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DESIGN OF A GSM-BASED REMOTELY OPERATED ELECTRICAL ENERGY MANAGEMENT SYSTEM

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Abstract
Electrical energy is a scarce resource in most developing countries. This has prompted numerous research into ways in which commercially deployed wireless communication technologies can be used to monitor, control and manage such energy. Analysis of many of such electrical energy management systems reveal inherent complexities in their deployment and operation. This has therefore motivated the proposal of a remotely operated electrical energy management system (ROEEMS). The proposed system is designed to manage electrical energy from three different sources such as commercial grid, photovoltaic arrays, and portable generator, and give an output depending on requirements of its operator. ROEEMS has been designed to overcome some challenges in existing systems such as system complexity and security demands (as is typical of Internet and server-based systems). The proposed design allows ROEEMS to achieve a truly remote operation mode while requiring limited operator skills and a comparatively reduced cost of installation and operation.

Keywords: Auto logic, Electrical Energy, Feedback, Photovoltaic, SMS, Utility Power Supply.

1.0 INTRODUCTION

Even though electricity is relatively easy to generate, transmit and utilize, there is a huge gap between its demand and supply in most developing countries, especially Nigeria. For example, as at August 2021, Nigeria was only able to generate 6,056 MW of electricity [1] to serve a population of about 212 million people [2]. It is therefore evident that there is an electrical energy crisis in the country due to the insufficiency of supply. Where and when electrical power supply is available, its cost per kWh is relatively high for different customer classes [1] as compared with other crude oil dependent economies of similar purchasing power parity (such as Angola) [3], [4]. This, alongside findings in research such as [5] therefore bring to the fore the need to carefully and efficiently manage the electrical energy resources available in Nigeria.

The utilization and management of electrical energy has several connotations [6], but this article is only concerned with the monitoring, controlling, and conserving electrical energy in a building or organization in an efficient manner. In recent times, theoretical research such as [7] –[9], have been carried out to explore the efficiency limits and to optimize and control electrical energy managements under different power grid networks and usage scenarios. These include the real-life energy management system reported in [10] and the autonomous hybrid micro-grid system presented in [11]. The systems are reported to be capable of managing electrical energy sources and energy consumption rates and the data they obtain/generate are usually logged in real time to remote servers. For example, the system in [11] is reported to be fully autonomous and does not give room for user alteration of its operations. It may be inferred that the complexity of operation of such systems do not make them easy to be adopted in regions with poor or no internet connectivity. Such conditions make remote access almost impossible. Also, such systems require special skills to understand and/or operate. This is why the decision to develop ROEEMS that depends on the widely used short message service (SMS) GSM protocol in the control and real-time monitoring of different electrical energy sources is a worthwhile endeavour.

2.0 METHODOLOGY

A top-level architecture of the ROEEMS is shown in Figure 1. The major components comprise a logic unit and a GSM module. The basis for system design is to allow electrical energy to be sourced from utility power supply (mains), solar (photovoltaic) supply and supply from a portable diesel or petrol generator. The system should then be able to output both AC and DC voltages to power different types of loads. To achieve this, the logic unit should be able to make decisions based on available input sources and efficiently give outputs to achieve uninterruptible power supply to various different loads.

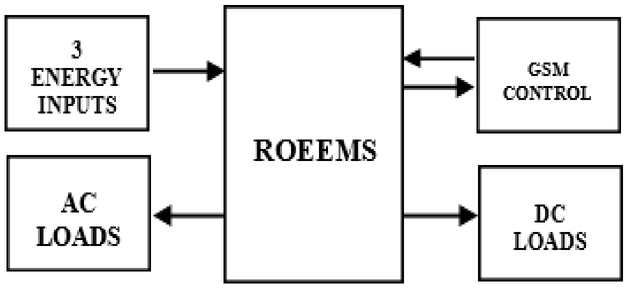

Figure 1: Top level architecture of ROEEMS

To achieve the design objectives of ROEEMS, various design questions are asked and an attempt is made at answering those questions in this section. Some of the design questions include:

(a) What is the range of voltages and currents expected as input into the ROEEMS?
(b) How much input and output power is ROEEMS expected to handle?
(c) What are the possible application areas of ROEEMS?

ROEEMS was conceived to manage power from three different sources and operate in two different modes: the remote-controlled mode and auto-mode. In the remote-controlled mode; its output would be determined by a user's commands delivered via a GSM network from any device capable of SMS messaging. This choice is based on the design objective of simplicity and ease of remote access as SMS is the most common mode of delivering mobile-enabled services [12]. A more detailed description of ROEEMS is presented in Figure 2, where the interconnectivity of the component parts is shown. The three power sources, some major components, and the design range of voltages and currents are presented in the following.

