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Abstract—This paper presents the design and implementation of a low-cost, low-complexity, energy-efficient controller with remote recharge and load shedding capability. The system is recharged remotely by an SMS sent to a registered SIM card in a GSM module, a voltage and current sensor measures the load power usage, a microcontroller is used to keep track of the power consumption and signals the relay in order to execute the load shedding when the predetermined threshold is reached. The whole system is powered by a power supply unit which converts the 220V AC from the supply mains to a 5V DC. After the design and upon testing, the energy measurement circuit worked with minimal error, the relay switch executed the load shedding function without delay, the GSM showed good network reception and the operation of the system was cheap and simple thus satisfying the objective of the research.

Keywords—*Automation and Control; Energy Management; Load Shedding; Remote Recharge; Smart Prepaid Meter;*

I. INTRODUCTION

Electric meters measure the amount of energy consumption of a residence, business, or commercial load. These meters fall into two basic categories (electromechanical and electronic) and are typically calibrated in billing units, commonly in kilowatt hour (*kWh*) [1]. Electromechanical energy meters have inbuilt mechanical disks rotating with a speed proportional to the applied load and the analogue meter reading increases with the rotation of the disk [2]. Electronic meters are relatively more efficient in registering every small unit of energy consumption with the digital readings displayed on an LCD/LED. Smart meters are improvements over electronic meters due to the utilization of internet for automatic data transmission and connection to the power utility company [3].

In Nigeria, Power Holding Company of Nigeria (PHCN) has been recently deploying energy prepaid meters to replace the old post-paid meters. Standard Transfer Specification (STS) standard is used by some electricity distribution companies in the manufacture of these prepaid meters as well as the vending system used to vend prepaid vouchers with the aid of standard cryptography and cryptographic keys [4]. Adoption of these prepaid meters will increase revenue, ease operation with automation, help in energy demand forecasting, reduce overhead costs and curb tampering and fraudulent practices [5]. However, these prepaid meters are faced with challenges tied to billing errors, recharge issues, systemic faults, payment bottlenecks, and lack of regular monitoring and proper maintenance. These challenges necessitate immediate action and urgent shift from the status quo to an alternative innovative solution that will minimize metering errors, reduce technical faults and automate the control and management of these meters. This research addresses these challenges by developing a low-cost low-complexity energy-efficient controller with remote recharge and load shedding capabilities for prepaid meters. This system is recharged from a remote location via SMS to a registered SIM card in the prepaid meter while energy conservation is ensured through automatic shedding of low priority load whenever the residual account balance drops to a predetermined threshold of 500 *mWh*.

The hardware design stage consists of PIC18F4550 microcontroller, regulated power supply unit, SIM800L GSM module, voltage sensing circuit, 20x4 LCD, current sensing circuit, relay switch modules and interface circuit. The software development phase for this embedded system is based on C# using Microsoft Visual Studio IDE where the codes are compiled to the PIC18F4550 memory using PIC kit 3 in-circuit programmer. The designed system displayed satisfactory performance upon verification and testing. The energy measuring circuit interfaced with PIC18F4550 operated with minimal errors of 6% and 13% for single and double load respectively from our calculations in section III. The LED of SIM800L module blinked uninterruptedly every three seconds which is an indication of reliable operation under good network reception. The relay switch module executed load shedding function instantaneously for a threshold of 500*mWh*. The implementation and operation of the designed system was relatively cheap and simple making it satisfy the core objectives of this research.

II. RELATED WORKS

Some researchers implemented a microprocessor-based automatic meter reading system which provides a cost-effective, reliable, and interference-free data transfer between remote meter reading units and utility control center. The meter reading and management processes are free from human involvement. Based on existing telephone networks, it is very flexible for utility companies to access, operate and maintain this meter reading system. A user-friendly and window-based user interface is designed which fully utilizes PC's terminal and programming technique to achieve communications between the remote meter reading units and PCs in utility control center [6].

Automatic Meter Reading (AMR) system was proposed by researchers using IEEE 802.15.4-compliant wireless networks to communicate with energy meter. The mesh network based Automatic Utility Data Collection System (AUDCS) provides a cost-efficient solution by exploring self-organization, self-healing capabilities of mesh networks and utilizing semiconductor chips and radio transceivers compliant with IEEE 802.15.4 standard. The peer-to-peer mode is chosen for the AUDCS system, as it is more flexible and robust. The application data characteristics are exploited in the data gathering and dissemination to achieve better energy efficiency. Another web services-based system was developed for the purpose of enhancing management of meter reading of power enterprises using GPRS technology [7].

