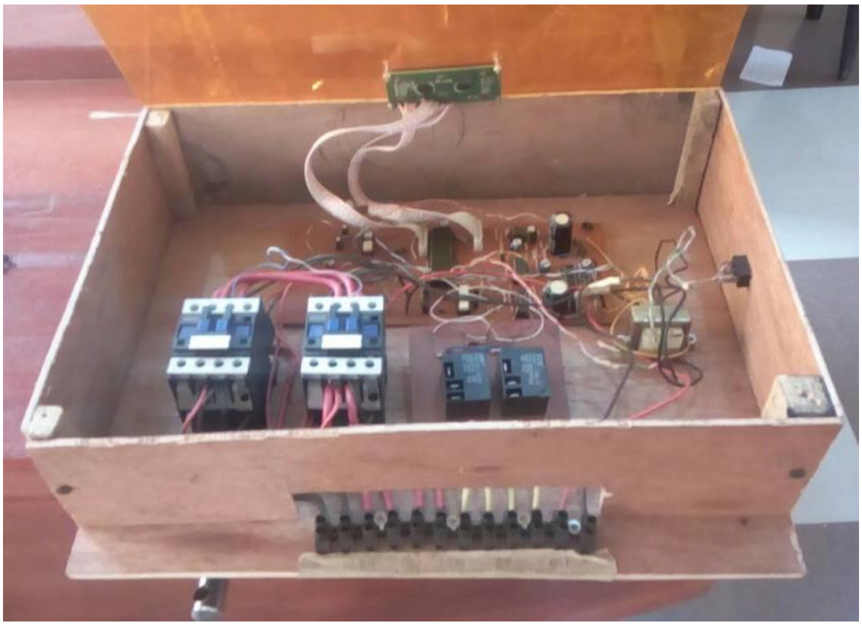

Figure 3.18: Fabricated design showing internal circuitry

Figure 3.19: View of the finished fabricated model

3.5 Experimental Setup

After construction, the next stage was to test for the performance of the system. As shown in the following plates, the prototype of the grid-connected micro-grid control module was powered by a 12V battery. The module displays a welcome message on the LCD screen.

Thereafter, it displays which power source powers the load, whether DC power source, grid power or generator. The prototype also switches over the power source in accordance to the battery level and the pre-programmed operation strategy.

Parallel experimental set-ups were made for the designed control module (developed strategy) and the conventional commercial arrangement (considered as the baseline scenario).

3.5.1 Developed Strategy

Figure 3.20 shows the schematics of the developed strategy

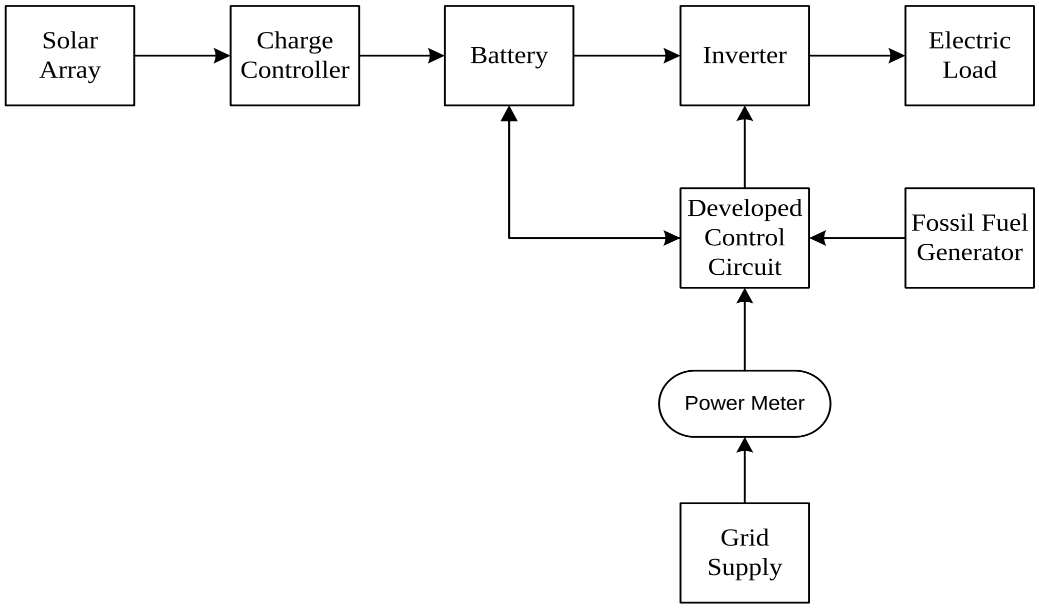

Figure 3.20: Schematics of the developed strategy

A 300 W solar panel was connected through the charge controller to charge a 200Ah battery. A 1kVA inverter was used to power a 200W load. The grid electricity supply was connected to the inverter through the designed module. The power meter records the amount of grid power consumed over time. The designed module also starts, stops and connects the fossil fuel generator in the event that other power sources are unavailable.

The designed circuit also has a two way connection with the battery. It powers the control circuit. On the other hand, the control circuit monitors the voltage level of the battery in other to determine the course of action to take. Figure 3.21 shows the experimental setup for the developed strategy.

Figure 3.21: Experimental setup for the developed operation strategy

A multi-meter was connected to the battery terminals to measure its voltage. Voltage values were recorded every three minutes. The voltage and current coming from the solar panel were recorded from the solar charge controller. The watt-hour meter was also being monitored to ascertain the amount of electricity is consumed from the utility grid. The values obtained are presented in chapter 4.

3.5.2 Baseline Scenario

Figure 3.22 shows the schematics of the traditional strategy (baseline scenario), while the experimental setup is shown in Figure 3.23.

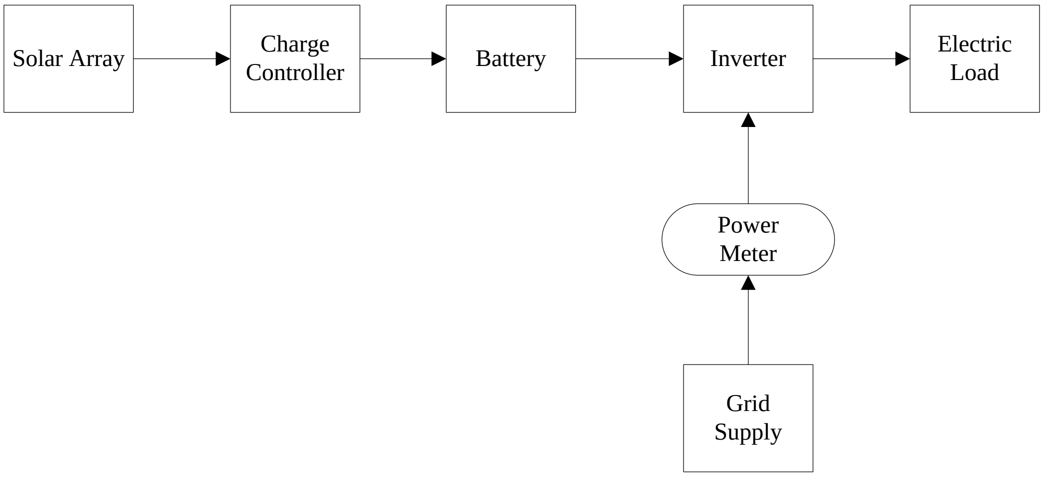

Figure 3.22: Schematics of the baseline scenario

Figure 3.23: Experimental setup for the conventional strategy (baseline scenario)

For ease of comparison, two identical solar panels with ratings of 300Watts each (Figure 3.24), analogue meters and charge controllers (Figure 3.25), and batteries (200Ah) were used for both experiments. The grid supply was connected to the AC input of the inverter terminal and the load to the ac output terminal of the inverter. Table 3.1 shows the main characteristics of measuring instrument used in this study.

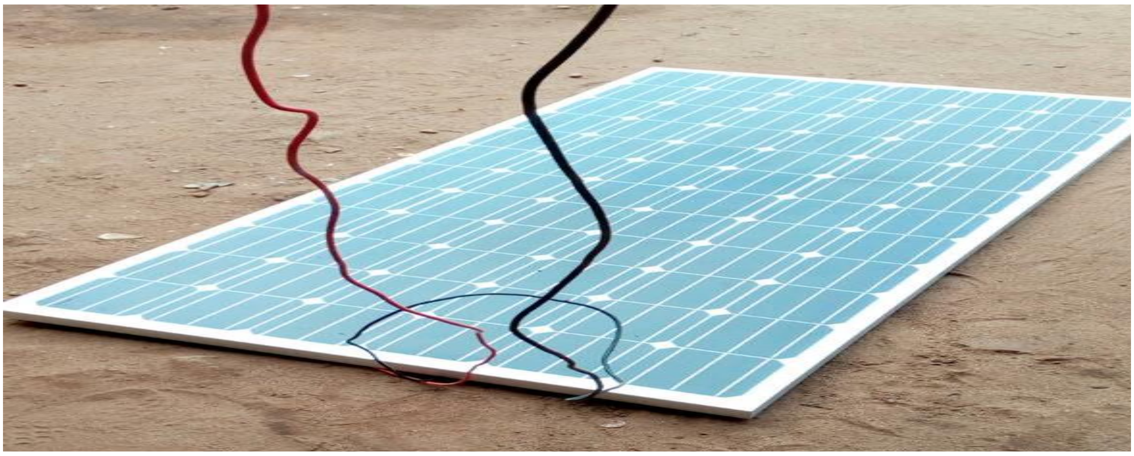

Figure 3.24: 300W Solar panel used for the experiment

Figure 3.25: Analogue watt-hour meter and charge controller used for the experiments

Table 3.1: Main characteristics of measuring instrument used in this study

Instrument	Measurement Range	Recording Resolution	Accuracy (%)
Milliammeter	0 – 200mA	0.5mA	80
DC Voltmeter	0 – 20V	0.05V	75
Ohmmeter	0 – 200KΩ	0.01Ω	87
Measuring tape	100m	0.005m	87
Stop watch	60s	0.01s	99
Analogue Wattmeter	0.00 – 10000kWh	0.005kWh	80

The analogue meter was used because it presents a continuous reading of the amount of power consumed over time.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Results

Table 4.1 shows the average measured power characteristics of the developed micro-grid while Table 4.2 shows the average measured power characteristics for the baseline scenario. Detailed values measured throughout the experiment for typical days (February 18 and 19, 2018) are presented in Appendix C.

Table 4.1: Average measurements taken every 30 minutes with the developed strategy on a typical day (February 18, 2018)

Time (h)	Average Battery Current (A)	Average Solar Panel Current (A)	Average Battery Voltage (V)	Average Solar Panel Voltage (V)	Grid Consumption (kWh)	Cumulative Grid Consumption (kWh)
9:30	0.80	0.80	13.10	13.90	0.00	0.00
10:00	0.89	0.89	12.57	13.55	0.00	0.00
10:30	1.19	1.19	12.50	13.19	0.00	0.00
11:00	1.26	1.25	12.44	13.10	0.00	0.00
11:30	0.87	0.88	12.37	13.42	0.00	0.00
12:00	1.53	1.49	12.33	12.77	0.00	0.00
12:30	4.53	4.85	12.33	12.39	0.00	0.00
13:00	4.51	4.62	12.29	12.35	0.00	0.00
13:30	4.63	4.81	12.25	12.28	0.00	0.00
14:00	1.23	1.21	12.13	12.74	0.00	0.00
14:30	2.08	2.10	12.07	12.10	0.00	0.00
15:00	1.69	1.62	11.99	12.75	0.00	0.00
15:30	1.65	1.58	11.89	12.03	0.00	0.00
16:00	1.05	0.99	11.73	12.08	0.00	0.00
16:30	0.10	0.10	12.03	12.01	0.07	0.07
16:57	0.10	0.10	11.95	12.00	0.06	0.13

Table 4.2: Average measurements taken every 30 minutes with the baseline strategy on a typical day (February 19, 2018)

Time (h)	Battery Current (A)	Solar Panel Current (A)	Battery Voltage (V)	Solar Panel Voltage (V)	Grid Consumption (kWh)	Cumulative Grid Consumption (kWh)
9:30	0.60	0.60	13.10	14.50	0.00	0.00
10:00	0.81	0.87	13.63	14.65	0.02	0.02
10:30	1.07	1.06	12.59	13.61	0.00	0.02
11:00	1.24	1.23	12.50	12.90	0.00	0.02
11:30	1.07	1.09	12.43	13.32	0.00	0.02
12:00	3.53	3.64	12.38	12.50	0.00	0.02
12:30	4.92	4.96	12.35	12.39	0.00	0.02
13:00	4.62	4.56	12.29	12.35	0.00	0.02
13:30	4.51	4.09	12.23	12.27	0.00	0.02
14:00	3.66	3.69	12.13	12.17	0.00	0.02
14:30	4.79	4.93	12.02	12.27	0.00	0.02
15:00	1.61	1.77	12.98	12.99	0.18	0.20
15:30	2.18	2.39	13.04	13.05	0.19	0.39
16:00	1.40	1.43	12.35	12.35	0.00	0.39
16:21	1.20	1.20	11.93	12.47	0.00	0.39

As observed from Table 4.1, the developed strategy supplies power for a total of 7 hours 27 minutes (7.45hours). It took the developed strategy 7.45 hours to discharge a fully charged 12V battery from 13.1V to 11.3V. The Benin Electricity Distribution Company (BEDC) makes electricity available for 3 hours in a 9 hours cycle (9:00 – 18:00) for a typical grid supply schedule in Benin City. With the developed strategy, the power supply availability of the grid can be enhanced from 3hours to 7.45 hours, with a corresponding improvement in the power supply reliability from 33% to 82.8%. Conversely, the power supply availability of the baseline scenario (Table 4.2) is between 09:30 and 16:21hours (a duration of 6 hours 51minutes or 6.85hours). This accounts for improvement in the power supply reliability from 33% to 76.1%. This result indicates that developed strategy has power supply reliability improvement of 6.5% compared to the traditional technology.

There is a slight variation between the average solar panel current (1.78A) and average battery current (1.76A). The variation could be attributed to losses in the conductors. The result shows that no grid power was drawn during the first 7 hours. This is because, the DC (battery) level was high enough to power the load demand during the period. For the baseline scenario, a current deviation of 0.02A was also observed but with a higher average solar panel current (2.50A) and average battery current (2.48A). The higher average battery current suggests that the traditional technique has a lower rate of discharge of the battery, which is justified by the higher cumulative grid power drawn by the baseline scenario (390W) compared to the developed strategy (130W) during the duration of the experiment for an experimental load of 200W. Figure 4.1 shows different snapshots of the meter readings.

(a) (b)

Figure 4.1: Snapshots of meter readings (a) 080014.1 kWh (b) 080015.7 kWh

Figures 4.2 – 4.4 show the battery current, solar panel current and the grid consumption profiles of the developed and baseline strategies respectively.

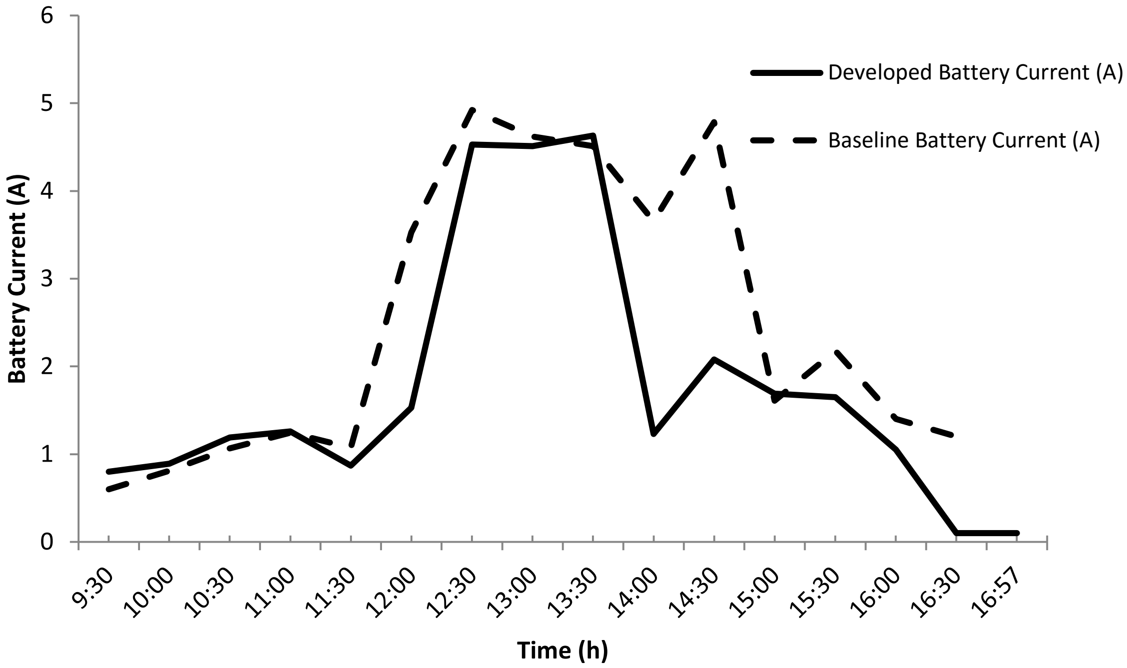

Figure 4.2: Battery current profile for the developed and baseline strategies

It was observed that the highest battery voltages were recorded at mid-day. The peak average battery current for the developed strategy was 4.63A recorded at 13:30 hours while that of the baseline strategy was found to be 4.96A at 12:30 hours. The battery delivers more current with higher solar radiation. Hence, it can be deduced that the higher the solar radiation, the more current available to the battery. Figure 4.3 shows the solar panel current profile of the developed and baseline micro-grids.

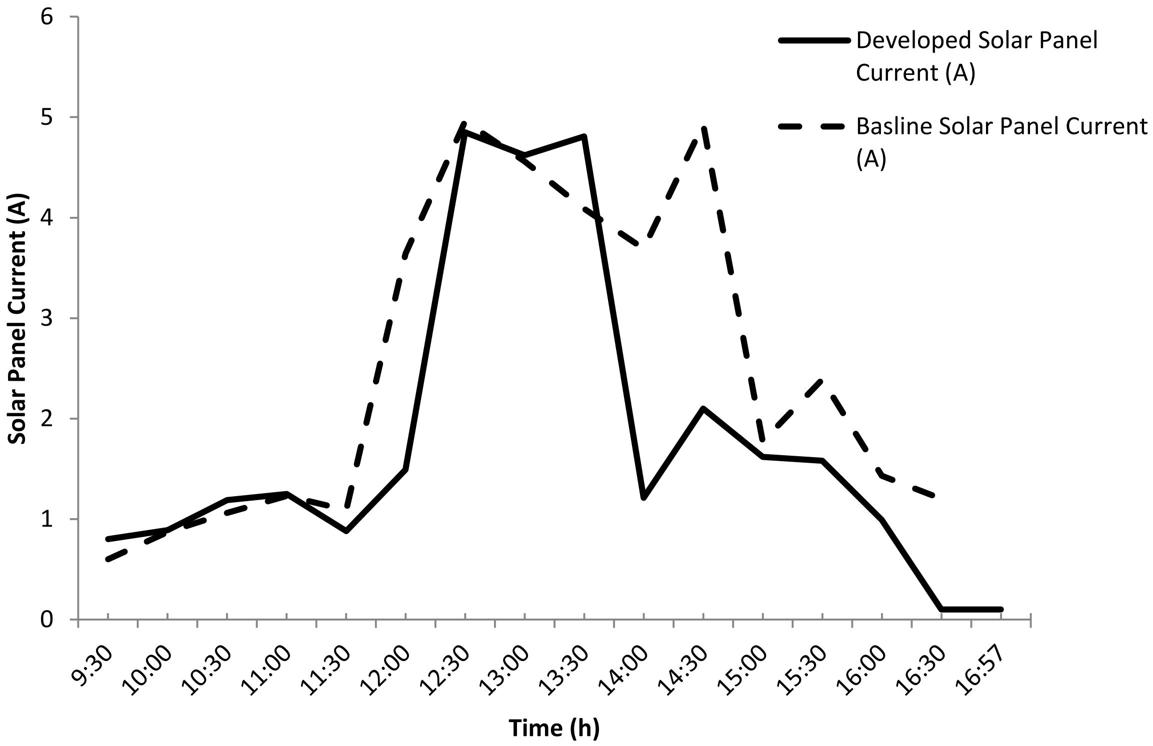

Figure 4.3: Solar panel current profile for the developed and baseline strategies

As observed (Figure 4.3), the solar panels deliver more current at mid-day when the solar irradiance is highest. The graphs of solar panel current against time show similar patterns for developed and baseline strategies. However, there are slight variations, which have been seen to be an average of 0.02A.The grid power consumption profiles are shown in Figure 4.4.