Solar

Solar power input to ROEEMS is derived by means of photovoltaic arrays. The intermittent nature of insolation and the large input voltage swing necessitates the presence of a charge controller (CC), whose output is delivered to an inverter unit for DC to AC conversion. The AC power output from the inverter supplies AC loads when the solar source is activated by ROEEMS. In the presented design, solar is the primary source of power and a battery bank (not shown in Figure 2) can be added to store excess solar power.

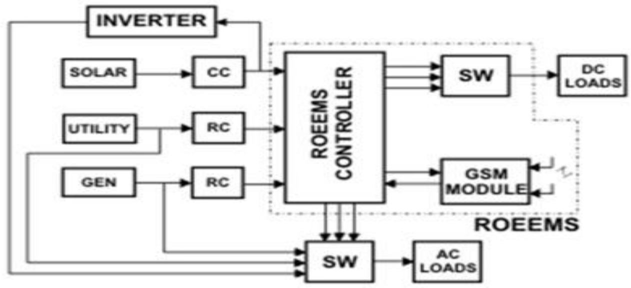

Figure 2: Detailed sub unit interconnectivity of ROEEMS

Utility

This is the public/commercial grid power source. Since this source is already in AC form, it can be fed directly to AC loads via an appropriately rated switching device (SW). The utility source is rectified (RC) and buck converted for the purpose of signalling the ROEEMS controller. This source is taken as second priority in the auto-mode operation and is activated only when solar supply is insufficient and the stored energy (in batteries) have been depleted to a pre-determined level.

Generator

This is a portable generator that utilizes a hydro-carbon fuel for its operation. This source is only activated when the primary and secondary sources fail. It is taken as the lowest priority since it is the most expensive of the three sources [13] and limiting its use would help keep greenhouse emissions to a minimum.

Range of Voltages and Currents

Since ROEEMS has been primarily designed for domestic consumer applications, its AC switching devices (relays and contactors) are rated for an input and output voltage of 220V and a current of 16A. The power wheeling components of the DC circuitry (the CC) is rated for a maximum input voltage and current of 145V and 21A respectively. The maximum output DC voltage and current are respectively 30V and 100A.

The CC here has been actualized using a commercial off the shelf (COT) maximum power point tracking (MPPT) solar charge controller unit. Several modes of MPPT operation are available and ROEEMS used one of the algorithms in [14]. The AC specifications provided gives ROEEMS a load capacity of 3kW and ensures an additional 520W tolerance for safety. This is more than enough to power the essential loads in an average Nigerian household [5].

The ROEEMS Controller Unit

The ROEEMS controller unit is made up of an Arduino Uno module and a NAND gate integrated circuit (IC7400). These two units are interfaced with a GSM module for remote monitoring and control. The Arduino Uno module was chosen for simplicity of implementation, especially given that the Arduino Integrated Development Environment (IDE) provides a friendly environment for coding, debugging and testing of codes before actual implementation. The module is operated with 12V DC, 1A and the truth table for its operation is given in Table 1.

Table 1: Truth Table for the operation of the microcontroller

INPUT			OUTPUT		
S (A1)	G (A3)	N (A2)	S (B1)	G (B3)	N (B2)
0	0	0	0	1	0
0	0	1	0	0	1
0	1	0	0	1	0
0	1	1	0	0	1
1	0	0	1	0	0
1	0	1	1	0	0
1	1	0	1	0	0
1	1	1	1	0	0

The IC7400 NAND gates IC was selected for implementing the automatic switching mode. This mode is activated by the microcontroller within the Arduino board. Its actions are as specified by the Truth Table in Table 1, which ensures that two different power sources are not switched on at the same time. The connections of its circuitry is as shown in Figure. 3. The IC is operated with 5V DC, 200mA.

The GSM module chosen for the design is the SIM 900A unit. This was selected because of its low cost and robust voltage tolerance. This GSM module is usually used for voice calls and SMS messaging functions. Even though SMS is not end-to-end encrypted, it is a relatively secure means of communications based on its reliance on the A5 family of cryptographic algorithms [15]. ROEEMS leverages on this security provided the GSM module's subscriber identity module (SIM) access number is kept private and not divulged to unauthorized third parties. The GSM module is operated with 5V DC and draws a maximum current of 1A.