Researchers designed and tested a smart energy metering system made up of two sections, namely; hardware and software. The microcontroller unit is AT89C52 which receives input from GSM unit by sending signal to trigger ON or OFF the relay. Meter recharging is done from the phone while ADC is the interface between energy meter and microcontroller. Signals sent contain useful information as unit consumed, unit left, and unit recharged displayed on LCD. The software section contains embedded 'C' program consisting of a string of 'AT' command set. The source code was transferred to a Kiel compiler software for conversion to 'Hex file' for microcontroller. This section also contains system simulation with Proteus ISIS professional version 7.8 SP2 [8]. The limitation of this design is its inability to shed critical/low priority load when recharge balance is running low.

A GSM-based digital energy meter was designed that works on the basis of blinks of the LEDs located inside the meter. LCD is connected to microcontroller to display current cycle by calculating billing amount using standard local rates and sends both total consumption and billing amount to GSM module through RS232 cable. GSM module is connected to microcontroller via MAX 232 IC which converts RS232 levels into TTL logic levels. The GSM module is programmed using AT commands to wirelessly transmit information received, to user in form of SMS [9]. This design does not have ability of remote payment for end users.

Some researchers designed a system where consumers can receive energy consumption and billing information on their GSM. The components used are 16×2 LCD, AT89S52 microcontroller, GSM module; buzzer and relay [10]. The limitation of this design is absence of remote recharge capability. Another system was proposed that allows consumer to receive consumption of power and if balance gets to minimum level, consumer is automatically disconnected [11]. Limitations of this system are absence of remote recharge capability and load shedding feature.

A system was developed that can measure energy consumption, recharge the meter via SMS and cut off power supply when the credit gets exhausted. This was achieved by using voltage and current transformers, DC power supply, ATMEGA32 MCU, GSM Modem and LCD Screen [12]. Limitation of this design is the absence of load shedding capability. A remotely controlled prepaid meter was designed that can be recharged remotely using a mobile application by making use of single-phase meter, AVR ATL 16-bits microcontroller and GSM module [13]. Limitation of this design is absence of low priority load shedding for efficient energy management.

An intelligent prepaid energy meter that can recharge meter via GSM technology and detect bypass (energy theft) was constructed by some researchers. The major components used in this design are AVR microcontroller, voltage and current transformer, LCD, relay and load [14]. Limitation of this research is lack of automatic cut off when bypass is detected. Other researchers have presented design and modelling of GSM-based energy recharge system for prepaid metering. The single-phase meter was modelled with MATLAB [15]. This system lacks energy management capability through load shedding.

A wireless GSM-based prepaid meter was proposed that utilizes ZigBee-based microcontroller to provide remote recharge and meter reading using android-based mobile application [16]. Limitation of this design is absence of load shedding capability. Another author developed efficient system for domestic electricity management which implements DSM for load management, smart consumption sequence, efficient monitoring and control of power generation [17]. Each appliance is assigned with local smart controller while ZigBee wireless communication is established between central energy management controller and smart controllers present in home environment. Utility can individually send commands to consumers utilizing GSM wireless communication whenever there is mismatch between demand and supply. Load control is implemented based on consumer preferences at each home. These researchers addressed problem of energy management through automatic load shedding of low priority load when recharged balance decreases to certain level [17]. Hence, this work presents a major improvement over designs and research works discussed in this section.

III. DESIGN IMPLEMENTATION AND TESTING

A. System Architecture

The design procedure for the proposed system is divided into hardware and software design. The proposed system takes real-time energy usage which is communicated to microcontroller by taking appropriate calculated readings and displays result (current kW reading) to LCD. GSM modem is incorporated to this system to be able to recharge meter unit. The circuit diagram of the proposed system design is as shown in Fig.1.