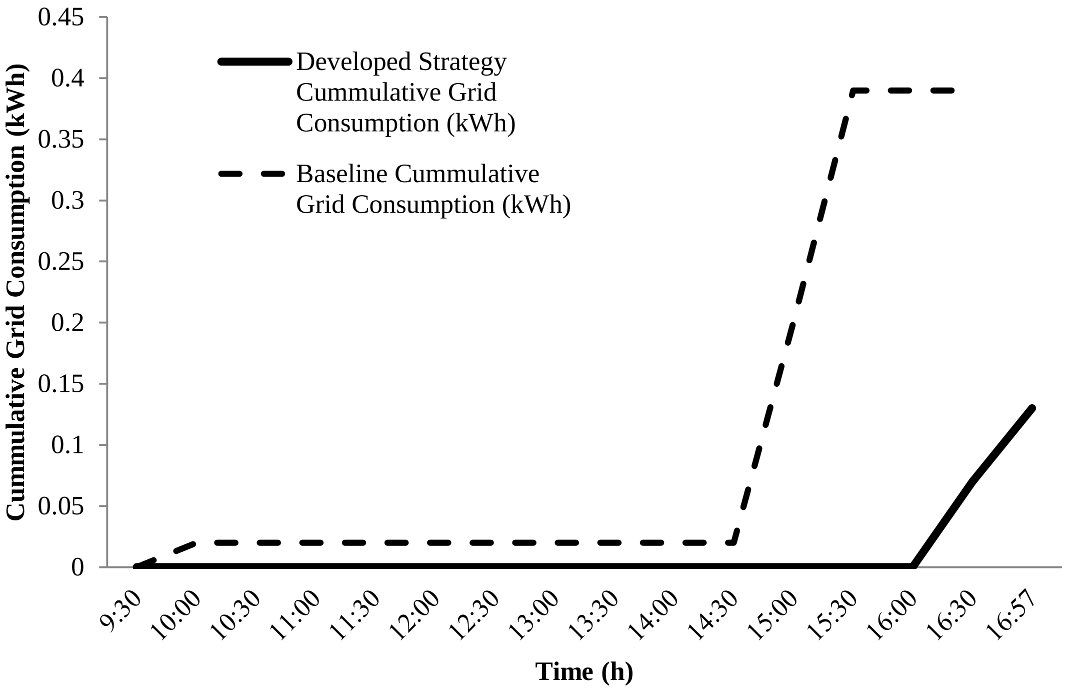

Figure 4.4: Grid consumption profile for the developed and baseline strategies

It is observed in the developed strategy that, no grid consumption between 09:30 hours and 16:00 hours, 0.07kW of power was drawn between 16:00 hours and 16:30 hours and 0.06kW was drawn between 16:30 hours and 16:57 hours when the battery cuts off at the lower reference voltage level. This accounts for the cumulative grid consumption of 0.13kW. Using the analogue watt-hour meter, grid consumption is always displayed in a cumulative manner.

Similarly, the baseline graph indicates that there was less time of grid power availability throughout the experimental period and a cumulative grid consumption of 0.39kW was drawn for an experimental load of 200W.

Table 4.3 shows the sum and average battery and solar panel current for developed and baseline strategies conducted on the 18th and 19th of February, 2018 respectively. It is observed that the baseline strategy delivered more current because the solar panel supplied more current due to relatively higher solar radiation. Hence, on the average the there is a fair basis of comparison of results received on the different days.

Table 4.3: Average and total battery current and solar panel current for both experiments.

	Average Battery Current (Amp)	Total Battery Current (Amp)	Average Solar Panel Current (Amp)	Total Solar Panel Current (Amp)
Developed Strategy (February 18, 2018)	1.76	240.40	1.78	240.90
Baseline Strategy (February 19, 2018)	2.48	317.00	2.50	313.70

In summary, in terms of energy savings, the cumulative grid energy consumption of the conventional technique within the experimental period of 9 hours (9:00 – 18:00) for a typical day is 0.39kWh (390Wh) compared to 0.13kWh (130Wh) for the developed strategy. This indicates that the developed operation strategy for the grid-connected micro-grid gives energy savings of 66.7%. 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. Moreover, the improved availability of power supply of the traditional approach from 76.1% to 82.6% by the developed strategy can reduce the dependence on fossil fuel as an alternative source of power by 6.5%. This could make the environment more eco-friendly and conducive.

4.3 Findings

The effectiveness of this experiment depends largely on the similarity and sameness of the load, battery, solar panels and other apparatus of this experiment. It also depends on having both the baseline model and the developed model under the same climatic condition. Haven placed both models under similar conditions, the following findings were reached.

1. The developed operation strategy of the micro-grid gives a power supply reliability improvement of 6.5% compared to the conventional technique. This improvement can reduce the dependence on fossil fuel as an alternative source of power; hence, could make the environment more eco-friendly and conducive.

2. The developed operation strategy of the micro-grid gives a grid power saving of 66.7% compared to the conventional technique. The energy savings translates into high monetary benefits, especially with the high cost of utility grid supply in Nigeria.

3. There was a slight variation of 0.02 A between the battery current and solar panel current for both the developed operation strategy and the traditional technique. This variation can be accounted for by losses in the connecting cables.

4.4 Contribution to knowledge

This study has contributed to knowledge in the following ways:

1. a cost-effective operation strategy for grid connected micro-grids has been designed;

2. a more reliable micro-grid system for regions with unreliable grid networks has been developed; and

3. real-time energy profiles of a grid-connected micro-grid has been deduced for Benin City, Nigeria.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

To ensure the sustainability of electric power, the micro-grid is used to integrate energy sources in an effective way following a functional operation strategy. The traditional (baseline) operations strategy recognises grid power as the primary power supply source. Hence, it takes precedence when available. With the rising cost of grid power supply, the need to develop a more reliable and cost effective operations strategy arose. The operations strategy guides the energy flow, reduces monetary cost of the power system and ensures maximal utilisation of both the micro-grid components and power sources. In addition, the operation strategy monitors the battery voltage and decides which of the power sources can power the load. This essentially can ensure energy sustainability and reduce cost.

In this study, a control switching system for a micro-grid made up of the utility grid, PV/battery source and a fossil fuel generator was designed, simulated and fabricated. The system design was realised through the use of discrete electronics components. The design was simulated before fabrication using the Proteus ISIS simulation software. This helped to ascertain the outcome of the design before fabrication was embarked upon. The components were soldered on the Vero board and were cased in a wooden and Perspex container. Upon testing, the device performed in line with the expected results.

It was found at that the developed strategy reduces the grid power consumption by 66.7% with an improved power supply reliability of 6.5% over 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.

5.2 Recommendations

This study does not put into consideration the longevity of the battery. The research could be carried out or simulated for the product life of the constituent components so as to ascertain the durability, rate of replacement and cost of the battery.

REFERENCES

AESO (Africa Energy Sector Outlook)–2040, Study on programme for infrastructure development in Africa. Retrieved from: http://www.foresightfordevelopment.org-/library/55/1341-africa-energy-outlook-2040 (accessed: April 20, 2017).

Ahmed, N. A., Al-Othman, A., and Al-Rashidi M. (2011). Development of an efficient utility interactive combined wind/photovoltaic/fuel cell power system with MPPT and DC bus voltage regulation, *Electrical Power System Research*, *81*, 1096-1106.

Almi, M., and Marrouf, M. (2010). Connection of photovoltaic generator to domestic three phase electrical network supply trough voltage source inverter," in *Proceedings of the International Symposium on Environment Friendly Energies in Electrical Applications*, 2-4.

Arul, P. G., Ramachandaramurthy, V. K., and Rajkumar, R. K. (2015). Control strategies for a hybrid renewable energy system: A review, *Renewable and Sustainable Energy Reviews*, *42*, 597-608

Bo, D., Li, Y., and Zheng Z., (2010). Energy management of hybrid DC and AC bus linked micro-grid, in *2010 2nd IEEE International Symposium on Power Electronics for Distributed Generation Systems (PEDG)*, 713-716.

Canizares, R. P., and Palma-Behnke, R. (2014). Trends in micro-grid control, *IEEE Trans Smart Grid*, *5*(4):1905–1919.

Chen Y., Cheng C., and Wu, H. (2006). Grid-connected hybrid PV/wind power generation system with improved DC bus voltage regulation strategy, in *Twenty-First Annual IEEE Conference and Exposition on Applied Power Electronics*.

Chen, C., Duan, S., Cai, T., Liu, B., and Hu, G. (2011). Smart energy management system for optimal micro-grid economic operation, *IET Renewable Power Generation*, *5*(3):258

Chuachan, A., and Saini, R. P. (2016). Discrete harmony search based size optimisation of Integrated Renewable Energy System for remote rural areas of Uttarakhand state in India, *Renewable Energy*, *94*, 587-604.

Dahmane, M., Bosche, J., El-Hajjaji, A., and Dafarivar, M. (2013). Renewable energy management algorithm for stand-alone system, in: *proceedings of the International Conference on Renewable Energy Research and Applications*, 621–626.

Dali, M., Belhadj, J., and Roboam X. (2010). Hybrid solar–wind system with battery storage operating in grid-connected and standalone mode: control and energy management–experimental investigation, *Energy*, *35*, 2587-2595.

Das, D., Esmaili, R., Xu, L., and Nichols, D. (2005). An optimal design of a grid connected hybrid wind/photovoltaic/fuel cell system for distributed energy production, in *31st Annual Conference of IEEE on Industrial Electronics Society*.

Diniș, C. M., Popa, G. N., and Iagar, A. (2015). Study on sources of charging lead acid batteries. *International Conference on Applied Sciences Materials Science and Engineering,* 85 012011.

Dursun, E., and Kilic, O. (2012). Comparative evaluation of different power management strategies of a stand- alone PV/wind/PEMFC hybrid power system, *International Journal of Electrical Power Energy System*, 34(1): 81–89.

Dweikak, A. Yazori, M. A., Al-daraghmeh, S. (2012). Motochair: a fully motorized operated-voice wheelchair, Graduation Project Report, German Jordanian University, Amman Jordan.

Esmaili, R., Xu L., and Nichols, D. (2005). A new control method of permanent magnet generator for maximum power tracking in wind turbine application, in *2005 IEEE Power Engineering Society General Meeting*, 2090-2095.

Fernandez, A., Paul, J. (2015). Smart micro grid implementation, *International Research Journal of Engineering and Technology,* 2, 5.

Guerrero J. M., Vicuna, D., Garcia, L., Matas, J., Castilla, M. and Miret, J., (2005). Output impedance design of parallel-connected UPS inverters with wireless load-sharing control, *IEEE Transactions on Industrial Electronics*, *52*, 1126-1135.

Han, Y., Chen, W., and Li, Q. (2017). Energy management strategy based on multiple operating states for a photovoltaic/fuel cell/energy storage DC micro-grid, *Energies*, *10*, 136; doi:10.3390/en10010136

Ipsakis, D., Voutetakis, S., Seferlis, P., Stergiopoulos, F., Papadopoulou, S., and Elmasides, C. (2008). The effect of the hysteresis band on power management strategies in a stand-alone power system, *Energy*, *33*(10): 1537–1550.

Ismail, M. S., Moghavvemi, M., and Mahlia, T. M. I. (2013). Design of an optimised photovoltaic and micro-turbine hybrid power system for a remote small community: case study of Palestine, *Energy Conversion and Management*, 75:271–281.

Jiang, S., Wang, W., Jin, H., and Xu, D. (2011). Power management strategy for micro-grid with energy storage system, *37th Annual Conference of the IEEE Industrial Electronics Society (IECON 2011)*, November 2011, Melbourne, Australia.

Jiang, Z., and Yu, X. (2009). Active power—Voltage control scheme for islanding operation of inverter-interfaced micro-grids, in *IEEE Power & Energy Society General Meeting*2009, 1-7.

Jurasz, J., and Piasecki, A. (2017). A simulation and simple optimisation of a wind-solar-hydro micro power source with a battery bank as an energy storage device, *EDP Sciences*, *140*, 10; doi: 10.1051/e3sconf/20171401017

Karami, N., Moubayed, N., and Outbib, R. (2014). Energy management for a PEMFC–PV hybrid system, *Energy Conversion and Management*, *82*, 154–168.

Khodayar, M. E., Barati, M., Shahidehpour, M. (2012) Integration of high reliability distribution system in micro-grid operation, *IEEE Trans Smart Grid*, *3*(4):1997–2006

Kim, H., Bae, J., Baek, S., Nam, D., Cho, H., and Chang, H. J. (2017). Comparative analysis between the Government micro-grid plan and computer simulation results based on real data: the practical case for a South Korean Island, *Sustainability*, *9*, 197; doi:10.3390/su9020197

Kong, X., Bai, L., Hu, Q., Li, F., Wang, C. (2016). Day-ahead optimal scheduling method for grid-connected micro-grid based on energy storage control strategy, *Journal of Modern Power System and Clean Energy*, *4*(4): 648–658

Lanre, O., Mekhilef, S., Ismail, M. S., and Moghavvemi, M. (2016). Energy management strategies in hybrid renewable energy systems: A review, *Renewable and Sustainable Energy Reviews*, *62*, 821-835.

Li, X., Zhang, D., Li, Y., and Xu, Y., (2012). Multi-string photovoltaic grid-connected inverter based on alternate single-phase PWM control, in *Power and Energy Engineering Conference (APPEEC)*, Asia-Pacific, 1-4.

Li, Y. W., and Kao, C. (2009). An accurate power control strategy for power-electronics-interfaced distributed generation units operating in a low-voltage multibus micro-grid, *IEEE Transactions on Power Electronics*, vol. 24, pp. 2977-2988, 2009.

Liao, Z., and Ruan, X. (2009). A novel power management control strategy for stand-alone photovoltaic power system. In: *proceedings of the IEEE 6th International Power Electronics and Motion Control Conference*, 445–449.

Marques, L., and Pacheco F. (2007). REMPLI discreet event simulation system, technical report Hurray-TR-070903, Polytechnic Institute of Porto (ISEP-IPP), Portugal, 1-15.

Matas, J., Castilla, M., de Vicuna, L. G., Miret J., and Vasquez, J. C. (2010). Virtual impedance loop for droop-controlled single-phase parallel inverters using a second-order general-integrator scheme, *IEEE Transactions on Power Electronics*, *25*, 2993-3002.

Menniti, D., Pinnarelli, A., Sorrentino, N. (2009). A method to improve micro-grid reliability by optimal sizing PV/WIND plants and storage systems, *20th International Conference on Electricity Distribution*.

Nie, T., Wei, Q., and Shao, D. (2011). A fuzzy and decoupled DQ based inverter control strategy for micro-grid in islanding operation, *International Forum on Strategic Technology* (IFOST), 2011 6th 425-428.

Okundamiya, M. S. (2016). Power electronics for grid integration of wind power generation system, *Journal of Communications Technology, Electronics and Computer* Science, *9*, 10-16.

Okundamiya, M. S. 2015. Modelling and optimization of a hybrid energy system for GSM base transceiver station sites in emerging cities, Ph.D. thesis, Benin City, Nigeria: University of Benin.

Okundamiya, M. S., Akpaida, V. O. A., and Omatahunde, B. E. (2014). Optimization of a hybrid energy system for reliable operation of automated teller machines, *Journal of Emerging Trends in Engineering and Applied Sciences*, *5*, 153-158.

Okundamiya, M. S., and Ogujor, E. A. (2017). Power electronics technology: enabling large-scale injection of wind energy into the grid. *Advances in Energy Research*, 27 (Chapter 3), Acosta, M. J. Ed. USA: Nova Science Publishers Inc.

Okundamiya, M. S., and Ojieabu, C. E. (2017). Optimum design, simulation and performance analysis of a micro-power system for electricity supply to remote sites, *Journal of Communications Technology, Electronics and Computer Science, 12,* 6 – 12.

Okundamiya, M. S., and Omorogiuwa, O. (2015). Viability of a photovoltaic diesel battery hybrid power system in Nigeria, *Iranica Journal of Energy and Environment*, *6*(1): 5-12.

Okundamiya, M. S., Emagbetere, J. O., and Ogujor, E. A. (2014a). Design and control strategy for a hybrid green energy system for mobile telecommunication sites, *Journal of Power Sources*, *257*, 335-343.

Okundamiya, M. S., Emagbetere, J. O., and Ogujor, E. A. (2014b). Assessment of renewable energy technology and a case of sustainable energy in mobile telecommunication sector, *Scientific World Journal*, vol. 2014, 1-13.

Okundamiya, M. S., Emagbetere, J. O., and Ogujor, E. A. (2015). Techno-economic analysis of a grid-connected hybrid energy system for developing regions, *Iranica Journal of Energy & Environment*, *6*(4): 243 – 254.

Okundamiya, M. S., Emagbetere, J. O., and Ogujor, E. A. (2017). Modeling and optimum capacity allocation of micro-grids considering economy and reliability, *Journal of Telecommunication, Electronic and Computer Engineering, 9*(4): 55-61.

Okundamiya, M. S., Nzeako, A. N. (2010). Energy storage models for optimizing renewable power applications, *Journal of Electrical and Power Engineering, 4*(2): 54-65.

Okundamiya, M. S., Omorogiuwa, O. (2016). Analysis of an isolated micro-grid for Nigerian terrain, Proceeding of the *2016 IEEE 59th International Midwest Symposium on Circuits and Systems*, Abu Dhabi, UAE, pp. 485-488.

Prutianu, F., and Popescu, V. (2010). Control of single phase inverters for wind energy conversion using PWM techniques, in *9th International Symposium on Electronics and Telecommunications (ISETC*), 95-98.

Ramdas, T. S. (2017). Renewable energy based elevator system by using BLDC motor, *International Engineering Research Journal*, *2*(9): 3256-3259.

Rebours, Y. G., Kirschen, D. S., Trotignon, M., Rossignol, S. (2007). A survey of frequency and voltage control ancillary services: Part I: technical features", *IEEE Transactions on Power Systems*, *22*, 350-357.

Ruban, A., Selvakumar, K., Hemavathi, N., Rajeswari, N. (2017). Hardware realization of two level fuzzy based energy management system using wireless sensor network, *International Journal of Latest Engineering and Management Research*.

Torreglosa, J. P., Garcia-Trivino, P., Fernandez-Ramirez, L. M., and Jurado, F. (2016). Control based on techno-economic optimisation of renewable hybrid energy system for stand-alone applications, *Expert System Application*, *51*, 59–75.

Tsikalakis, A. G., and Hatziargyriou, N. D. (2008). Centralized control for optimizing micro-grids operation, *IEEE Transactions on Energy Conversion*, *23*(1): 241–248.

UNDP-GEF (United Nations Development Programme- Global Environment Facility), (2013). End-use metering campaign for residential houses in Nigeria, in *Metering Campaign Report,* draft version, p.148, September, 2013.

Vasquez, J., Guerrero, J., Miret, J., Castilla, M., and deVicuna, L. G. (2010). Hierarchical control of intelligent micro-grids, *IEEE Industrial Electronics Magazine*, *4*(4): 23–29.

Veeramani, M., Gladson, J. P., Sundarabalan, C. K., and Sanjeevikumar, J. (2016). An efficient micro-grid management system for rural area using Arduino, *International Journal of Engineering Trends and Technology*.