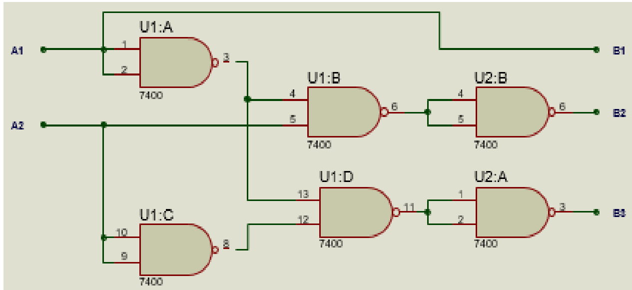

Figure 3: NAND Gate IC configuration

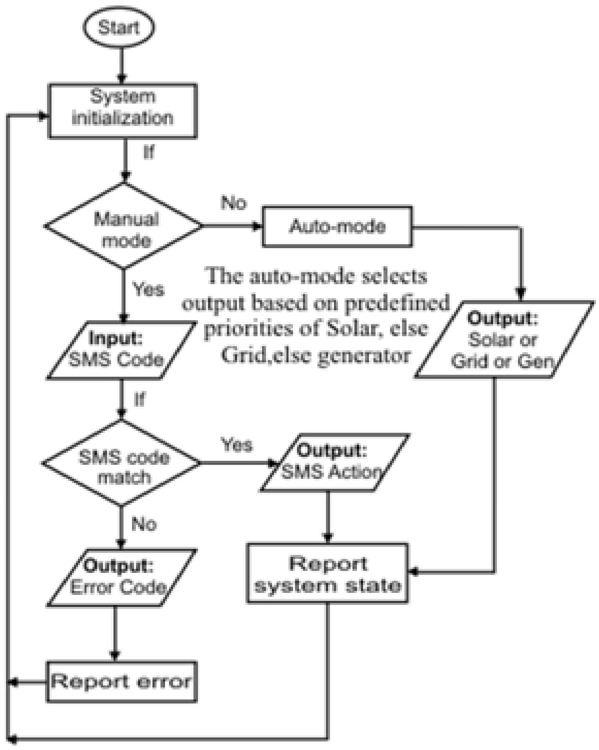

Figure 4: Program Flow chart

Algorithm for the Operation of ROEEMS

The algorithm for the operation of ROEEMS as shown in Figure 4 is based on two operational modes: the auto-control and the remote-control modes. In the auto-control mode, the system takes responsibility of choosing the input energy sources according to predefined priorities. The priorities were set in consideration to cutting down CO_2 emission and cost, and to drastically reduce dependence on grid supply due to its epileptic nature in Nigeria. After the system initializes, the default system state is set to the remote (manual) control state. This gets the system ready at all times to receive instruction codes. In the initialization phase, the system updates the remote user via SMS of the states of all the energy sources and gets ready for the task of supplying power to user loads.

Automatic control is activated by applying the appropriate codes. Once activated, the system manages power supply without the direct intervention of a remote user. This mode of operation can be changed by also applying specific source-codes as shown in Table 2, where S is Solar, G represents Generator and U represents Utility.

Table 2: Input Codes (SMS) and Response of ROEEMS

S/NO.	Control Code	ROEEMS Action
1.	#A. UTILITY ON*	S, G == LOW U == HIGH
2.	#A. GEN ON*	S, U == LOW G == HIGH
3.	#A. SOLAR ON*	U, G == LOW S == HIGH
4.	#A. AUTO ON*	Activates Auto mode

A feedback system was incorporated into the design to ensure system compliance to remote instructions sent by the user. Also, the feedback serves as the channel through which the system's state is obtained. With this, a user is able to query the system for system state information as regards the available sources and current output state. This gives a full sense of control while operating ROEEMS and fulfils the closed loop operational capabilities of the system. The feedback system is summarized in Table 3.

Table 3: Feedback System for ROEEMS

S/NO.	System State	Feedback
1.	U == HIGH	UTILITY ON!
2.	G == HIGH	GEN ON!
3.	S == HIGH	SOLAR ON!

Constructing the ROEEMS Prototype

The constructed ROEEMS prototype is shown in Figures 5 and 6. In both figures, the GSM module and the microcontroller system are slightly visible at the top left and right respectively. They are both shielded from the metallic frame to avoid short-circuiting of conducting surfaces. Also, the component boards were equally insulated and prevented from having direct contact with the metallic shield/casing. The length, type and cross-sectional area of the insulated conductors used in constructing ROEEMS were chosen based on specifications and constraints of cost minimization and energy loss reduction.

The choice of switches and fuses were limited to a rating of 5A and a manual change over switch and a reset button were included for safety and ease of operation. The reset button was provided to allow for a user to toggle between automatic and manual operation modes. The system also included a cooling fan to keep the temperature of the passive and active internal components within recommended operating range.