APPENDIX A

Micro-controller source code

```
=================================================================

; THIS IS A CIRCUIT THAT WILL SUPPLY THE POWER TO A LOAD USING DC POWER FROM RENEWABLE SOURCES.
;IN THE EVENT THAT THE DC POWER FAILS, THE SYSTEM TAKES POWER FROM THE GRID, HOWEVER, THIS IS ONLY POSSIBLE IF THE GRID POWER IS OPTIMUM (NOT TOO HIGH OR LOW)
;THEN WHEN THE GRID POWER FAILS, THE SYSTEM TURNS ON A GENERATOR AND POWERS THE LOAD VIA IT. HOWEVER, THIS IS ALSO POSSIBLE IF THE OVER RIDE SWITCH IS NOT ACTIVATED
;AN ALARM SOUNDS EACH TIME THETRE IS A POWWR SWITCH OR ERROR WITH GENERATOR OPERATION
;A DISPLAY UNIT SHOIWS ALL TGHE ACTIVITIES BEING CARRIED OUT BY THE SYSTEM
;THE GENBERATOR CONTROL, ENSURES THAT THE GENERATOR CONTROL IS SAFE BY CRATING A MAXIMUMNUMBER OF STARTING

;DECLARATIONS for simulations
LCD_PORT                EQU     P3
RS_BIT                  EQU     P2.5
RW_BIT                  EQU     P2.6
EN_BIT                  EQU     P2.7

DC_POWER                EQU     P1.0
GRID_POWER              EQU     P1.3
GEN_DETECTOR            EQU     P1.1
LOAD_DETECTOR           EQU     P1.2
GEN_SWITCH              EQU     P2.1
GRID_SWITCH             EQU     P2.0
ALARM           EQU     P2.4
STAT            EQU     P2.2
STOP            EQU     P2.3
OVERIDE         EQU     P1.4


;DECLARATIONS for REAL LIFE
;LCD_PORT               EQU     P2
;RS_BIT                 EQU     P3.7
;RW_BIT                 EQU     P3.6
;EN_BIT                 EQU     P3.5

;DC_POWER               EQU     P1.3
;GRID_POWER             EQU     P1.0
;GEN_DETECTOR           EQU     P1.5
;LOAD_DETECTOR          EQU     P1.4
;GEN_SWITCH             EQU     P1.2
;GRID_SWITCH            EQU     P1.1
;ALARM                  EQU     P1.6
;STAT                   EQU     P0.2
;STOP                   EQU     P0.1
;OVERIDE                        EQU     P0.0


;INITIALIZATIONS

        SETB DC_POWER                   ;MAKE INPUTS
        SETB GRID_POWER
        SETB GEN_DETECTOR
        SETB LOAD_DETECTOR
        SETB OVERIDE

        CLR GEN_SWITCH                  ;OFF THE CIRCUITS
        CLR GRID_SWITCH
        CLR ALARM                       ;ON THE ALARM
        CLR STOP
        CLR STAT
```

==

```
                LCALL PROJ1
                LCALL PROJ2
                LCALL LONG_DELAY
                SETB ALARM
                LCALL CHECKING
                LCALL STATUS
                LCALL LONG_DELAY
                LCALL LONG_DELAY

FIRST_CHECK:    JB DC_POWER,CHECK1B             ;SYSTEM STAYS IN DC POWER SUPPLY MODE WHEN THE
POWER IS AVAILABLE
                LCALL DC_BUSBAR
                LCALL IS_OPTIMUM
                CLR ALARM
                LCALL LONG_DELAY
                SETB ALARM
                LCALL SYSTEM_ON
                LCALL DC_POWERS
CHECK1A:        JNB DC_POWER,CHECK1A
                CLR ALARM
                LCALL LONG_DELAY
                SETB ALARM
                JNB DC_POWER,CHECK1A
                SJMP CHECK1B

CHECK1B:        LCALL DC_BUSBAR
                LCALL NOT_OPTIMUM
                LCALL LONG_DELAY
                LCALL CHECKING_OTHER
                LCALL POWER_SOURCES
                LCALL LONG_DELAY
                SJMP SECOND_CHECK

SECOND_CHECK:   JNB GRID_POWER,CHECK2B ;SYSTEM STAYS IN THE GRID POWER MODE WHEN THE DC POWER
FAILS AND GRID OSAV
                LCALL GRID_POWER_UP
                LCALL IS_OPTIMUM
                LCALL LONG_DELAY
                SETB GRID_SWITCH
                CLR GEN_SWITCH
                LCALL HALF_SEC
                LCALL SYSTEM_ON
                LCALL GRID_POWER_DOWN
CHECK2A:        JNB DC_POWER,FIRST_RESTORE
                JB GRID_POWER,CHECK2A
                SJMP CHECK2B

CHECK2B:        LCALL GRID_POWER_UP
                LCALL NOT_OPTIMUM
                CLR ALARM
                LCALL HALF_SEC
                SETB ALARM
                CLR GRID_SWITCH
                CLR GEN_SWITCH
                LCALL LONG_DELAY
                SJMP THIRD_CHECK

FIRST_RESTORE:  ;LCALL DC_BUSBAR
                ;LCALL IS_OPTIMUM
                CLR GRID_SWITCH
                CLR GEN_SWITCH
                ;CLR ALARM                      ;WHEN ON GRID AND DC POWER IS RESTORED,
SYSTEMJUMPS BACK TO GRID
                ;LCALL LONG_DELAY
                ;SETB ALARM
                SJMP FIRST_CHECK

THIRD_CHECK:    LCALL CHECKING_GEN
                LCALL STATUS
                LCALL LONG_DELAY
                JNB OVERIDE,CHECK3A
                SJMP CHECK3B
```

==

```
=============================================================================================
CHECK3A:        LCALL GENERATOR_ON
                LCALL OVERIDE_MODE
                CLR ALARM
                LCALL LONG_DELAY
                SETB ALARM
CHECK3AA:       JNB DC_POWER,FIRST_RESTORE          ;WHEN THE SYSTEM IS ON OVEERIDE
                JB GRID_POWER,SECOND_RESTORE
                JNB OVERIDE,CHECK3AA
                SJMP CHECK3B

CHECK3B:        LCALL GENERATOR_ON
                LCALL OPERATIONAL_MODE
                LCALL LONG_DELAY
                LCALL STARTING_THE
                LCALL GENERATOR
                ;JNB DC_POWER,FIRST_RESTORE         ;WHEN THE SYSTEM IS ON OVEERIDE
                ;JB GRID_POWER,SECOND_RESTORE       ;WAIT FOR OTHER SOURCES TO COME BACK
                ;CLR GRID_SWITCH
                ;JNB OVERIDE,THIRD_CHECK
                SJMP GEN_OPERATION                  ;OR JUMP TO GENERATOR OPERATIONS

SECOND_RESTORE:         ;LCALL GRID_POWER_UP
                ;LCALL IS_OPTIMUM
                CLR GRID_SWITCH
                CLR GEN_SWITCH
                CLR ALARM                           ;WHERE SYSTEM WIL RESTORE THE GRID POWER
MODE
                LCALL ONE_SEC
                SETB ALARM
                LJMP SECOND_CHECK

GEN_OPERATION:  CLR ALARM                           ;WHEN GEN IS ALLOWED TO WORK. THGIS IS THE
OPERATION IS WILL TAKE
                LCALL ONE_SEC
                SETB ALARM
                LCALL HALF_SEC
                MOV R7,#06
REAPS:          SETB STAT
                LCALL LONG_DELAY
                CLR STAT
                LCALL LONG_DELAY
                JNB GEN_DETECTOR,GOOD_GEN
                DJNZ R7,REAPS
                LCALL OPERATION
                LCALL NOT_SUCCESSFUL
                SJMP BAD_GEN

GOOD_GEN:       LCALL OPERATION
                LCALL IS_SUCCESSFUL
                CLR ALARM                   ;WHE THE GEN STARTING IS PERFECT
                LCALL LONG_DELAY
                SETB ALARM
                LCALL CHANGING_OVER
                LCALL GENERATOR
                LCALL LONG_DELAY
                LCALL LONG_DELAY
                LCALL LONG_DELAY
                SETB GEN_SWITCH
                LCALL ONE_SEC
                LCALL SYSTEM_ON
                LCALL GENERATOR
                SJMP FOURTH_CHECK

BAD_GEN:        CLR ALARM                   ;WHEN GEN RFUSE TO START
                JB GRID_POWER,GRID_COME
                JNB DC_POWER,DC_COME
                SJMP BAD_GEN

FOURTH_CHECK:   JB GRID_POWER,GRID_COME                     ;WHILE RUNNING ON GEN
                JNB DC_POWER,DC_COME
                JNB GEN_DETECTOR,FOURTH_CHECK
```

```
==========================================================================================
DC_COME:        LCALL DC_POWER
                LCALL IS_OPTIMUM
                CLR GEN_SWITCH                          ;WHEN GRID POWER COMES BACK ON
                CLR GRID_SWITCH
                LCALL LONG_DELAY
                LCALL STOPPING_THE
                LCALL GENERATOR
                LCALL LONG_DELAY
                SETB STOP
                LCALL LONG_DELAY
                LCALL LONG_DELAY
                LCALL LONG_DELAY
                CLR STOP
                LCALL OPERATION
                LCALL IS_SUCCESSFUL
                CLR ALARM
                LCALL LONG_DELAY
                SETB ALARM
                LCALL SYSTEM_ON
                LCALL DC_POWERS
                LJMP CHECK1A

GRID_COME:      LCALL GRID_POWER_UP
                LCALL IS_OPTIMUM
                CLR ALARM
                CLR GEN_SWITCH                          ;WHEN GRID POWER COMES BACK ON
                CLR GRID_SWITCH
                LCALL ONE_SEC
                SETB GRID_SWITCH
                LCALL LONG_DELAY
                SETB ALARM
                LCALL STOPPING_THE
                LCALL GENERATOR
                SETB STOP
                LCALL LONG_DELAY
                LCALL LONG_DELAY
                LCALL LONG_DELAY
                LCALL LONG_DELAY
                LCALL LONG_DELAY
                CLR STOP
                LCALL OPERATION
                LCALL IS_SUCCESSFUL
                LJMP SECOND_CHECK

;DISPLAY SUBS
PROJ1:          MOV DPTR,#UPCOM
C01:            CLR A
                MOVC A,@A+DPTR
                LCALL COMNWRT2
                LCALL SHORT_DELAY
                INC DPTR
                JZ SEND_DAT01
                SJMP C01
SEND_DAT01:     MOV DPTR,#MYDATA1               ;DISPLAYS "  DESIGN AND"
D01:            CLR A
                MOVC A,@A+DPTR
                LCALL DATAWRT2
                LCALL SHORT_DELAY
                INC DPTR
                JZ EXIT01
                SJMP D01
EXIT01:         NOP
                RET

PROJ2:          MOV DPTR,#DOWNCOM
C02:            CLR A
                MOVC A,@A+DPTR
                LCALL COMNWRT2
                LCALL SHORT_DELAY
                INC DPTR
                JZ SEND_DAT02
                SJMP C02
```

```
=====================================================================================================
SEND_DAT02:     MOV DPTR,#MYDATA2               ;DISPLAYS "  CONSTRUCTION OF"
D02:            CLR A
                MOVC A,@A+DPTR
                LCALL DATAWRT2
                LCALL SHORT_DELAY
                INC DPTR
                JZ EXIT02
                SJMP D02
EXIT02:         NOP
                RET

CHECKING:               MOV DPTR,#UPCOM
C03:            CLR A
                MOVC A,@A+DPTR
                LCALL COMNWRT2
                LCALL SHORT_DELAY
                INC DPTR
                JZ SEND_DAT03
                SJMP C03
SEND_DAT03:     MOV DPTR,#MYDATA3               ;DISPLAYS " A GSM BASED BABY "
D03:            CLR A
                MOVC A,@A+DPTR
                LCALL DATAWRT2
                LCALL SHORT_DELAY
                INC DPTR
                JZ EXIT03
                SJMP D03
EXIT03:         NOP
                RET

STATUS:  MOV DPTR,#DOWNCOM
C04:            CLR A
                MOVC A,@A+DPTR
                LCALL COMNWRT2
                LCALL SHORT_DELAY
                INC DPTR
                JZ SEND_DAT04
                SJMP C04
SEND_DAT04:     MOV DPTR,#MYDATA4               ;DISPLAYS "  MONITOR DEVICE"
D04:            CLR A
                MOVC A,@A+DPTR
                LCALL DATAWRT2
                LCALL SHORT_DELAY
                INC DPTR
                JZ EXIT04
                SJMP D04
EXIT04:         NOP
                RET

DC_BUSBAR:              MOV DPTR,#UPCOM
C05:            CLR A
                MOVC A,@A+DPTR
                LCALL COMNWRT2
                LCALL SHORT_DELAY
                INC DPTR
                JZ SEND_DAT05
                SJMP C05
SEND_DAT05:     MOV DPTR,#MYDATA5               ;DISPLAYS "  BY     "
D05:            CLR A
                MOVC A,@A+DPTR
                LCALL DATAWRT2
                LCALL SHORT_DELAY
                INC DPTR
                JZ EXIT05
                SJMP D05
EXIT05:         NOP
                RET
```

```
=========================================================================================
IS_OPTIMUM:             MOV DPTR,#DOWNCOM
C06:            CLR A
                MOVC A,@A+DPTR
                LCALL COMNWRT2
                LCALL SHORT_DELAY
                INC DPTR
                JZ SEND_DAT06
                SJMP C06
SEND_DAT06:     MOV DPTR,#MYDATA6               ;DISPLAYS "  ADIYU NNEKA JOY "
D06:            CLR A
                MOVC A,@A+DPTR
                LCALL DATAWRT2
                LCALL SHORT_DELAY
                INC DPTR
                JZ EXIT06
                SJMP D06
EXIT06:         NOP
                RET

NOT_OPTIMUM:            MOV DPTR,#DOWNCOM
C07:            CLR A
                MOVC A,@A+DPTR
                LCALL COMNWRT2
                LCALL SHORT_DELAY
                INC DPTR
                JZ SEND_DAT07
                SJMP C07
SEND_DAT07:     MOV DPTR,#MYDATA7               ;DISPLAYS "  MAT NUMBER "
D07:            CLR A
                MOVC A,@A+DPTR
                LCALL DATAWRT2
                LCALL SHORT_DELAY
                INC DPTR
                JZ EXIT07
                SJMP D07
EXIT07:         NOP
                RET

SYSTEM_ON:              MOV DPTR,#UPCOM
C08:            CLR A
                MOVC A,@A+DPTR
                LCALL COMNWRT2
                LCALL SHORT_DELAY
                INC DPTR
                JZ SEND_DAT08
                SJMP C08
SEND_DAT08:     MOV DPTR,#MYDATA8               ;DISPLAYS "  DEPARTMENT OF EEE"
D08:            CLR A
                MOVC A,@A+DPTR
                LCALL DATAWRT2
                LCALL SHORT_DELAY
                INC DPTR
                JZ EXIT08
                SJMP D08
EXIT08:         NOP
                RET

DC_POWERS:              MOV DPTR,#DOWNCOM
C09:            CLR A
                MOVC A,@A+DPTR
                LCALL COMNWRT2
                LCALL SHORT_DELAY
                INC DPTR
                JZ SEND_DAT09
                SJMP C09
SEND_DAT09:     MOV DPTR,#MYDATA9               ;DISPLAYS "  UNIBEN "
D09:            CLR A
                MOVC A,@A+DPTR
                LCALL DATAWRT2
                LCALL SHORT_DELAY
                INC DPTR
                JZ EXIT09
                SJMP D09
```

```
================================================================================================
EXIT09:             NOP
                    RET

CHECKING_OTHER:                 MOV DPTR,#UPCOM
C10:                CLR A
                    MOVC A,@A+DPTR
                    LCALL COMNWRT2
                    LCALL SHORT_DELAY
                    INC DPTR
                    JZ SEND_DAT10
                    SJMP C10
SEND_DAT10:         MOV DPTR,#MYDATA10          ;DISPLAYS "  SCANNING "
D10:                CLR A
                    MOVC A,@A+DPTR
                    LCALL DATAWRT2
                    LCALL SHORT_DELAY
                    INC DPTR
                    JZ EXIT10
                    SJMP D10
EXIT10:             NOP
                    RET

POWER_SOURCES:          MOV DPTR,#DOWNCOM
C11:                CLR A
                    MOVC A,@A+DPTR
                    LCALL COMNWRT2
                    LCALL SHORT_DELAY
                    INC DPTR
                    JZ SEND_DAT11
                    SJMP C11
SEND_DAT11:         MOV DPTR,#MYDATA11          ;DISPLAYS "  AREA...."
D11:                CLR A
                    MOVC A,@A+DPTR
                    LCALL DATAWRT2
                    LCALL SHORT_DELAY
                    INC DPTR
                    JZ EXIT11
                    SJMP D11
EXIT11:             NOP
                    RET

GRID_POWER_UP:          MOV DPTR,#UPCOM
C12:                CLR A
                    MOVC A,@A+DPTR
                    LCALL COMNWRT2
                    LCALL SHORT_DELAY
                    INC DPTR
                    JZ SEND_DAT12
                    SJMP C12
SEND_DAT12:         MOV DPTR,#MYDATA12          ;DISPLAYS "  AREA.... "
D12:                CLR A
                    MOVC A,@A+DPTR
                    LCALL DATAWRT2
                    LCALL SHORT_DELAY
                    INC DPTR
                    JZ EXIT12
                    SJMP D12
EXIT12:             NOP
                    RET

CHANGING_OVER:          MOV DPTR,#UPCOM
C13:                CLR A
                    MOVC A,@A+DPTR
                    LCALL COMNWRT2
                    LCALL SHORT_DELAY
                    INC DPTR
                    JZ SEND_DAT13
                    SJMP C13
```

```
=====================================================================================================
SEND_DAT13:     MOV DPTR,#MYDATA13              ;DISPLAYS "  SECURED "
D13:            CLR A
                MOVC A,@A+DPTR
                LCALL DATAWRT2
                LCALL SHORT_DELAY
                INC DPTR
                JZ EXIT13
                SJMP D13
EXIT13:         NOP
                RET

GRID_POWER_DOWN:                MOV DPTR,#DOWNCOM
C14:            CLR A
                MOVC A,@A+DPTR
                LCALL COMNWRT2
                LCALL SHORT_DELAY
                INC DPTR
                JZ SEND_DAT14
                SJMP C14
SEND_DAT14:     MOV DPTR,#MYDATA14              ;DISPLAYS "  INTRUDER "
D14:            CLR A
                MOVC A,@A+DPTR
                LCALL DATAWRT2
                LCALL SHORT_DELAY
                INC DPTR
                JZ EXIT14
                SJMP D14
EXIT14:         NOP
                RET

CHECKING_GEN:           MOV DPTR,#UPCOM
C15:            CLR A
                MOVC A,@A+DPTR
                LCALL COMNWRT2
                LCALL SHORT_DELAY
                INC DPTR
                JZ SEND_DAT15
                SJMP C15
SEND_DAT15:     MOV DPTR,#MYDATA15              ;DISPLAYS "  ALERT "
D15:            CLR A
                MOVC A,@A+DPTR
                LCALL DATAWRT2
                LCALL SHORT_DELAY
                INC DPTR
                JZ EXIT15
                SJMP D15
EXIT15:         NOP
                RET

OVERIDE_MODE:           MOV DPTR,#DOWNCOM
C16:            CLR A
                MOVC A,@A+DPTR
                LCALL COMNWRT2
                LCALL SHORT_DELAY
                INC DPTR
                JZ SEND_DAT16
                SJMP C16
SEND_DAT16:     MOV DPTR,#MYDATA16              ;DISPLAYS "  ALERT "
D16:            CLR A
                MOVC A,@A+DPTR
                LCALL DATAWRT2
                LCALL SHORT_DELAY
                INC DPTR
                JZ EXIT16
                SJMP D16
EXIT16:         NOP
                RET
```

```
==========================================================================================
GENERATOR_ON:           MOV DPTR,#UPCOM
C17:                CLR A
                    MOVC A,@A+DPTR
                    LCALL COMNWRT2
                    LCALL SHORT_DELAY
                    INC DPTR
                    JZ SEND_DAT17
                    SJMP C17
SEND_DAT17:         MOV DPTR,#MYDATA17              ;DISPLAYS "  ALERT "
D17:                CLR A
                    MOVC A,@A+DPTR
                    LCALL DATAWRT2
                    LCALL SHORT_DELAY
                    INC DPTR
                    JZ EXIT17
                    SJMP D17
EXIT17:             NOP
                    RET

OPERATIONAL_MODE:               MOV DPTR,#DOWNCOM
C18:                CLR A
                    MOVC A,@A+DPTR
                    LCALL COMNWRT2
                    LCALL SHORT_DELAY
                    INC DPTR
                    JZ SEND_DAT18
                    SJMP C18
SEND_DAT18:         MOV DPTR,#MYDATA18              ;DISPLAYS "  ALERT "
D18:                CLR A
                    MOVC A,@A+DPTR
                    LCALL DATAWRT2
                    LCALL SHORT_DELAY
                    INC DPTR
                    JZ EXIT18
                    SJMP D18
EXIT18:             NOP
                    RET

STARTING_THE:           MOV DPTR,#UPCOM
C19:                CLR A
                    MOVC A,@A+DPTR
                    LCALL COMNWRT2
                    LCALL SHORT_DELAY
                    INC DPTR
                    JZ SEND_DAT19
                    SJMP C19
SEND_DAT19:         MOV DPTR,#MYDATA19              ;DISPLAYS "  ALERT "
D19:                CLR A
                    MOVC A,@A+DPTR
                    LCALL DATAWRT2
                    LCALL SHORT_DELAY
                    INC DPTR
                    JZ EXIT19
                    SJMP D19
EXIT19:             NOP
                    RET

STOPPING_THE:           MOV DPTR,#UPCOM
C20:                CLR A
                    MOVC A,@A+DPTR
                    LCALL COMNWRT2
                    LCALL SHORT_DELAY
                    INC DPTR
                    JZ SEND_DAT20
                    SJMP C20
SEND_DAT20:         MOV DPTR,#MYDATA20              ;DISPLAYS "  ALERT "
D20:                CLR A
                    MOVC A,@A+DPTR
                    LCALL DATAWRT2
                    LCALL SHORT_DELAY
                    INC DPTR
                    JZ EXIT20
                    SJMP D20
```

```
====================================================================================================
EXIT20:         NOP
                RET

GENERATOR:              MOV DPTR,#DOWNCOM
C21:            CLR A
                MOVC A,@A+DPTR
                LCALL COMNWRT2
                LCALL SHORT_DELAY
                INC DPTR
                JZ SEND_DAT21
                SJMP C21
SEND_DAT21:     MOV DPTR,#MYDATA21              ;DISPLAYS "  ALERT "
D21:            CLR A
                MOVC A,@A+DPTR
                LCALL DATAWRT2
                LCALL SHORT_DELAY
                INC DPTR
                JZ EXIT21
                SJMP D21
EXIT21:         NOP
                RET

IS_SUCCESSFUL:  MOV DPTR,#DOWNCOM
C22:            CLR A
                MOVC A,@A+DPTR
                LCALL COMNWRT2
                LCALL SHORT_DELAY
                INC DPTR
                JZ SEND_DAT22
                SJMP C22
SEND_DAT22:     MOV DPTR,#MYDATA22              ;DISPLAYS "  ALERT "
D22:            CLR A
                MOVC A,@A+DPTR
                LCALL DATAWRT2
                LCALL SHORT_DELAY
                INC DPTR
                JZ EXIT22
                SJMP D22
EXIT22:         NOP
                RET

OPERATION:              MOV DPTR,#UPCOM
C23:            CLR A
                MOVC A,@A+DPTR
                LCALL COMNWRT2
                LCALL SHORT_DELAY
                INC DPTR
                JZ SEND_DAT23
                SJMP C23
SEND_DAT23:     MOV DPTR,#MYDATA23              ;DISPLAYS "  ALERT "
D23:            CLR A
                MOVC A,@A+DPTR
                LCALL DATAWRT2
                LCALL SHORT_DELAY
                INC DPTR
                JZ EXIT23
                SJMP D23
EXIT23:         NOP
                RET

NOT_SUCCESSFUL:         MOV DPTR,#DOWNCOM
C24:            CLR A
                MOVC A,@A+DPTR
                LCALL COMNWRT2
                LCALL SHORT_DELAY
                INC DPTR
                JZ SEND_DAT24
                SJMP C24

====================================================================================================
```

```
=====================================================================================================
SEND_DAT24:     MOV DPTR,#MYDATA24              ;DISPLAYS "  ALERT "
D24:            CLR A
                MOVC A,@A+DPTR
                LCALL DATAWRT2
                LCALL SHORT_DELAY
                INC DPTR
                JZ EXIT24
                SJMP D24
EXIT24:         NOP
                RET

FALSE_ALARM:            MOV DPTR,#UPCOM
C25:            CLR A
                MOVC A,@A+DPTR
                LCALL COMNWRT2
                LCALL SHORT_DELAY
                INC DPTR
                JZ SEND_DAT25
                SJMP C25
SEND_DAT25:     MOV DPTR,#MYDATA25              ;DISPLAYS "  ALERT "
D25:            CLR A
                MOVC A,@A+DPTR
                LCALL DATAWRT2
                LCALL SHORT_DELAY
                INC DPTR
                JZ EXIT25
                SJMP D25
EXIT25:         NOP
                RET

POWER_RESTORED:                 MOV DPTR,#UPCOM
C26:            CLR A
                MOVC A,@A+DPTR
                LCALL COMNWRT2
                LCALL SHORT_DELAY
                INC DPTR
                JZ SEND_DAT26
                SJMP C26
SEND_DAT26:     MOV DPTR,#MYDATA26              ;DISPLAYS "  ALERT "
D26:            CLR A
                MOVC A,@A+DPTR
                LCALL DATAWRT2
                LCALL SHORT_DELAY
                INC DPTR
                JZ EXIT26
                SJMP D26
EXIT26:         NOP
                RET

TROUBLE_WITH:           MOV DPTR,#UPCOM
C27:            CLR A
                MOVC A,@A+DPTR
                LCALL COMNWRT2
                LCALL SHORT_DELAY
                INC DPTR
                JZ SEND_DAT27
                SJMP C27
SEND_DAT27:     MOV DPTR,#MYDATA27              ;DISPLAYS "  ALERT "
D27:            CLR A
                MOVC A,@A+DPTR
                LCALL DATAWRT2
                LCALL SHORT_DELAY
                INC DPTR
                JZ EXIT27
                SJMP D27
EXIT27:         NOP
                RET
```

```
=====================================================================================================
RENEWABLE:              MOV DPTR,#UPCOM
C28:            CLR A
                MOVC A,@A+DPTR
                LCALL COMNWRT2
                LCALL SHORT_DELAY
                INC DPTR
                JZ SEND_DAT28
                SJMP C28
SEND_DAT28:     MOV DPTR,#MYDATA28              ;DISPLAYS "  ALERT "
D28:            CLR A
                MOVC A,@A+DPTR
                LCALL DATAWRT2
                LCALL SHORT_DELAY
                INC DPTR
                JZ EXIT28
                SJMP D28
EXIT28:         NOP
                RET

AVAILABLE:              MOV DPTR,#DOWNCOM
C29:            CLR A
                MOVC A,@A+DPTR
                LCALL COMNWRT2
                LCALL SHORT_DELAY
                INC DPTR
                JZ SEND_DAT29
                SJMP C29
SEND_DAT29:     MOV DPTR,#MYDATA29              ;DISPLAYS "  ALERT "
D29:            CLR A
                MOVC A,@A+DPTR
                LCALL DATAWRT2
                LCALL SHORT_DELAY
                INC DPTR
                JZ EXIT29
                SJMP D29
EXIT29:         NOP
                RET

UNAVAILABLE:            MOV DPTR,#DOWNCOM
C30:            CLR A
                MOVC A,@A+DPTR
                LCALL COMNWRT2
                LCALL SHORT_DELAY
                INC DPTR
                JZ SEND_DAT30
                SJMP C30
SEND_DAT30:     MOV DPTR,#MYDATA30              ;DISPLAYS "  ALERT "
D30:            CLR A
                MOVC A,@A+DPTR
                LCALL DATAWRT2
                LCALL SHORT_DELAY
                INC DPTR
                JZ EXIT30
                SJMP D30
EXIT30:         NOP
                RET

;ldc commands and lcd data
COMNWRT2:                                       ;SEND COMMAND TO LCD
                MOV LCD_PORT,A                  ;COPY REG A TO P1
                CLR RS_BIT                      ;RS=0 FOR COMMAND
                CLR RW_BIT                      ;R/W= FOR WRITE
                SETB EN_BIT                     ;E=1 FOR HIGH PULSE
                LCALL SHORT_DELAY               ;GIVE LCD SOMETIME
                CLR EN_BIT                      ;E=0 FOR H-TO-L PULSE
                RET

=====================================================================================================
```

```
==================================================================================================
DATAWRT2:                                              ;WRITE DATA TO LCD
                MOV LCD_PORT,A                         ;COPY REG A TO PORT 1
                SETB RS_BIT                            ;RS=1 FOR DATA
                CLR RW_BIT                             ;R/W=0 FOR WRITE
                SETB EN_BIT                            ;E=1 FOR HIGH PULSE
                LCALL SHORT_DELAY                      ;GIVE LCD SOME TIME
                CLR EN_BIT                             ;E=0 FOR H-TO-L PULSE
                RET

;delay subroutines
LONG_DELAY:     MOV 35H,#20
BACK3:          MOV 36H,#255
BACK2:          MOV 37H,#255
BACK1:          DJNZ 37H,BACK1
                DJNZ 36H,BACK2
                DJNZ 35H,BACK3
                RET

ONE_SEC:        MOV 35H,#12
SEC3X:          MOV 36H,#255
SEC2X:          MOV 37H,#255
SEC1X:          DJNZ 37H,SEC1X
                DJNZ 36H,SEC2X
                DJNZ 35H,SEC3X
                RET

HALF_SEC:       MOV 35H,#5
SEC30:          MOV 36H,#255
SEC20:          MOV 37H,#255
SEC10:          DJNZ 37H,SEC10
                DJNZ 36H,SEC20
                DJNZ 35H,SEC30
                RET

SHORT_DELAY:    MOV 38H,#255
AGAIN3:         DJNZ 38H,AGAIN3
                RET

DELAY:          MOV 35H,#2
SEC30X:         MOV 36H,#255
SEC20X:         MOV 37H,#255
SEC10X:         DJNZ 37H,SEC10X
                DJNZ 36H,SEC20X
                DJNZ 35H,SEC30X
                RET

;Display data and command routines
MYDATA1:        DB "  SOLAR HYBRID  ",0
MYDATA2:        DB "  POWER SYSTEM  ",0
MYDATA3:        DB "CHECKING SYSTEM ",0
MYDATA4:        DB "  STATUS.....   ",0
MYDATA5:        DB "   DC BUS-BAR   ",0
MYDATA6:        DB "   IS OPTIMUM   ",0
MYDATA7:        DB " IS NOT OPTIMUM ",0                ;UP
MYDATA8:        DB "  SYSTEM IS ON  ",0                ;UP
MYDATA9:        DB "    DC POWER    ",0                ;DOWN
MYDATA10:       DB " CHECKING OTHER ",0                ;UP
MYDATA11:       DB " POWER SOURCES  ",0
MYDATA12:       DB "   GRID POWER   ",0
MYDATA13:       DB "CHANGING OVER TO",0
MYDATA14:       DB "   GRID POWER   ",0
MYDATA15:     DB " CHECKING GEN   ",0
MYDATA16:       DB "  OVERIDE MODE  ",0
MYDATA17:       DB "  GENERATOR ON  ",0
MYDATA18:       DB "OPERATIONAL MODE",0
MYDATA19:       DB "  STARTING THE  ",0
MYDATA20:       DB "  STOPPING THE  ",0
MYDATA21:       DB "    GENERATOR   ",0
MYDATA22:       DB " IS SUCCESSFUL  ",0
MYDATA23:       DB "   OPERATION    ",0
MYDATA24:       DB " NOT SUCCESSFUL ",0
```

```
==================================================================================================
MYDATA25:       DB "  FALSE ALARM   ",0
MYDATA26:       DB " POWER RESTORED ",0
MYDATA27:       DB "  TROUBLE WITH  ",0
MYDATA28:       DB "RENEWABLE ENERGY",0
MYDATA29:       DB "   AVAILABLE    ",0
MYDATA30:       DB "  UNAVAILABLE   ",0



UPCOM:          DB 38H,06,0FH,80H,01,0 ;COMMANDS AND NULL
DOWNCOM:        DB 38H,06,0FH,0C0H,0

END
```