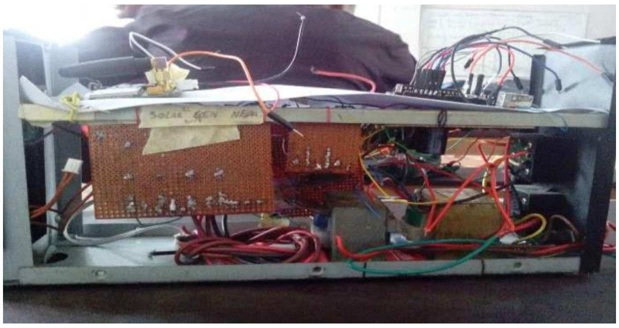

Figure 5: The ROEEMS component assembly

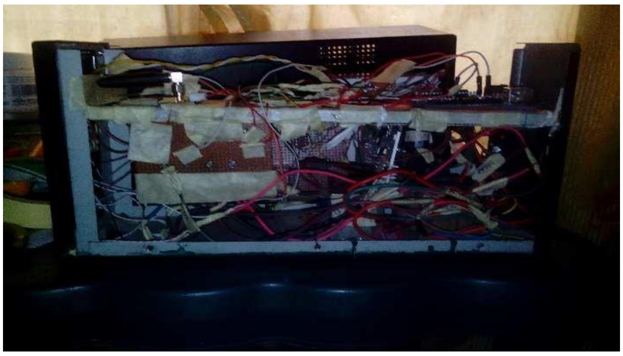

Figure 6: Completed ROEEMS circuitry

The output of the device was implemented using two 13A sockets for easy connection of loads while the input terminals were achieved using free-flying wires to allow for connection to output panels as found on portable generators, utility power supply distribution boards and solar inverters. The outer case was made of metallic material which was chosen for its rigidity and durability and for mechanical protection. The metallic casing was coated against rust and to provide electrical insulation.

3.0 RESULTS AND DISCUSSION

The operation of ROEEMS was tested both in the auto-control and remote control modes. Testing in the auto-control mode involved manually changing the available input power supply and observing if the system would automatically notify a user of the status of available power supply via SMS. Testing in the remote control operation mode involved sending instructions via SMS to the system and observing if the system would respond to the instructions sent. The testing procedure and the results obtained (responses) are discussed below.

Auto-Control Mode

To observe the response of ROEEMS to changes in the status of electrical power sources while in the auto-control mode, the auto mode function was first activated via the SMS command, #A. AUTO ON*. To simulate a situation where utility power supply was unavailable, this source had to be manually switched off. It was then observed that ROEEMS successfully switched to supplying power to the load using the available solar source via the embedded inverter. It was also observed that the message, SOLAR ON! was sent via SMS to the user. Thus, the user was updated on the current power source.

To simulate solar supply unavailability, the manual switch off procedure was repeated by switching off the solar source while allowing the utility source to remain in the on position. The system responded as expected by automatically switching to the utility source and the message, UTILITY ON! was delivered via SMS to the user. The last test in the auto-control mode was to simulate a situation where both utility and solar power supplies were unavailable. When this was carried out through the manual switch off operation, it was observed that ROEEMS successfully switched to a portable generator source and the message, GEN ON! was sent via SMS to the user. Hence, it was confirmed that ROEEMS was able to automatically switch and obtain power from any of the three available sources in order to power the connected loads. Each time this switch occurred, the user was appropriately notified via SMS.

Remote Control Mode

To observe the response of ROEEMS to instructions to change the available electrical power source, the auto mode was deactivated by sending the SMS command, #A. AUTO OFF*. This command put the system into its default operating mode, which is the remote control mode. While in this mode of operation, SMS instructions (as in Table 2) were then sent to the system, and its response was observed. It was observed that the system responded to all the control codes as expected. In all observations, the control codes were delivered in approximately one second. When a control code was received to switch on a certain power source, it was observed that the system first switched off the current source before switching on the requested source. This was an inbuilt safety feature of the system. It is important to note that remote control of the system depends on the availability of the GSM network at the location of the device and in the vicinity of the remote controller. This mode ensures that system remains in a more stable state compared with the auto-control mode given the cyclic nature of solar power availability and the erratic nature of utility power supply in Nigeria.

4.0 CONCLUSION AND RECOMMENDATION

The constructed ROEEMS prototype was able to effectively manage electrical energy from three different sources. The system reliably provided power when a utility supply was not available and ensured that the use of a generator was kept to a minimum. The system thereby helped in cutting the cost of electricity for domestic use and invariably helped limit CO_2 emissions while operating in a truly remote mode via auto-control and manual control.

The good GSM coverage in Nigeria gives ROEEMS an edge in remote control over systems that depend on other technologies such as Bluetooth and the internet. Although network failures (outages) may delay instruction delivery, such instructions will certainly be delivered as soon as the network is restored. Unlike Bluetooth and internet access where every connectivity failure requires another trial from the operator, the GSM network provides buffers that assure the delivery of the same instruction codes for up to 24 hours. Since ROEEMS is GSM control-based, remote control proved to be only limited by coverage but not distance. Therefore, it is possible to control ROEEMS internationally. ROEEMS is therefore recommended for use in small households and businesses. It is especially useful for small businesses that operate in the daytime, when solar power is abundantly available.

For future work, ROEEMS can be improved by including better power quality control, overload protection and isolation. Also, operational cost comparisons should be done between when ROEEMS is used and without the use of ROEEMS.

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