APPENDIX B

Simulation procedures and results with different scenarios

Figures B1 – B16 show the different stages of the simulation process and the corresponding results.

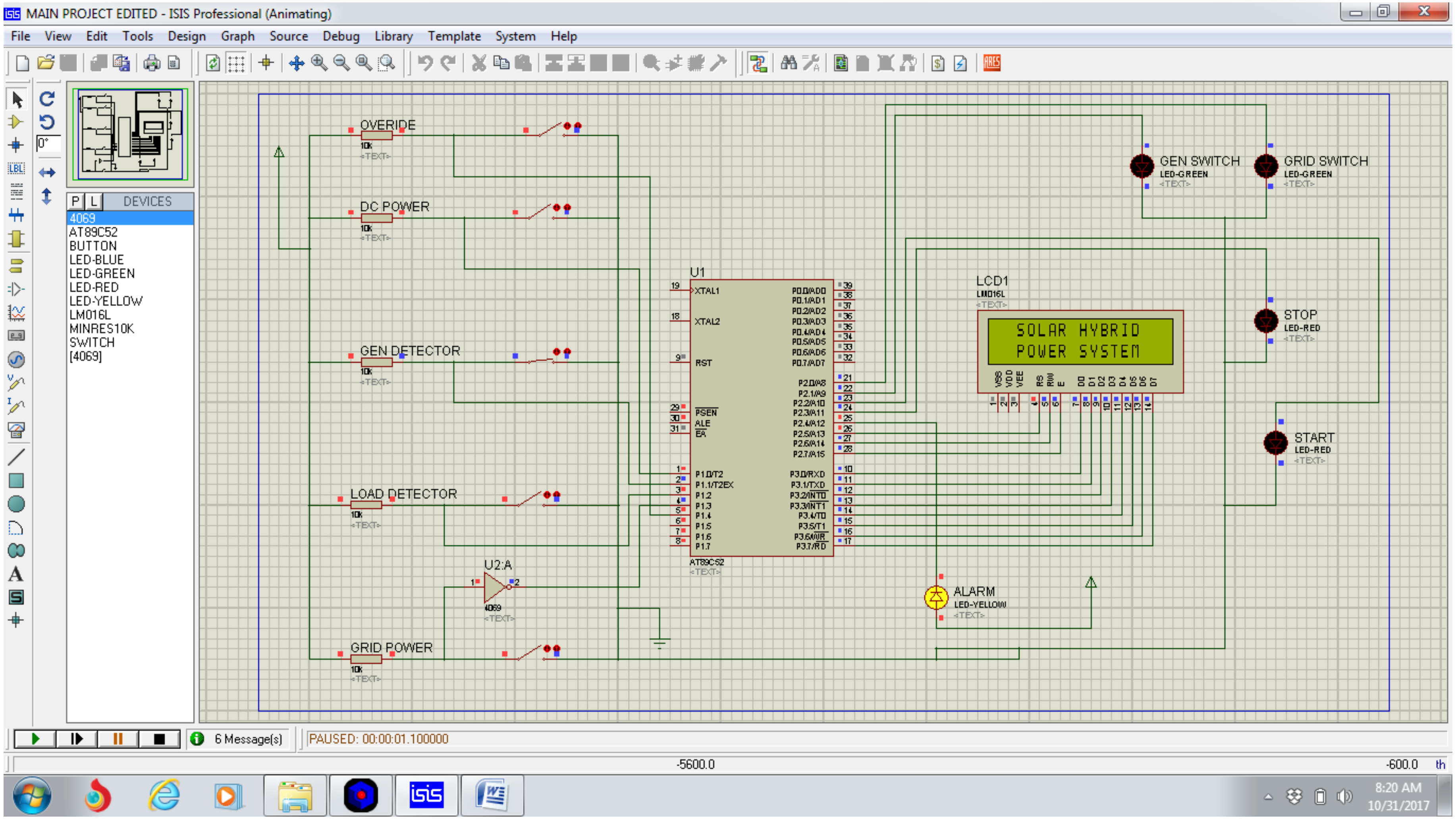

Figure B1: The welcome home screen

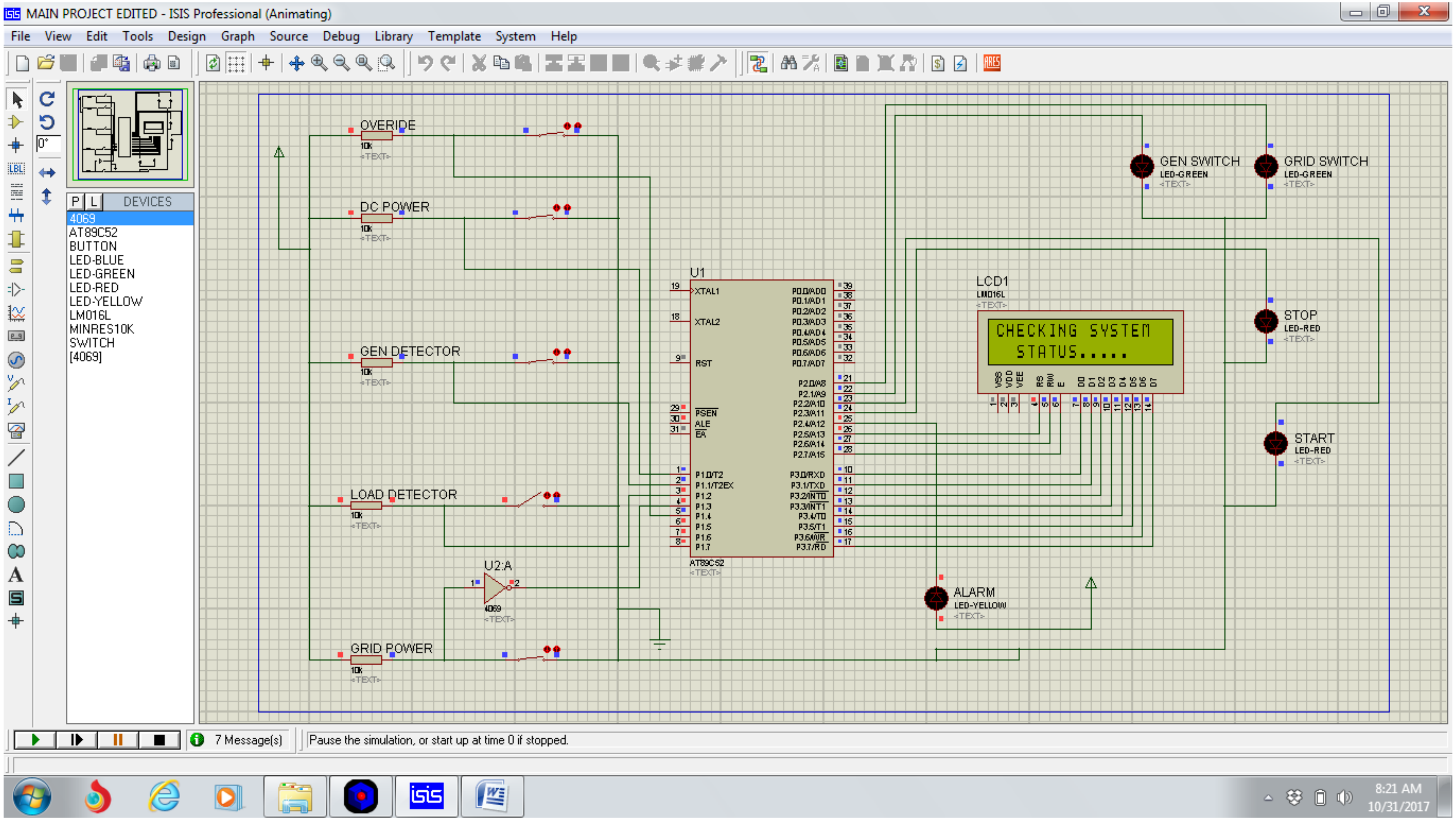

Figure B2: Checking battery voltage level

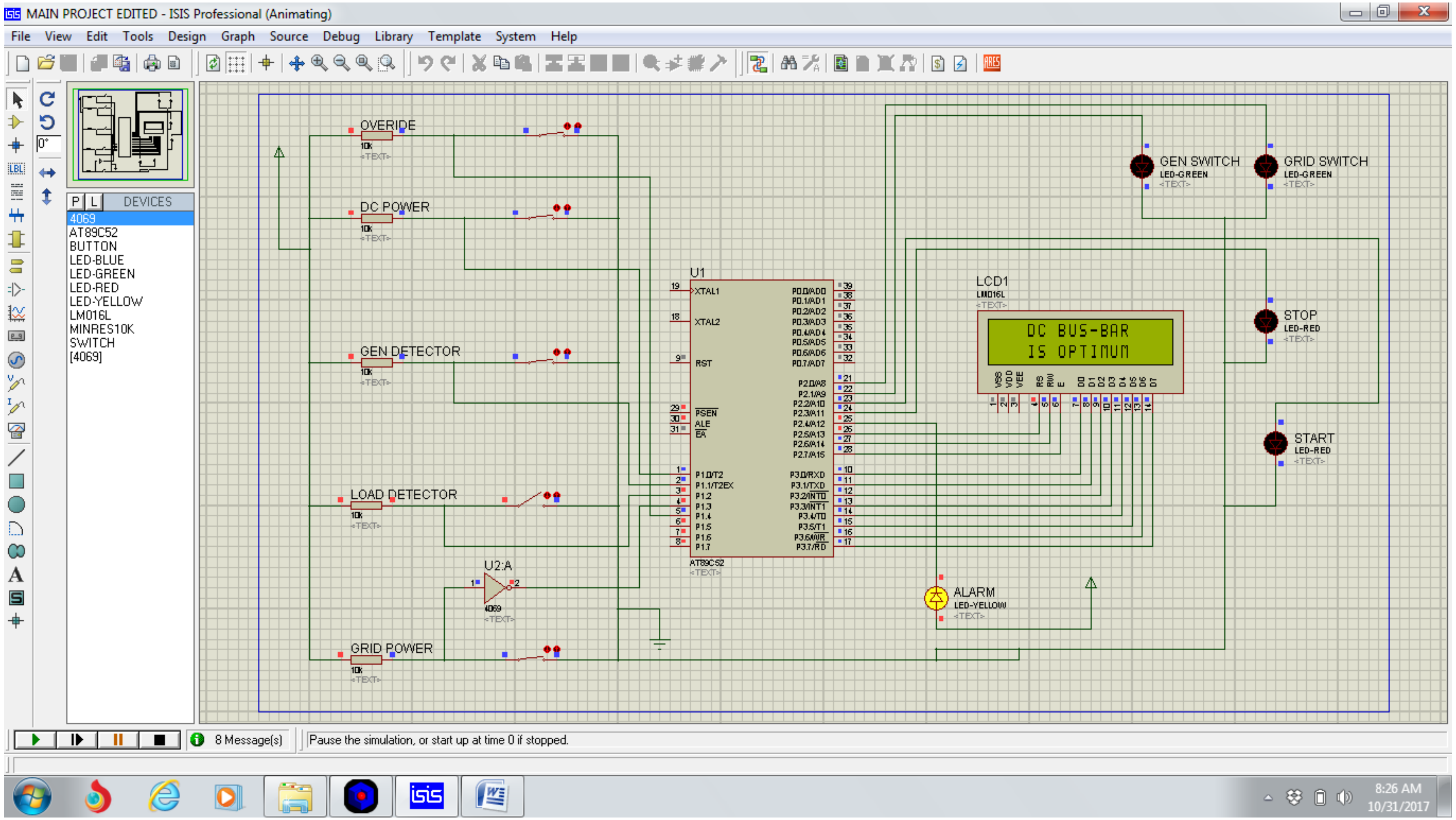

Figure B3: When dc power is optimum

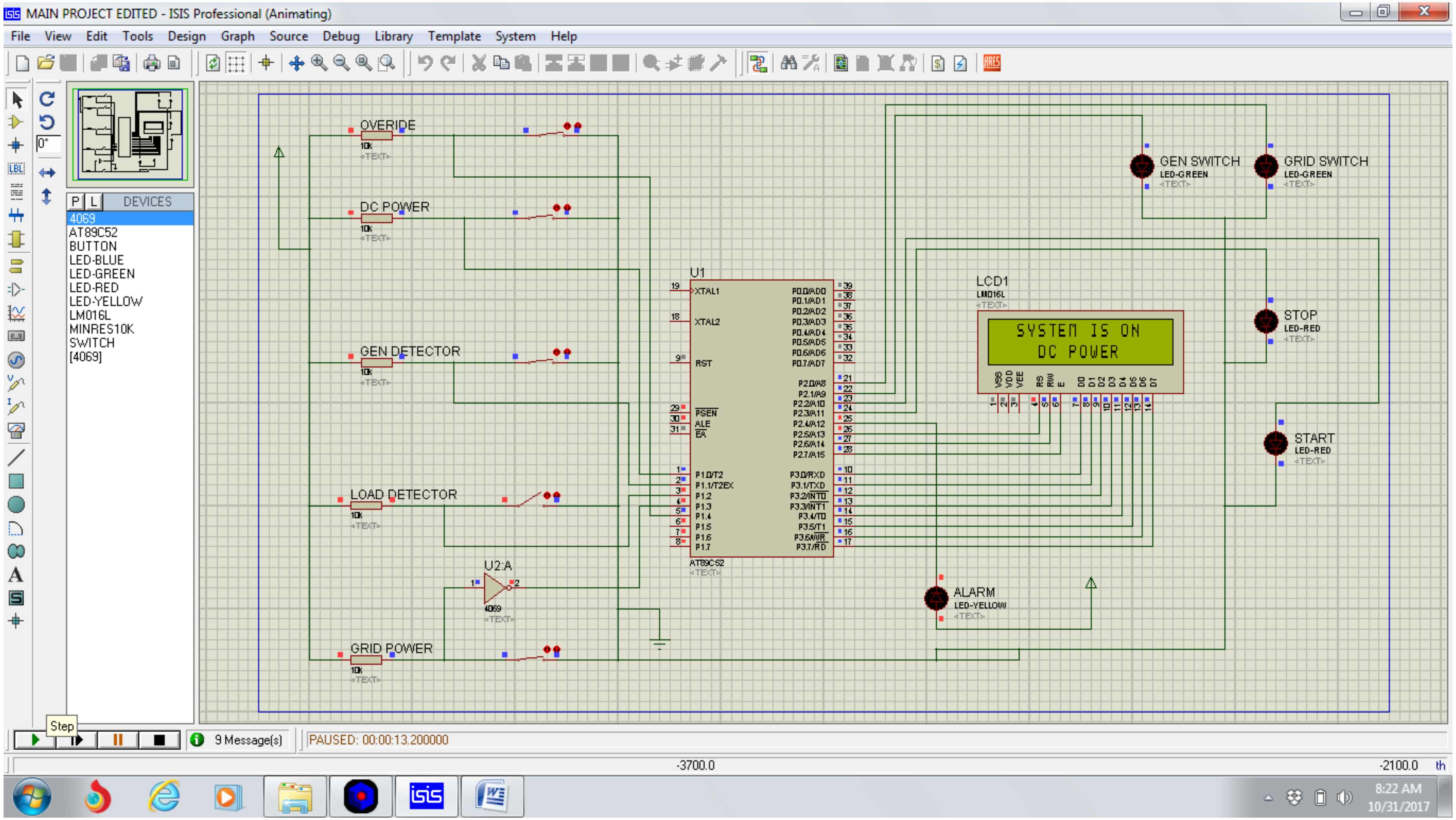

Figure B4: System running on dc power

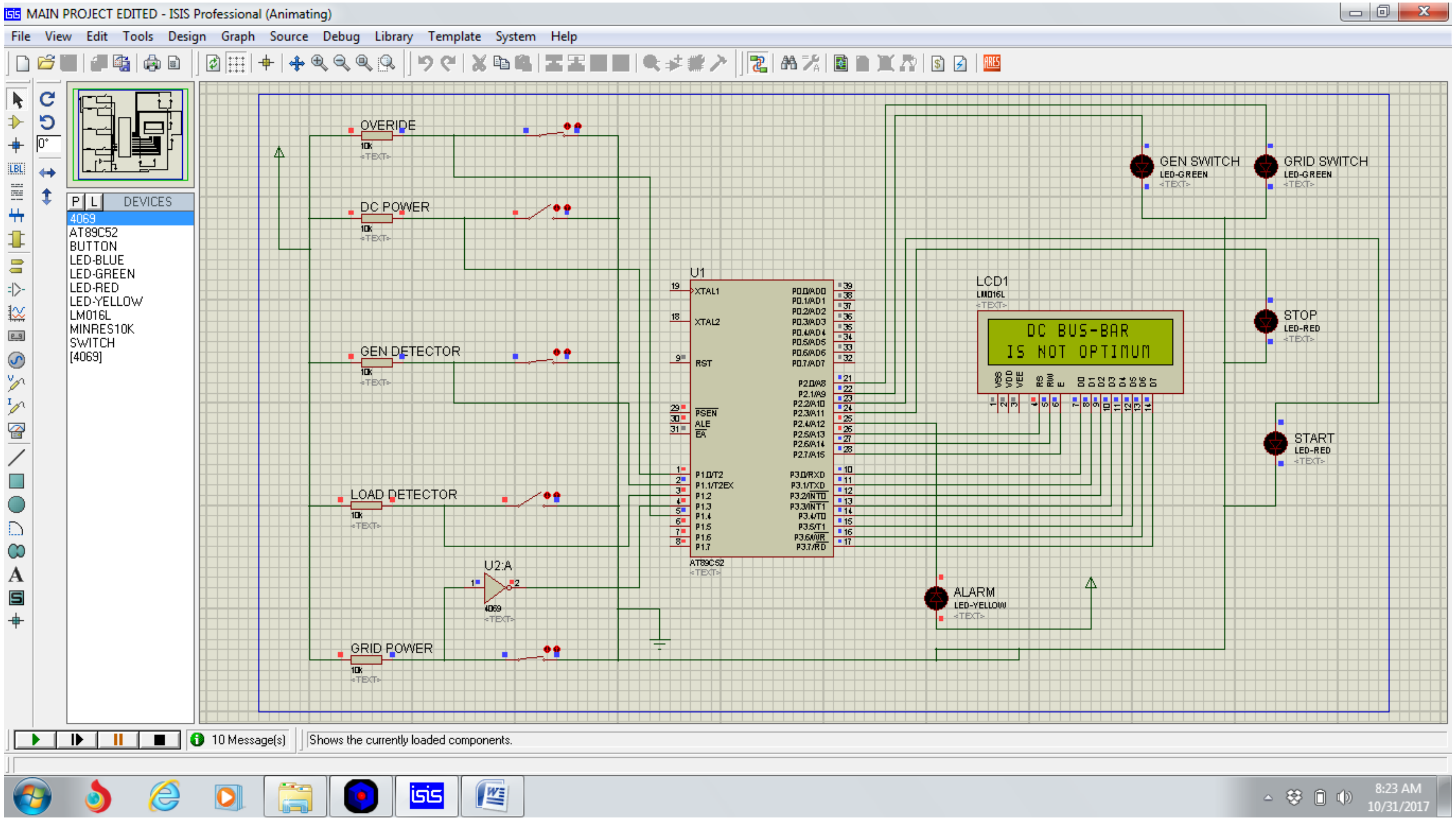

Figure B5: When DC power is not optimum

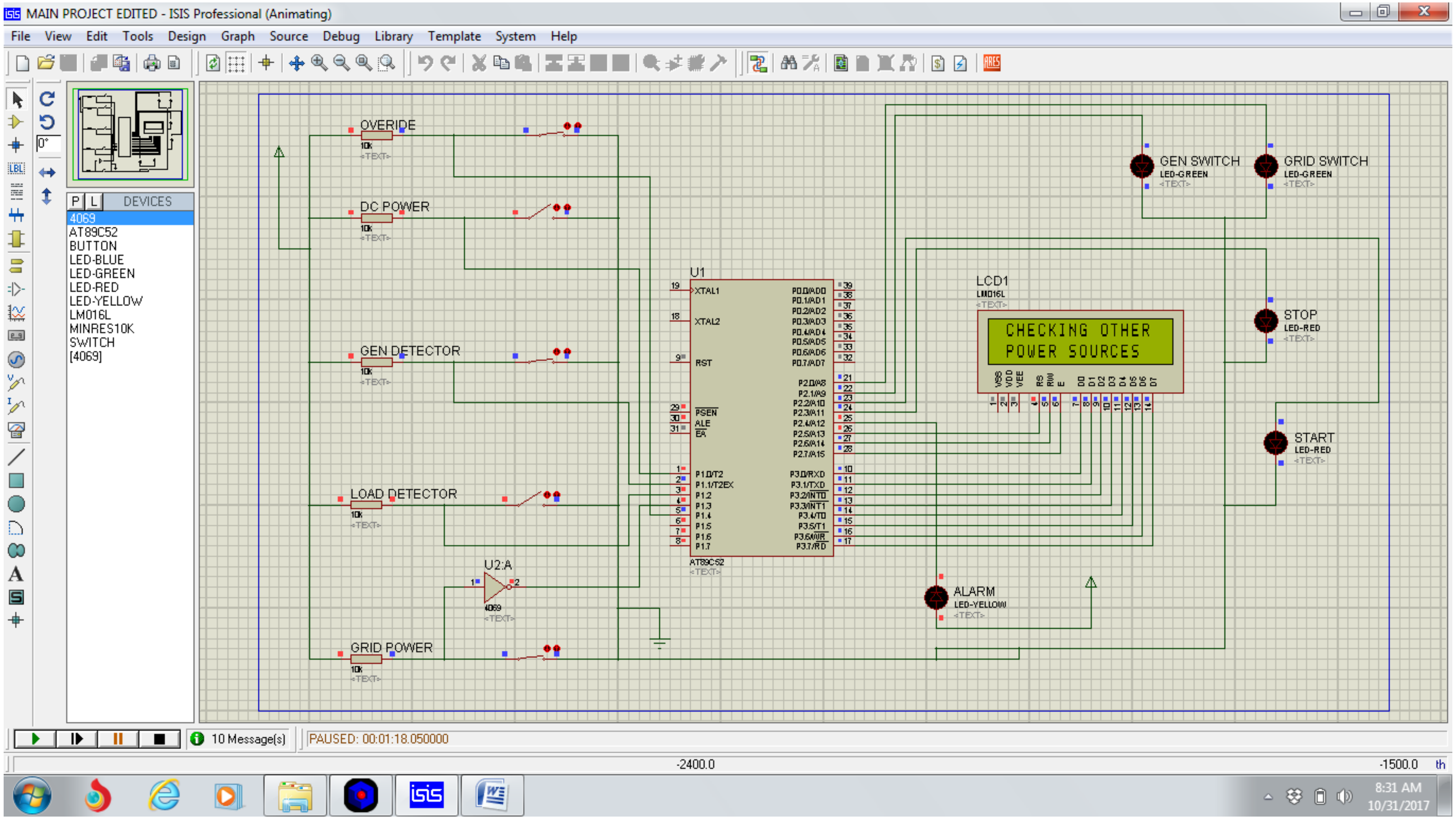

Figure B6: Alternate actions when a power source fails

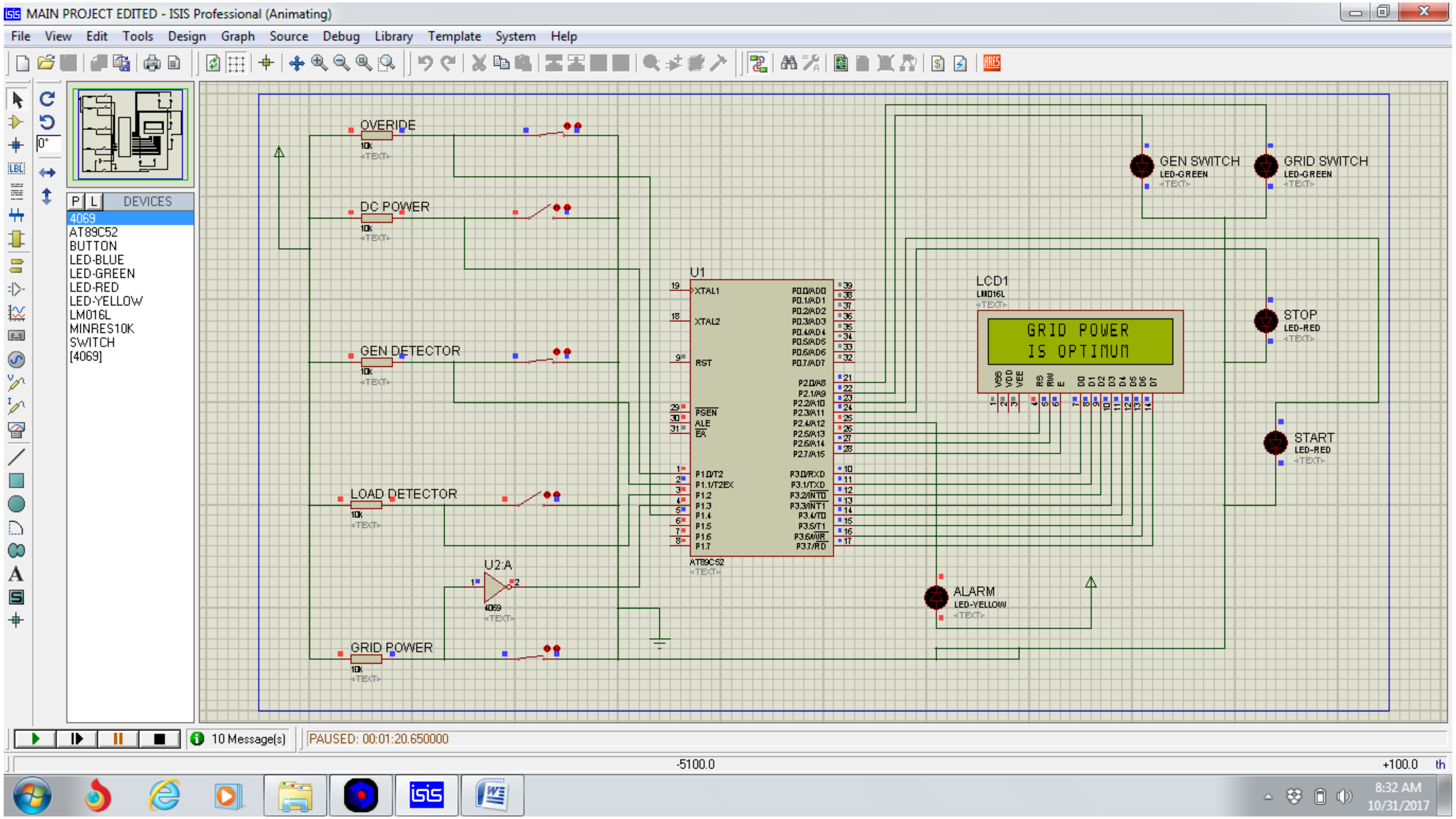

Figure B7: When grid power is optimum

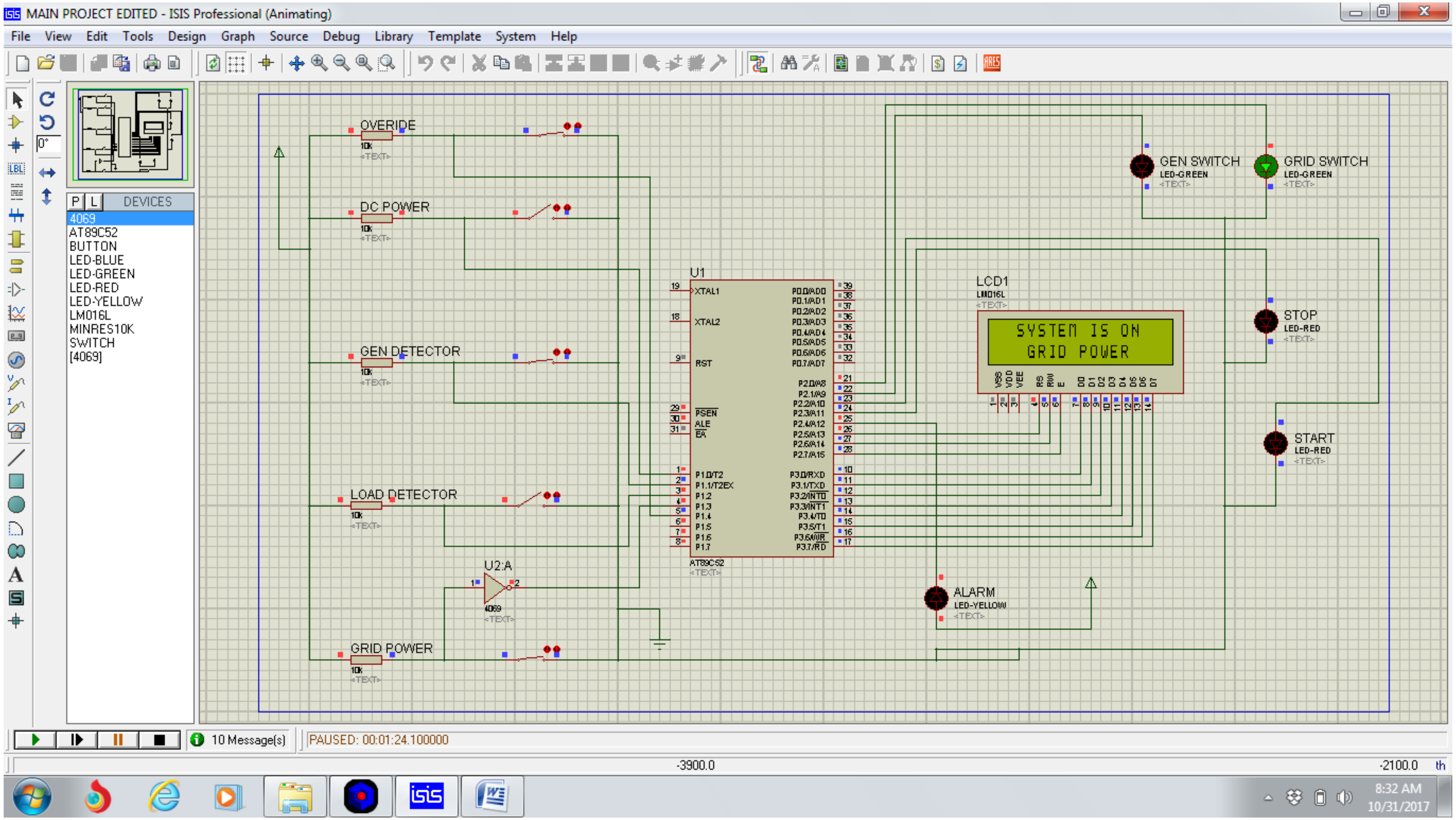

Figure B8: System is on grid power

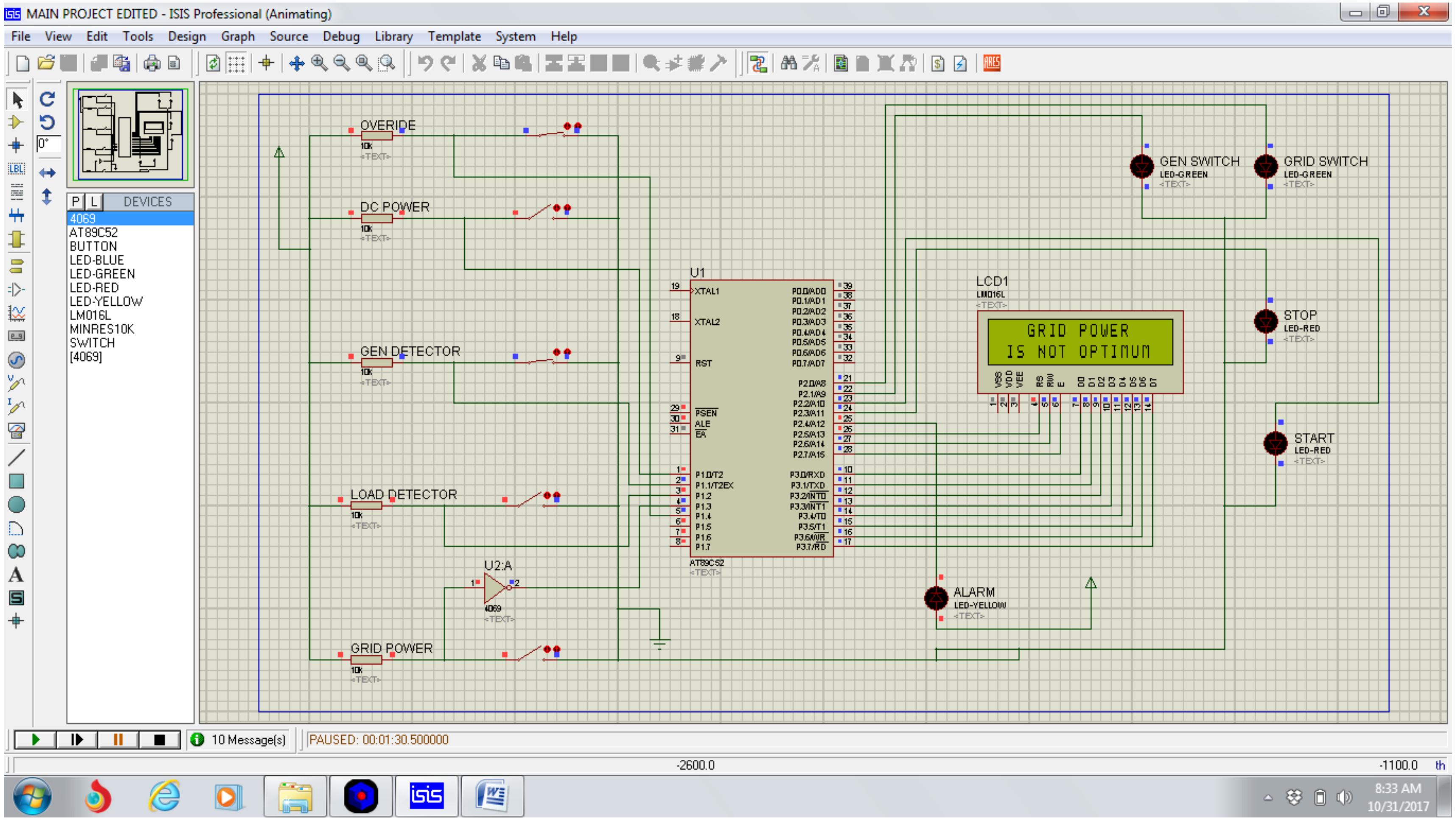

Figure B9: When grid power become not optimum

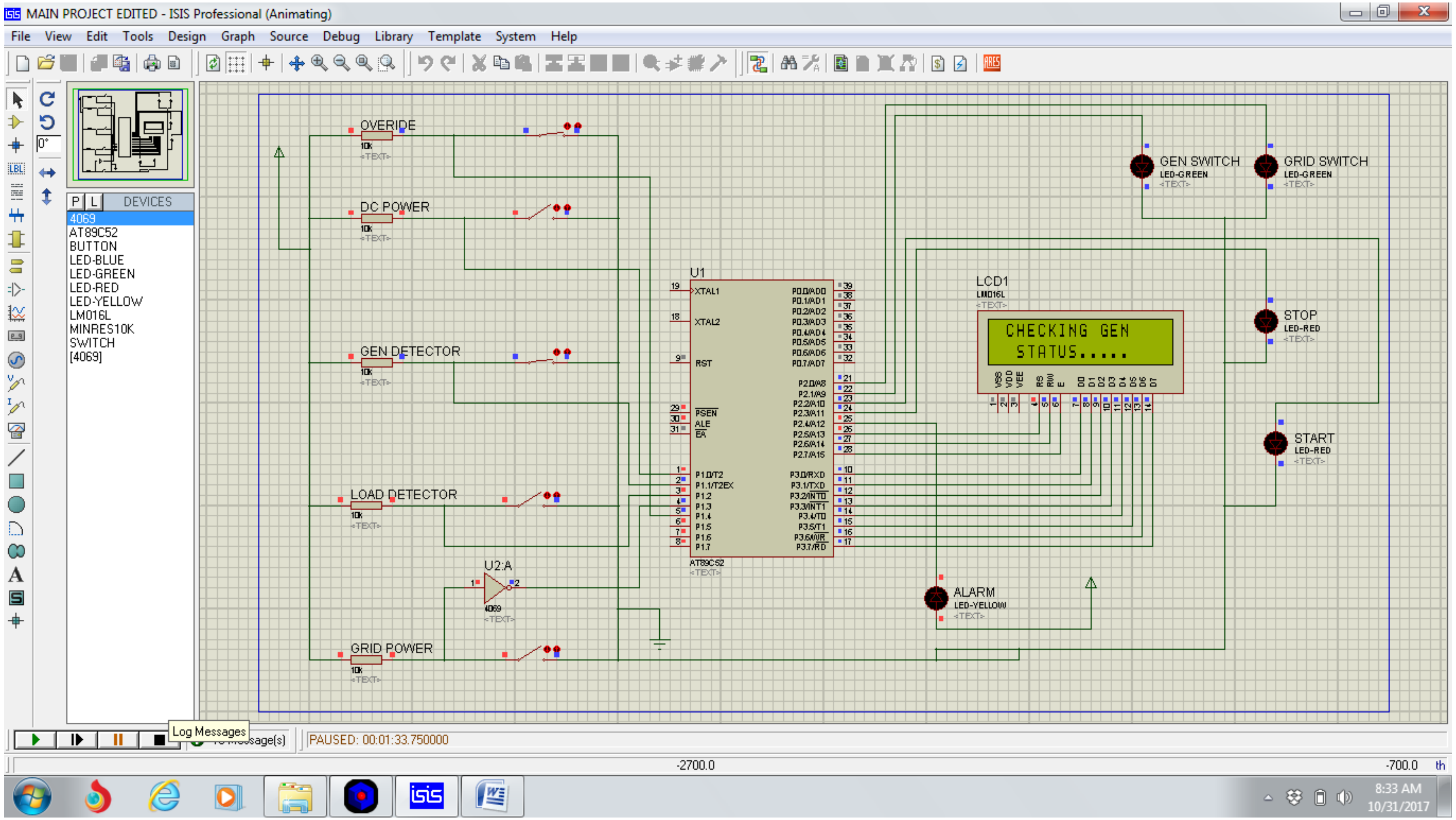

Figure B10: Checking the generator status

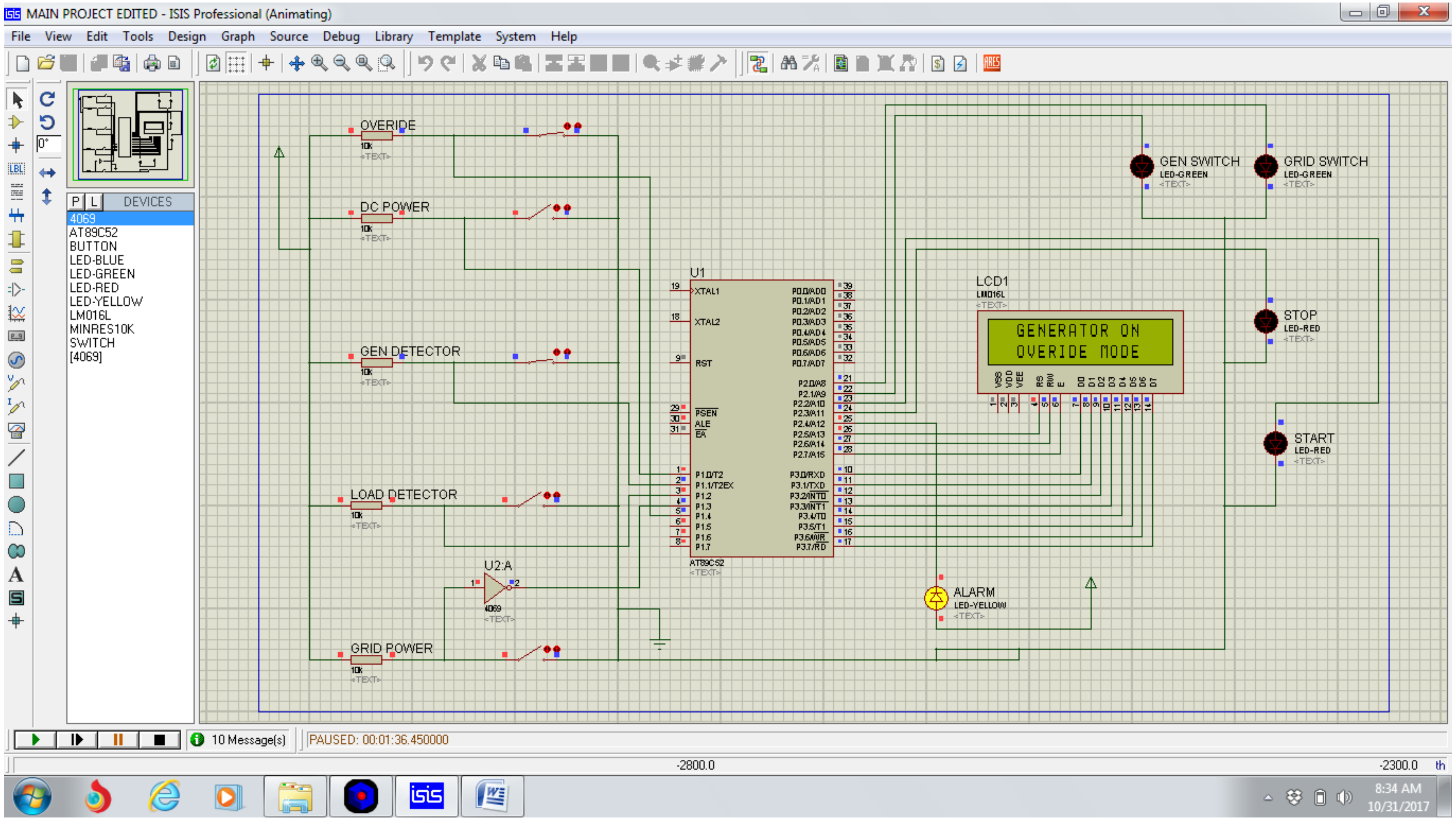

Figure B11: When generator is on override mode

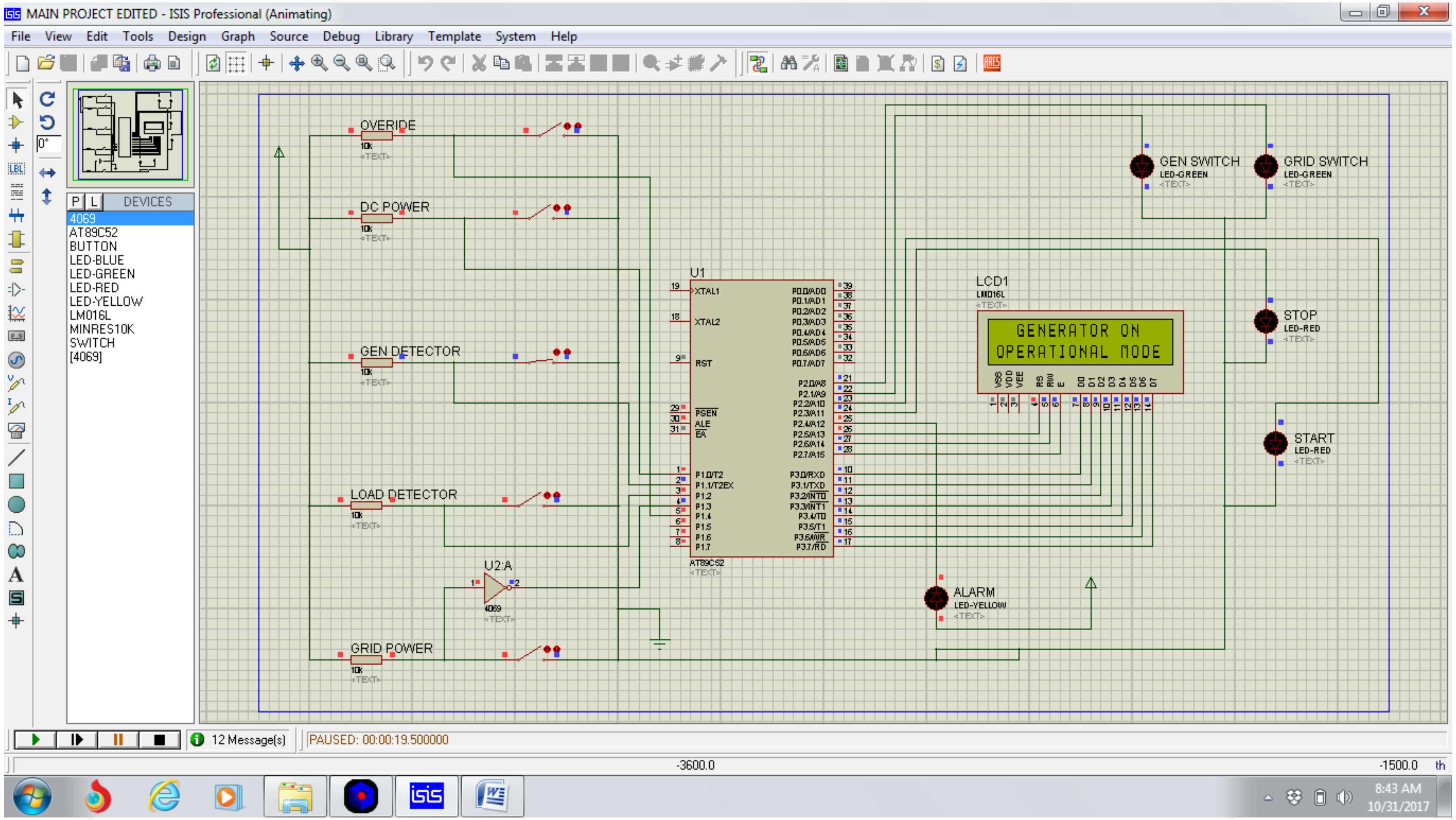

Figure B12: When generator is on operational mode

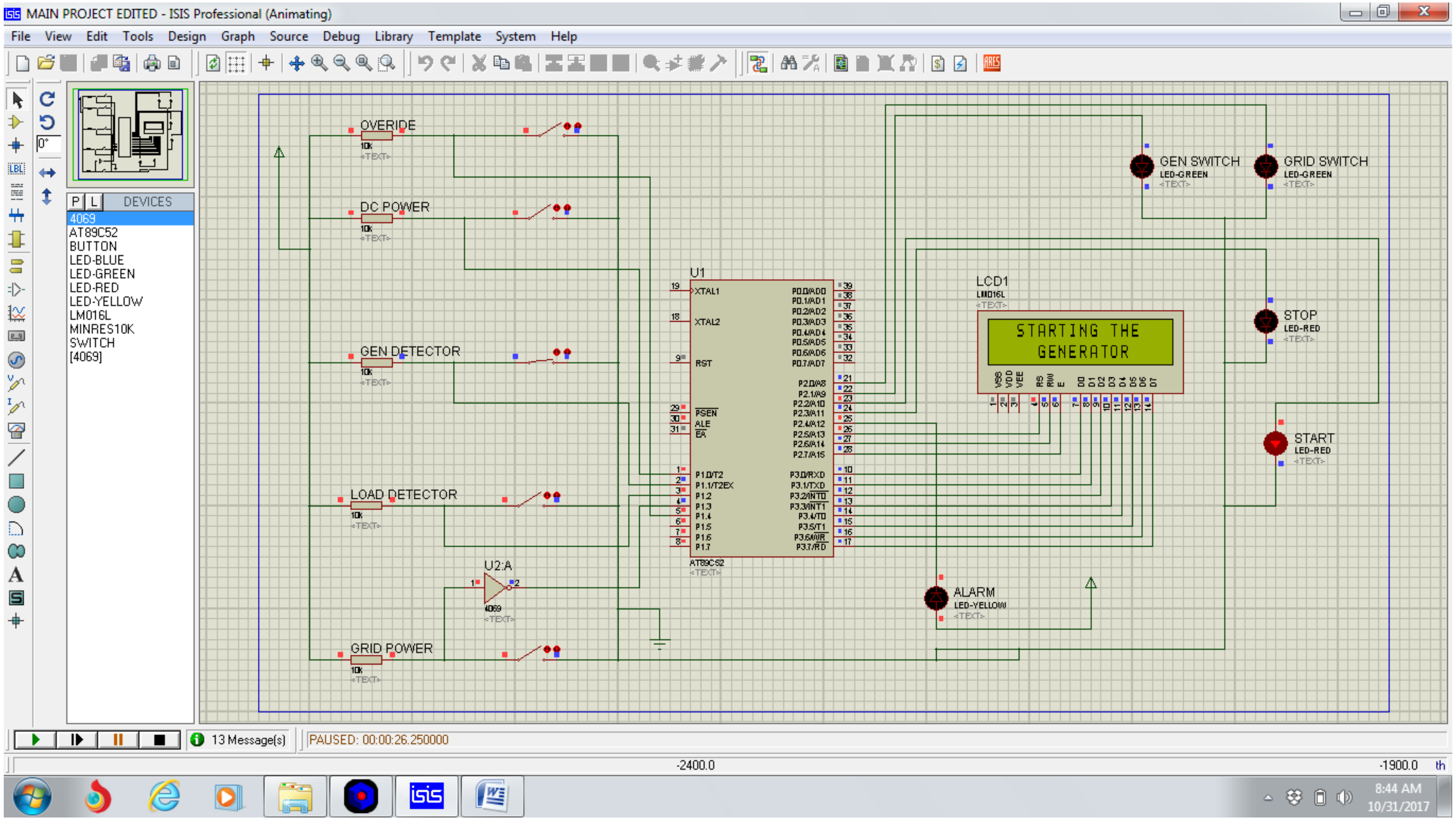

Figure B13: System starts the generator

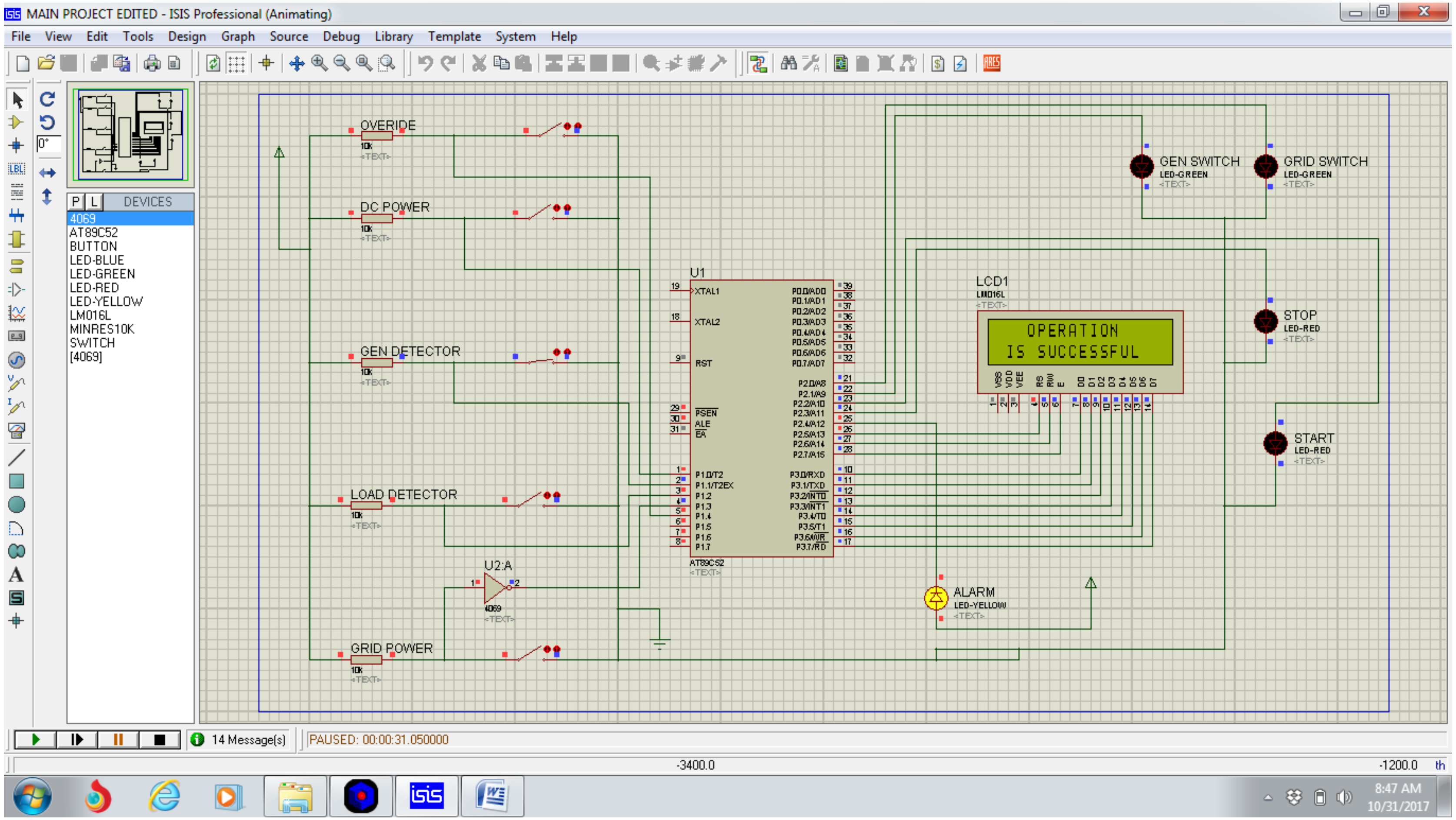

Figure B14: When the generator activation is successful

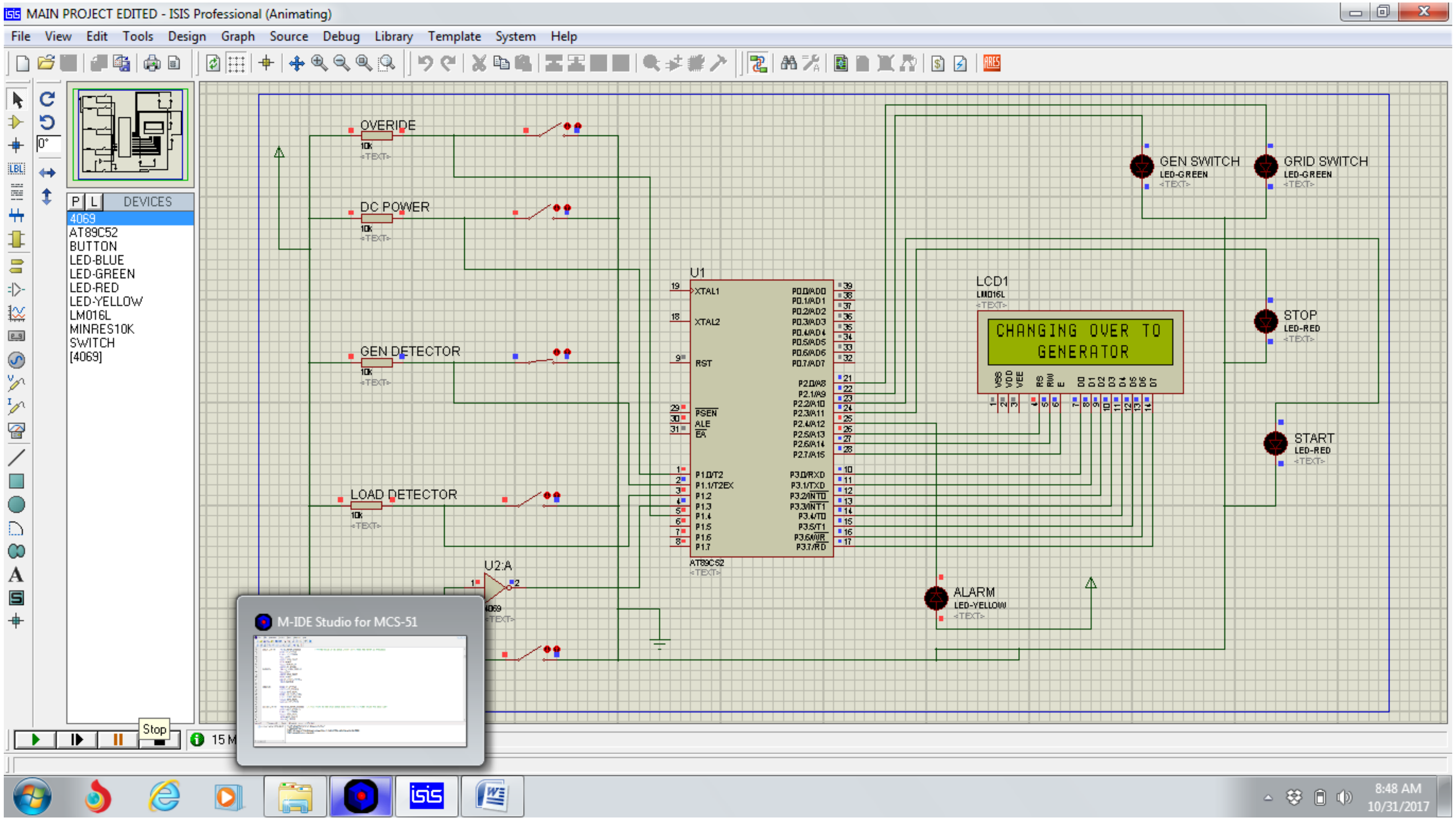

Figure B15: System changing over to generator power supply

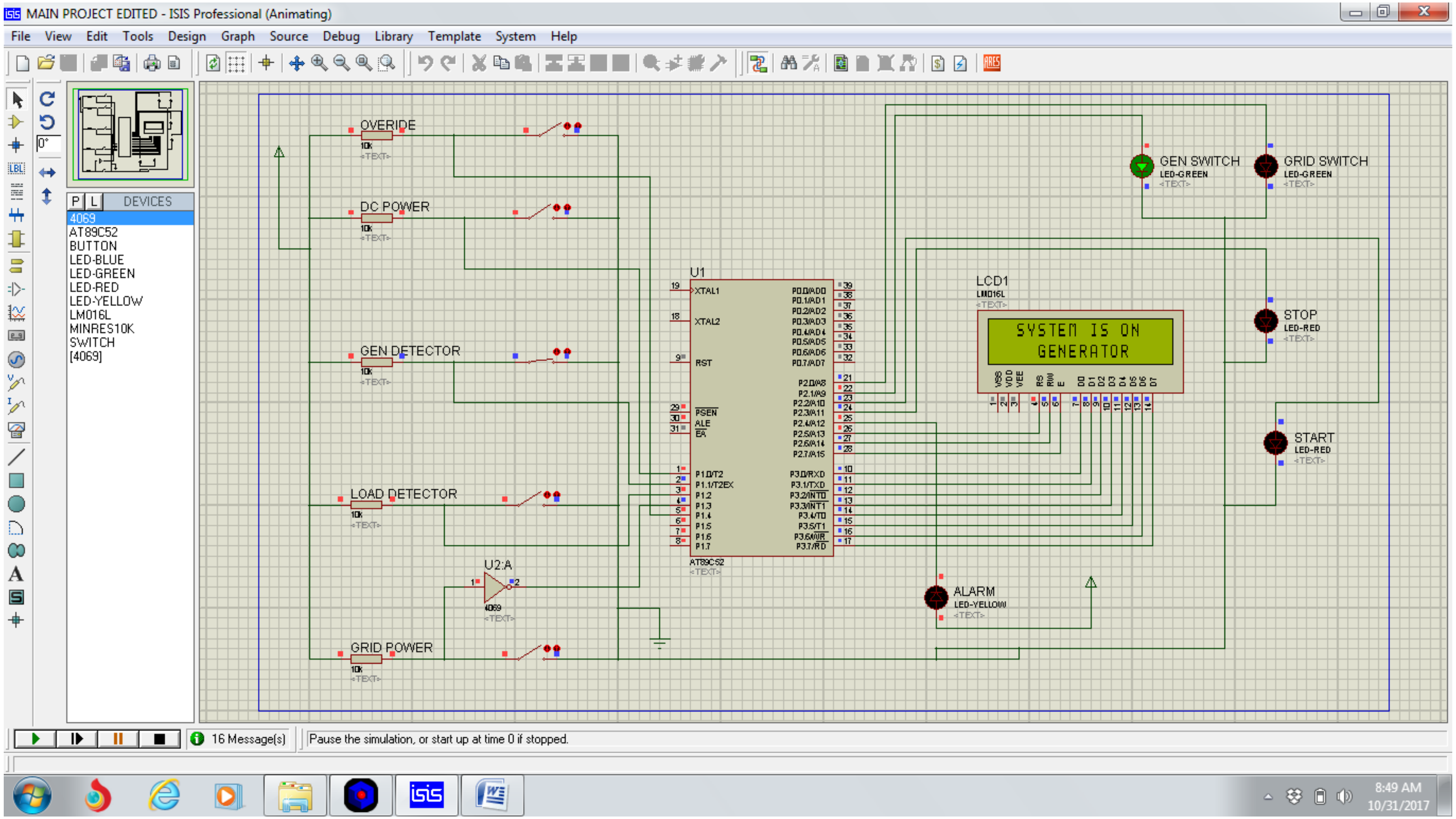

Figure B16: System runs on generator

APPENDIX C

Measured Experimental Results

Table C1: Measured values taken for the developed micro-grid strategy for February 18, 2018

Time (h)	Battery Voltage (V)	Battery Current (A)	Solar Panel Voltage (V)	Solar Panel Current (A)	Wattmeter Reading (kWh)	Grid Consumption (kWh)	Cumulative Grid Consumption (kWh)
9:30	13.1	0.8	13.9	0.8	08001.44	0.00	0.00
9:33	12.5	0.8	13.5	0.8	08001.44	0.00	0.00
9:36	12.49	0.8	13.5	0.8	08001.44	0.00	0.00
9:39	12.51	0.8	13.6	0.8	08001.44	0.00	0.00
9:42	12.52	0.8	13.6	0.8	08001.44	0.00	0.00
9:45	12.53	0.9	13.6	1.0	08001.44	0.00	0.00
9:48	12.53	0.9	13.6	0.9	08001.44	0.00	0.00
9:51	12.53	1.0	13.6	1.0	08001.44	0.00	0.00
9:54	12.53	1.0	13.6	1.0	08001.44	0.00	0.00
9:57	12.53	1.0	13.7	1.1	08001.44	0.00	0.00
10:00	12.52	1.3	12.8	1.3	08001.44	0.00	0.00
10:03	12.52	1.1	13.2	1.1	08001.44	0.00	0.00
10:06	12.52	1.2	13.4	1.2	08001.44	0.00	0.00
10:09	12.51	1.2	12.8	1.3	08001.44	0.00	0.00
10:12	12.50	1.1	13.2	1.1	08001.44	0.00	0.00
10:15	12.50	1.0	13.6	1.1	08001.44	0.00	0.00
10:18	12.49	1.0	13.6	1.0	08001.44	0.00	0.00
10:21	12.49	1.3	12.6	1.3	08001.44	0.00	0.00
10:24	12.48	1.2	13.2	1.2	08001.44	0.00	0.00
10:27	12.48	1.2	13.2	1.2	08001.44	0.00	0.00
10:30	12.47	1.2	13.1	1.2	08001.44	0.00	0.00
10:33	12.47	1.2	13.2	1.2	08001.44	0.00	0.00
10:36	12.46	1.1	13.6	1.1	08001.44	0.00	0.00
10:39	12.45	1.1	13.4	1.1	08001.44	0.00	0.00
10:42	12.45	1.3	12.4	1.4	08001.44	0.00	0.00

Table C1: Measured values taken for the developed micro-grid strategy for February 18, 2018 (Continued)

Time (h)	Battery Voltage (V)	Battery Current (A)	Solar Panel Voltage (V)	Solar Panel Current (A)	Wattmeter Reading (kWh)	Grid Consumption (kWh)	Cumulative Grid Consumption (kWh)
10:45	12.44	1.5	12.4	1.5	08001.44	0.00	0.00
10:48	12.43	1.4	12.4	1.4	08001.44	0.00	0.00
10:51	12.42	1.2	13.1	1.2	08001.44	0.00	0.00
10:54	12.41	1.0	13.5	1.1	08001.44	0.00	0.00
10:57	12.41	1.0	13.5	1.0	08001.44	0.00	0.00
11:00	12.40	1.0	13.5	1.0	08001.44	0.00	0.00
11:03	12.39	0.8	13.4	0.8	08001.44	0.00	0.00
11:06	12.38	0.7	13.4	0.8	08001.44	0.00	0.00
11:09	12.38	0.8	13.4	0.8	08001.44	0.00	0.00
11:12	12.38	0.9	13.5	0.9	08001.44	0.00	0.00
11:15	12.37	0.8	13.4	0.8	08001.44	0.00	0.00
11:18	12.36	0.8	13.4	0.8	08001.44	0.00	0.00
11:21	12.36	0.8	13.4	0.8	08001.44	0.00	0.00
11:24	12.36	1.0	13.5	1.0	08001.44	0.00	0.00
11:27	12.35	1.1	13.3	1.1	08001.44	0.00	0.00
11:30	12.35	1.1	13.5	1.1	08001.44	0.00	0.00
11:33	12.35	0.9	13.4	0.9	08001.44	0.00	0.00
11:36	12.34	1.0	13.5	1.0	08001.44	0.00	0.00
11:39	12.33	1.1	13.5	1.1	08001.44	0.00	0.00
11:42	12.33	1.0	13.5	1.1	08001.44	0.00	0.00
11:45	12.33	1.4	12.3	1.4	08001.44	0.00	0.00
11:48	12.32	1.5	12.3	1.5	08001.44	0.00	0.00
11:51	12.32	1.6	12.3	1.6	08001.44	0.00	0.00
11:54	12.32	1.8	12.3	1.8	08001.44	0.00	0.00
11:57	12.31	1.6	12.3	1.6	08001.44	0.00	0.00
12:00	12.32	2.3	12.3	2.4	08001.44	0.00	0.00

Table C1: Measured values taken for the developed micro-grid strategy for February 18, 2018 (Continued)

Time (h)	**Battery Voltage (V)**	**Battery Current (A)**	**Solar Panel Voltage (V)**	**Solar Panel Current (A)**	**Wattmeter Reading (kWh)**	**Grid Consumption (kWh)**	**Cumulative Grid Consumption (kWh)**
12:03	12.31	2	12.30	2.0	08001.44	0.00	0.00
12:06	12.35	5.2	12.40	5.2	08001.44	0.00	0.00
12:09	12.35	5.3	12.4	5.3	08001.44	0.00	0.00
12:12	12.35	5.2	12.4	5.2	08001.44	0.00	0.00
12:15	12.35	5.3	12.4	5.3	08001.44	0.00	0.00
12:18	12.34	5.3	12.4	5.3	08001.44	0.00	0.00
12:21	12.34	5.3	12.4	5.3	08001.44	0.00	0.00
12:24	12.28	1.8	12.3	1.8	08001.44	0.00	0.00
12:27	12.33	5.4	12.4	5.4	08001.44	0.00	0.00
12:30	12.32	5.0	12.4	5.0	08001.44	0.00	0.00
12:33	12.31	4.8	12.4	4.8	08001.44	0.00	0.00
12:36	12.31	5.2	12.4	5.2	08001.44	0.00	0.00
12:39	12.31	4.9	12.4	4.8	08001.44	0.00	0.00
12:42	12.31	5.0	12.4	5.0	08001.44	0.00	0.00
12:45	12.28	3.9	12.3	4.4	08001.44	0.00	0.00
12:48	12.29	5.1	12.4	5.2	08001.44	0.00	0.00
12:51	12.25	2.4	12.2	2.4	08001.44	0.00	0.00
12:54	12.29	5.5	12.4	5.4	08001.44	0.00	0.00
12:57	12.29	5.0	12.3	5.1	08001.44	0.00	0.00
13:00	12.27	4.3	12.3	4.3	08001.44	0.00	0.00
13:03	12.24	3.2	12.2	3.0	08001.44	0.00	0.00
13:06	12.27	5.1	12.3	5.1	08001.44	0.00	0.00
13:09	12.29	5.0	12.3	5.1	08001.44	0.00	0.00
13:12	12.27	5.3	12.3	5.1	08001.44	0.00	0.00
13:15	12.26	4.8	12.3	4.9	08001.44	0.00	0.00
13:18	12.25	5.1	12.3	5.3	08001.44	0.00	0.00
13:21	12.25	5.5	12.3	5.5	08001.44	0.00	0.00
13:24	12.25	5.7	12.3	5.7	08001.44	0.00	0.00

Table C1: Measured values taken for the developed micro-grid strategy for February 18, 2018 (Continued)

Time (h)	Battery Voltage (V)	Battery Current (A)	Solar Panel Voltage (V)	Solar Panel Current (A)	Wattmeter Reading (kWh)	Grid Consumption (kWh)	Cumulative Grid Consumption (kWh)
13:27	12.21	5.1	12.3	5.0	08001.44	0.00	0.00
13:30	12.18	1.9	12.2	1.8	08001.44	0.00	0.00
13:33	12.16	1.3	12.1	1.3	08001.44	0.00	0.00
13:36	12.15	1.1	12.7	1.1	08001.44	0.00	0.00
13:39	12.14	1.1	13.2	1.1	08001.44	0.00	0.00
13:42	12.14	1.0	13.2	1.0	08001.44	0.00	0.00
13:45	12.13	0.9	13.2	0.9	08001.44	0.00	0.00
13:48	12.12	1.0	13.2	1.0	08001.44	0.00	0.00
13:51	12.12	1.0	13.2	1.1	08001.44	0.00	0.00
13:54	12.11	1.3	12.4	1.3	08001.44	0.00	0.00
13:57	12.11	1.4	12.1	1.4	08001.44	0.00	0.00
14:00	12.10	1.5	12.1	1.5	08001.44	0.00	0.00
14:03	12:10	1.4	12.1	1.4	08001.44	0.00	0.00
14:06	12.09	1.7	12.1	1.6	08001.44	0.00	0.00
14:09	12.09	1.9	12.1	1.9	08001.44	0.00	0.00
14:12	12.08	1.6	12.1	1.6	08001.44	0.00	0.00
14:15	12.08	1.9	12.1	2.0	08001.44	0.00	0.00
14:18	12.08	2.5	12.1	2.5	08001.44	0.00	0.00
14:21	12.08	2.8	12.1	2.8	08001.44	0.00	0.00
14:24	12.07	2.4	12.1	2.4	08001.44	0.00	0.00
14:27	12.05	2.2	12.0	2.2	08001.44	0.00	0.00
14:30	12.05	2.4	12.1	2.5	08001.44	0.00	0.00
14:33	12.04	2.4	12.0	2.4	08001.44	0.00	0.00
14:36	12.05	3.6	12.1	3.1	08001.44	0.00	0.00
14:39	12.02	1.8	12.0	1.7	08001.44	0.00	0.00
14:42:	12.01	1.6	12.0	1.6	08001.44	0.00	0.00
14:45	11.99	1.4	12.0	1.4	08001.44	0.00	0.00
14:48	11.97	0.9	13.1	0.9	08001.44	0.00	0.00

Table C1: Measured values taken for the developed micro-grid strategy for February 18, 2018 (Continued)

Time (h)	Battery Voltage (V)	Battery Current (A)	Solar Panel Voltage (V)	Solar Panel Current (A)	Wattmeter Reading (kWh)	Grid Consumption (kWh)	Cumulative Grid Consumption (kWh)
14:51	11.97	1.1	13.1	1.1	08001.44	0.00	0.00
14:54	11.96	1.2	12.7	1.2	08001.44	0.00	0.00
14:57	11.95	1.2	12.4	1.2	08001.44	0.00	0.00
15:00	11.94	1.0	13.1	1.0	08001.44	0.00	0.00
15:03	11.93	1.0	13.1	1.0	08001.44	0.00	0.00
15:06	11.92	1.2	12.4	1.2	08001.44	0.00	0.00
15:09	11.91	1.3	11.9	1.3	08001.44	0.00	0.00
15:12	11.91	1.6	11.9	1.6	08001.44	0.00	0.00
15:15	11.90	2.0	11.9	2.0	08001.44	0.00	0.00
15:18	11.89	1.8	11.9	1.6	08001.44	0.00	0.00
15:21	11.89	1.3	11.8	1.3	08001.44	0.00	0.00
15:24	11.86	1.5	11.8	1.5	08001.44	0.00	0.00
15:27	11.85	2.3	11.8	1.8	08001.44	0.00	0.00
15:30	11.85	2.2	11.8	2.3	08001.44	0.00	0.00
15:33	11.85	3.1	11.9	2.7	08001.44	0.00	0.00
15:36	11.84	3.2	11.9	3.1	08001.44	0.00	0.00
15:39	11.81	2.3	11.8	2.3	08001.44	0.00	0.00
15:42	11.76	0.6	12.7	0.6	08001.44	0.00	0.00
15:45	11.72	0.3	12.4	0.3	08001.44	0.00	0.00
15:48	11.70	0.3	12.3	0.3	08001.44	0.00	0.00
15:51	11.67	0.2	12.1	0.2	08001.44	0.00	0.00
15:54	11.64	0.1	11.9	0.1	08001.44	0.00	0.00
15:57	11.60	0.2	11.9	0.1	08001.44	0.00	0.00
16:00	11.56	0.2	11.9	0.2	08001.44	0.00	0.00
16:01	11.50	0.1	11.8	0.1	08001.44	0.00	0.00
16:03	12.80	0.1	11.7	0.1	08001.45	0.01	0.01
16:04	11.55	0.1	12.2	0.1	08001.45	0.00	0.01
16:05	12.63	0.1	11.7	0.1	08001.45	0.00	0.01

Table C1: Measured values taken for the developed micro-grid strategy for February 18, 2018 (Continued)

Time (h)	**Battery Voltage (V)**	**Battery Current (A)**	**Solar Panel Voltage (V)**	**Solar Panel Current (A)**	**Wattmeter Reading (kWh)**	**Grid Consumption (kWh)**	**Cumulative Grid Consumption (kWh)**
16:05	11.53	0.1	12.2	0.1	08001.45	0.00	0.01
16:06	12.64	0.1	12.1	0.1	08001.45	0.00	0.01
16:07	12.65	0.1	11.7	0.1	08001.46	0.01	0.02
16:08	11.58	0.1	12.1	0.1	08001.46	0.00	0.02
16:09	11.56	0.1	11.7	0.1	08001.46	0.00	0.02
16:10	12.65	0.1	12.2	0.1	08001.46	0.00	0.02
16:11	11.56	0.1	12.7	0.1	08001.47	0.01	0.03
16:12	12.65	0.1	12.7	0.1	08001.47	0.00	0.03
16:13	12.65	0.1	12.2	0.1	08001.47	0.00	0.03
16:14	11.53	0.1	12.4	0.1	08001.47	0.00	0.03
16:15	12.65	0.1	11.9	0.1	08001.47	0.00	0.03
16:16	12.65	0.1	12.0	0.1	08001.48	0.00	0.04
16:17	11.53	0.1	12.3	0.1	08001.48	0.00	0.04
16:18	12.65	0.1	11.7	0.1	08001.48	0.00	0.04
16:19	12.65	0.1	11.7	0.1	08001.48	0.00	0.04
16:20	12.64	0.1	11.7	0.1	08001.49	0.01	0.05
16:21	11.53	0.1	12.2	0.1	08001.49	0.00	0.05
16:22	11.53	0.1	12.4	0.1	08001.49	0.00	0.05
16:23	12.65	0.1	11.7	0.1	08001.49	0.00	0.05
16:24	12.65	0.1	11.6	0.1	08001.50	0.01	0.06

Table C1: Measured values taken for the developed micro-grid strategy for February 18, 2018 (Continued)

Time (h)	Battery Voltage (V)	Battery Current (A)	Solar Panel Voltage (V)	Solar Panel Current (A)	Wattmeter Reading (kWh)	Grid Consumption (kWh)	Cumulative Grid Consumption (kWh)
16:24:52	11.53	0.1	12.0	0.1	08001.50	0.00	0.06
16:25:38	12.65	0.1	11.7	0.1	08001.50	0.00	0.06
16:26:09	11.53	0.1	12.3	0.1	08001.50	0.00	0.06
16:26:57	12.65	0.1	11.7	0.1	08001.50	0.00	0.06
16:27:25	11.51	0.1	12.0	0.1	08001.50	0.00	0.06
16:28:11	12.63	0.1	11.8	0.1	08001.50	0.00	0.06
16:28:40	11.52	0.1	12.2	0.1	08001.50	0.00	0.06
16:29:07	11.44	0.1	11.5	0.1	08001.51	0.01	0.07
16:30:01	11.38	0.1	11.1	0.1	08001.51	0.00	0.07
16:31:04	11.30	0.1	11.3	0.1	08001.51	0.00	0.07
16:32:43	11.17	0.1	11.2	0.1	08001.51	0.00	0.07
16:35:02	11.00	0.1	11.01	0.1	08001.51	0.00	0.07
16:35:55	12.65	0.1	12.5	0.1	08001.52	0.01	0.08
16:36:15	11.53	0.1	11.7	0.1	08001.52	0.00	0.08
16:37:01	12.62	0.1	11.5	0.1	08001.52	0.00	0.08
16:37:23	11.53	0.1	12.7	0.1	08001.52	0.00	0.08
16:38:14	12.65	0.1	12.1	0.1	08001.53	0.01	0.09
16:38:42	11.53	0.1	12.3	0.1	08001.53	0.00	0.09
16:39:19	12.62	0.1	11.6	0.1	08001.53	0.00	0.09
16:39:41	11.34	0.1	12.2	0.1	08001.53	0.00	0.09
16:40:23	12.63	0.1	11.7	0.1	08001.53	0.00	0.09
16:40:46	11.32	0.1	12.2	0.1	08001.53	0.00	0.09
16:41:25	12.62	0.1	12.2	0.1	08001.53	0.00	0.09
16:41:55	11.33	0.1	11.8	0.1	08001.53	0.00	0.09
16:42:26	12.62	0.1	12.2	0.1	08001.54	0.01	0.10
16:42:48	11.33	0.1	11.6	0.1	08001.54	0.00	0.10
16:43:32	12.63	0.1	11.7	0.1	08001.54	0.00	0.10
16:43:54	11.33	0.1	12.3	0.1	08001.54	0.00	0.10

Table C1: Measured values taken for the developed micro-grid strategy for February 18, 2018 (Continued)

Time (h)	Battery Voltage (V)	Battery Current (A)	Solar Panel Voltage (V)	Solar Panel Current (A)	Wattmeter Reading (kWh)	Grid Consumption (kWh)	Cumulative Grid Consumption (kWh)
16:44:36	12.63	0.1	11.9	0.1	08001.54	0.00	0.10
16:44:58	11.33	0.1	12.2	0.1	08001.54	0.00	0.10
16:45:40	12.63	0.1	12.2	0.1	08001.54	0.00	0.10
16:46:09	11.33	0.1	12.3	0.1	08001.54	0.00	0.10
16:46:38	12.62	0.1	12.7	0.1	08001.55	0.01	0.11
16:46:58	11.53	0.1	12.2	0.1	08001.55	0.00	0.11
16:47:36	12.62	0.1	11.8	0.1	08001.55	0.00	0.11
16:47:56	11.36	0.1	12.2	0.1	08001.55	0.00	0.11
16:48:39	12.61	0.1	11.8	0.1	08001.55	0.00	0.11
16:49:03	11.34	0.1	12.2	0.1	08001.55	0.00	0.11
16:49:42	12.61	0.1	11.6	0.1	08001.55	0.00	0.11
16:49:59	11.34	0.1	12.2	0.1	08001.55	0.00	0.11
16:50:40	12.63	0.1	12.7	0.1	08001.55	0.00	0.11
16:51:02	11.36	0.1	12.2	0.1	08001.55	0.00	0.11
16:51:41	12.62	0.1	11.7	0.1	08001.56	0.01	0.12
16:52:02	11.31	0.1	12.1	0.1	08001.56	0.00	0.12
16:52:41	12.62	0.1	11.5	0.1	08001.56	0.00	0.12
16:53:03	11.33	0.1	12.6	0.1	08001.56	0.00	0.12
16:53:40	12.65	0.1	12.2	0.1	08001.56	0.00	0.12
16:54:02	11.33	0.1	11.7	0.1	08001.57	0.01	0.13
16:57:02	10.95	0.1	12.2	0.1	08001.57	0.00	0.13

Table C2: Measured values taken for the baseline micro-grid strategy for February 19, 2018

Time (h)	Battery Voltage (V)	Battery Current (A)	Solar Panel Voltage (V)	Solar Panel Current (A)	Wattmeter Reading (kWh)	Grid Consumption (kWh)	Cumulative Grid Consumption (kWh)
9:30	13.1	0.6	14.5	0.6	08001.59	0.00	0.00
9:33	13.6	0.6	14.5	0.6	08001.60	0.01	0.01
9:36	13.6	0.7	14.6	0.7	08001.62	0.02	0.03
9:39	13.62	0.7	14.6	0.7	08001.64	0.02	0.05
9:42	13.61	0.7	14.6	0.7	08001.66	0.02	0.07
9:45	13.63	0.9	14.7	0.9	08001.68	0.02	0.09
9:48	13.64	1.0	14.7	1.1	08001.69	0.01	0.10
9:51	13.65	0.9	14.7	0.9	08001.71	0.02	0.12
9:54	13.65	1.1	14.7	1.1	08001.73	0.02	0.14
9:57	13.67	1.0	14.7	1.1	08001.74	0.01	0.15
10:00	13.66	0.9	14.7	0.9	08001.76	0.02	0.17
10:03	12.67	0.9	13.8	0.9	08001.76	0.00	0.17
10:06	12.65	0.8	13.7	0.8	08001.76	0.00	0.17
10:09	12.62	1.0	13.7	1.0	08001.76	0.00	0.17
10:12	12.60	1.2	13.5	1.2	08001.76	0.00	0.17
10:15	12.58	1.0	13.7	1.0	08001.76	0.00	0.17
10:18	12.57	1.0	13.7	1.0	08001.76	0.00	0.17
10:21	12.57	1.2	13.3	1.2	08001.76	0.00	0.17
10:24	12.56	1.2	13.3	1.2	08001.76	0.00	0.17
10:27	12.55	1.1	13.7	1.0	08001.76	0.00	0.17
10:30	12.54	1.0	13.7	1.0	08001.76	0.00	0.17
10:33	12.53	0.9	13.6	0.9	08001.76	0.00	0.17
10:36	12.53	1.1	13.7	1.1	08001.76	0.00	0.17
10:39	12.52	1.3	13.1	1.2	08001.76	0.00	0.17
10:42	12.51	1.2	12.7	1.2	08001.76	0.00	0.17
10:45	12.51	1.4	12.5	1.4	08001.76	0.00	0.17

Table C2: Measured values taken for the baseline micro-grid strategy for February 19, 2018 (Continued)

Time (h)	Battery Voltage (V)	Battery Current (A)	Solar Panel Voltage (V)	Solar Panel Current (A)	Wattmeter Reading (kWh)	Grid Consumption (kWh)	Cumulative Grid Consumption (kWh)
10:48	12.50	1.4	12.5	1.3	08001.76	0.00	0.17
10:51	12.49	1.2	12.5	1.3	08001.76	0.00	0.17
10:54	12.48	1.3	12.4	1.3	08001.76	0.00	0.17
10:57	12.47	1.0	13.6	1.0	08001.76	0.00	0.17
11:00	12.47	1.4	12.4	1.4	08001.76	0.00	0.17
11:03	12.45	1.1	13.1	1.1	08001.76	0.00	0.17
11:06	12.44	0.7	13.5	0.8	08001.76	0.00	0.17
11:09	12.44	0.9	13.5	0.8	08001.76	0.00	0.17
11:12	12.44	1.1	13.4	1.1	08001.76	0.00	0.17
11:15	12.43	1.2	13.0	1.3	08001.76	0.00	0.17
11:18	12.42	1.0	13.5	1.0	08001.76	0.00	0.17
11:21	12.41	1.0	13.5	1.0	08001.76	0.00	0.17
11:24	12.40	1.0	13.5	1.0	08001.76	0.00	0.17
11:27	12.40	1.1	13.5	1.1	08001.76	0.00	0.17
11:30	12.39	1.4	12.4	1.4	08001.76	0.00	0.17
11:33	12.43	4.6	12.5	4.6	08001.76	0.00	0.17
11:36	12.43	4.8	12.5	4.8	08001.76	0.00	0.17
11:39	12.42	4.7	12.5	4.7	08001.76	0.00	0.17
11:42	12.37	1.5	12.3	1.5	08001.76	0.00	0.17
11:45	12.36	1.0	12.3	1.0	08001.76	0.00	0.17
11:48	12.35	1.0	13.4	1.0	08001.76	0.00	0.17
11:51	12.35	1.3	12.3	1.3	08001.76	0.00	0.17
11:54	12.38	2.0	12.4	4.0	08001.76	0.00	0.17
11:57	12.35	2.5	12.4	3.3	08001.76	0.00	0.17
12:00	12.39	5.3	12.4	5.3	08001.76	0.00	0.17
12:03	12.38	5.2	12.4	5.2	08001.76	0.00	0.17
12:06	12.37	5.3	12.4	5.2	08001.76	0.00	0.17
12:09	12.36	4.9	12.4	5.0	08001.76	0.00	0.17

Table C2: Measured values taken for the baseline micro-grid strategy for February 19, 2018 (Continued)

Time (h)	**Battery Voltage (V)**	**Battery Current (A)**	**Solar Panel Voltage (V)**	**Solar Panel Current (A)**	**Wattmeter Reading (kWh)**	**Grid Consumption (kWh)**	**Cumulative Grid Consumption (kWh)**
12:12	12.36	5.1	12.4	5.1	08001.76	0.00	0.17
12:15	12.34	5.2	12.4	5.1	08001.76	0.00	0.17
12:18	12.35	5.1	12.4	5.1	08001.76	0.00	0.17
12:21	12.35	5.5	12.4	5.5	08001.76	0.00	0.17
12:24	12.34	5.0	12.4	5.1	08001.76	0.00	0.17
12:27	12.34	5.3	12.4	5.4	08001.76	0.00	0.17
12:30	12.29	2.7	12.3	2.9	08001.76	0.00	0.17
12:33	12.33	5.4	12.4	5.3	08001.76	0.00	0.17
12:36	12.28	2.6	12.4	2.7	08001.76	0.00	0.17
12:39	12.32	5.5	12.4	5.5	08001.76	0.00	0.17
12:42	12.31	5.7	12.4	5.7	08001.76	0.00	0.17
12:45	12.30	5.5	12.4	5.5	08001.76	0.00	0.17
12:48	12.30	5.5	12.4	5.5	08001.76	0.00	0.17
12:51	12.30	5.8	12.4	5.8	08001.76	0.00	0.17
12:54	12.26	2.5	12.2	2.2	08001.76	0.00	0.17
12:57	12.23	1.9	12.2	1.9	08001.76	0.00	0.17
13:00	12.28	5.8	12.3	5.5	08001.76	0.00	0.17
13:03	12.28	5.8	12.3	5.8	08001.76	0.00	0.17
13:06	12.27	5.9	12.4	6.0	08001.76	0.00	0.17
13:09	12.27	6.3	12.4	6.3	08001.76	0.00	0.17
13:12	12.26	6.2	12.3	5.7	08001.76	0.00	0.17
13:15	12.19	1.6	12.2	1.6	08001.76	0.00	0.17
13:18	12.19	1.9	12.2	1.9	08001.76	0.00	0.17
13:21	12.24	6.1	12.3	6.0	08001.76	0.00	0.17
13:24	12.17	1.9	12.1	1.8	08001.76	0.00	0.17
13:27	12.17	2.7	12.2	2.9	08001.76	0.00	0.17
13:30	12.23	6.7	12.3	6.7	08001.76	0.00	0.17
13:33	12.22	6.5	12.3	6.5	08001.76	0.00	0.17

Table C2: Measured values taken for the baseline micro-grid strategy for February 19, 2018 (Continued)

Time (h)	Battery Voltage (V)	Battery Current (A)	Solar Panel Voltage (V)	Solar Panel Current (A)	Wattmeter Reading (kWh)	Grid Consumption (kWh)	Cumulative Grid Consumption (kWh)
13:36	12.21	6.4	12.3	6.4	08001.76	0.00	0.17
13:39	12.14	2.3	12.1	2.3	08001.76	0.00	0.17
13:42	12.14	3.1	12.1	3.0	08001.76	0.00	0.17
13:45	12.19	6.4	12.3	6.4	08001.76	0.00	0.17
13:48	12.14	2.9	12.1	2.6	08001.76	0.00	0.17
13:51	12.09	1.7	12.1	1.7	08001.76	0.00	0.17
13:54	12.08	1.7	12.1	1.7	08001.76	0.00	0.17
13:57	12.07	1.9	12.1	1.9	08001.76	0.00	0.17
14:00	12.06	2.0	12.0	2.0	08001.76	0.00	0.17
14:03	12.08	5.7	12.2	5.9	08001.76	0.00	0.17
14:06	12.11	6.2	12.2	6.2	08001.76	0.00	0.17
14:09	12.10	6.1	12.2	6.1	08001.76	0.00	0.17
14:12	12.08	6.0	12.2	6.1	08001.76	0.00	0.17
14:15	12.02	3.0	12.0	2.7	08001.76	0.00	0.17
14:18	12.02	2.9	12.0	3.9	08001.76	0.00	0.17
14:21	11.97	2.6	12.0	2.3	08001.76	0.00	0.17
14:24	12.01	6.0	12.1	6.0	08001.76	0.00	0.17
14:27	11.98	4.5	12.2	5.5	08001.76	0.00	0.17
14:30	11.92	5.5	12.8	5.7	08001.76	0.00	0.17
14:33	12.95	2.5	12.9	2.3	08001.78	0.02	0.19
14:36	12.97	1.9	13.0	4.1	08001.80	0.02	0.21
14:39	12.99	1.9	12.9	1.8	08001.82	0.02	0.23
14:42:	13.01	1.4	12.9	1.3	08001.83	0.01	0.24
14:45	12.97	1.1	14.0	1.1	08001.85	0.02	0.26
14:48	12.97	1.3	13.5	1.2	08001.87	0.02	0.28
14:51	12.98	1.5	12.9	1.4	08001.89	0.02	0.30
14:54	12.98	1.6	12.9	1.6	08001.91	0.02	0.32
14:57	12.99	1.5	12.9	1.5	08001.93	0.02	0.34

Table C2: Measured values taken for the baseline micro-grid strategy for February 19, 2018 (Continued)

Time (h)	Battery Voltage (V)	Battery Current (A)	Solar Panel Voltage (V)	Solar Panel Current (A)	Wattmeter Reading (kWh)	Grid Consumption (kWh)	Cumulative Grid Consumption (kWh)
15:00	12.99	1.4	13.0	1.4	08001.94	0.01	0.35
15:03	12.99	1.3	12.9	1.3	08001.96	0.02	0.37
15:06	12.99	1.4	13.0	1.3	08001.98	0.02	0.39
15:09	13.05	4.2	13.1	4.1	08002.00	0.02	0.41
15:12	13.02	2.5	13.0	2.5	08002.02	0.02	0.43
15:15	13.01	1.4	13.0	1.4	08002.04	0.02	0.45
15:18	13.02	1.5	13.0	1.5	08002.06	0.02	0.47
15:21	13.09	4.0	13.1	3.4	08002.07	0.01	0.48
15:24	13.06	3.1	13.1	3.6	08002.09	0.02	0.50
15:27	13.06	2.1	13.0	2.0	08002.11	0.02	0.52
15:30	13.06	2.1	13.0	2.0	08002.13	0.02	0.54
15:33	13.03	1.2	13.2	2.0	08002.13	0.00	0.54
15:36	12.67	1.2	12.6	1.2	08002.13	0.00	0.54
15:39	12.30	1.3	12.5	1.3	08002.13	0.00	0.54
15:42	12.29	1.5	12.3	1.5	08002.13	0.00	0.54
15:45	12.26	1.5	12.2	1.5	08002.13	0.00	0.54
15:48	12.23	1.6	12.2	1.6	08002.13	0.00	0.54
15:51	12.21	1.5	12.2	1.5	08002.13	0.00	0.54
15:54	12.17	1.4	12.1	1.5	08002.13	0.00	0.54
15:57	12.14	1.4	12.1	1.4	08002.13	0.00	0.54
16:00	12.11	1.4	12.1	1.4	08002.13	0.00	0.54
16:03	12.06	1.3	12.0	1.3	08002.13	0.00	0.54
16:06	12.02	1.3	12.3	1.3	08002.13	0.00	0.54
16:09	11.97	1.2	12.5	1.2	08002.13	0.00	0.54
16:12	11.92	1.1	12.9	1.1	08002.13	0.00	0.54
16:15	11.86	1.2	12.3	1.2	08002.13	0.00	0.54
16:18	11.74	1.2	12.4	1.2	08002.13	0.00	0.54
16:21	11.30	1.1	12.4	1.1	08002.13	0.00	0.54

APPENDIX D

Bill of Engineering Measurement and Evaluation

Table D1 shows the Bill of Engineering Measurement and Evaluation for the developed micro-grid system.

Table D1: Bill of Engineering Measurement and Evaluation as at December, 2017.

S/N	Item	Quantity	Unit Cost (₦)*	Total (₦)*
1	Standard Resistors	15	10	150
2	Variable Resistors	24	25	600
3	Electrolytic capacitors	6	40	240
4	5mm LED	2	10	20
5	Buzzer	1	250	250
6	7805 Positive voltage regulator	1	100	100
7	LM 324 Operational Amplifier	5	120	600
8	CD 469 Not gate	3	200	600
9	IN 4007 Rectifier diodes	24	20	480
10	4N35 Auto transistor –based coupler	4	150	600
11	NE 555 555 Timer	1	100	100
12	16 X 2 LCD display.	1	2000	2000
13	BC 547 NPN Transistor	5	150	750
14	12 MHz Crystal Oscillator Piezoelectric device	1	50	50
15	12 V, 3 A DC coil Relay	4	350	1400
16	BT 136 Triac	2	250	500
17	CD 481 AND gate	1	150	150
18	Triac Pre driver	2	2000	4000
19	5kV, 25A Contactors	2	2500	5000

* **Note:** $1 ≈ ₦ 307 (Central Bank of Nigeria, accessed December 5, 2017)

Table D1: Bill of Engineering Measurement and Evaluation as at December, 2017 (Continued)

S/N	Item	Quantity	Unit Cost (₦)*	Total (₦)*
20	8089C52 8-bit microcontroller	1	2500	2500
21	Wood			2000
22	Perspex			1500
23	Screws			600
24	Glue			100
25	Vero board	2	250	500
26	Lead	1 Roll	2500	2500
	Total			**27,290**

* **Note:** $1 ≈ ₦ 307 (Central Bank of Nigeria, accessed December 5, 2017)