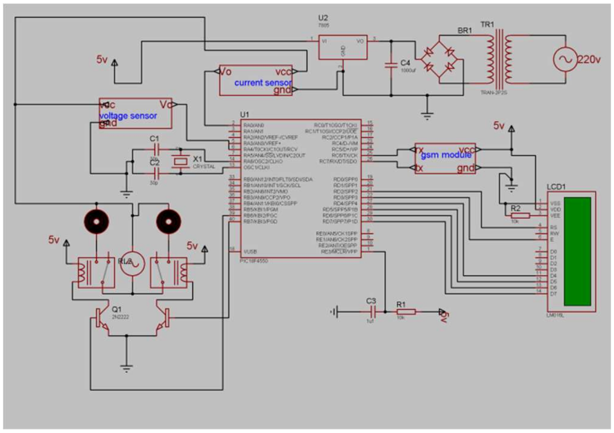

Fig. 1: Circuit Diagram of System Design

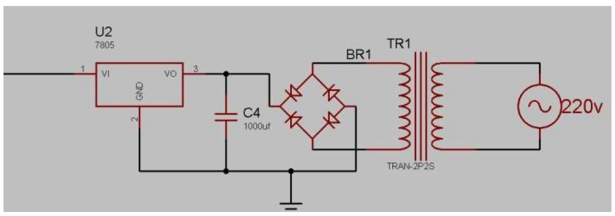

Fig. 2: Rectification and Regulating Circuit

B. Hardware Design

In this research work, the hardware stage consists of the following engineering components and circuit elements: PIC18F4550 microcontroller, regulated power supply unit, SIM800L GSM module, voltage sensing circuit, 20x4 LCD, current sensing circuit, relay switch modules and interface circuit. The output of PSU is 5 V. It consists of bridge rectifier, filtering capacitor, LED, current limiting resistor and three-terminal adjustable regulator. The rectification and regulating circuit is as shown in Fig. 2.

The transformer used in this research is 220 V/12 V, 50 Hz step-down transformer with 500 mA current rating. This transformer was chosen because of the need to reduce the supply voltage from the mains to a level that would not exceed the peak Inverse voltage of the diode rectifier and also to a level that will be acceptable to the voltage regulator (below 25V).

The peak voltage for the secondary of the transformer, V_m:

$$V_m = \sqrt{2} \times V_{rms} = 16.97 \text{ V} \qquad (1)$$

For the hardware design in this research, the calculations for the choice of diode for full wave bridge rectification:

$$PIV \geq 2 \times V_m \geq 33.94 \text{ V} \qquad (2)$$

Based on this analysis, IN4001 can be used with 2 Peak Inverse Voltage of 50 V. Average Rectified Output Current is 1 A. The output of the rectifier is:

$$V_p = V_m - 2VD = 15.57 \text{ V} \qquad (3)$$

Rectification output is oscillating with high ripple factor and not an ideal DC. As a result, filtering capacitor is used as this pulsating output is undesirable; by maintaining proper voltage supply into load circuit, hence creating desirable DC output. Working voltage is given as:

$$V_{wv} \geq 2V_p \geq 31.14 \text{ V} \qquad (4)$$

Therefore, capacitor with 50 V working voltage is selected for safety and tolerance. The value of the filter capacitor is calculated as:

$$C = \frac{I \times t}{V} = \frac{500\text{mA} \times 10\text{msec}}{8.57} = 583\ \mu\text{F} \qquad (5)$$

LM7805 is used to provide constant 5 V supply to microcontroller irrespective of input supply voltage with minimum input voltage, V_i = 7 V, maximum input voltage, V_i = 25 V, output current, I_o = 1.5 A and output voltage = 5 V. In this design, 30 pF capacitor was chosen to be used across crystal as also used in this design connected to PIN 9 and PIN 10 of the microcontroller. 20×4 LCD displays 20 characters per line and there are four such lines. In this LCD each character is displayed in 5×7 pixel matrix. 10 kΩ potentiometer connected to PIN 3 is used to adjust contrast of display.

ULN2803A has 18 pin 'chip' where PIN 1-8 receives low-level signals, PIN 9 is grounded. PIN 10 is the common on the high side while PIN 11-18 are outputs. ULN2803A is low-side switch with 2.7 kΩ series base resistor for each Darlington pair for operation directly with TTL or 5 V CMOS devices. For relay to operate suitably, pull-in and holding current should be passed through its coil. High current relay of 10 A, 12 V with 400 Ω resistance coil is chosen due to desired current carrying capacity. The relays used are five in number, represented as DFRTL command. Here, D is DB which is relay that serves as distribution board that feeds other relays with 220V AC. This DB must be automatically closed before other relays can receive power to supply to the loads. One or two or three or ALL can be at ON mode at a time depending on command sent from user's phone to GSM module. Otherwise, appliances are at OFF mode.

SIM card is inserted into slot of SIM800 module where LED blinks to indicate network availability to receive and transmit information. The module then transmits command sent as signal to PIC18F4550. SIM800 is interfaced with PIC18F4550 using USART feature to transmit command from mobile device to microcontroller where message is processed and transmitted to relays for activation.

C. Software Design and Setup

Being an embedded system, design program was written in C# using Microsoft Visual Studio IDE. Design program was compiled to memory of PIC18F4550 using PIC kit 3 in-circuit programmer. According to hardware circuit design features, load energy reading terminal program was introduced. First the system initializes, and then continuously reads the load power consumption.

Prior to implementation of the system, Proteus Design Suite 8 was initially used to design system circuit. Design program was written in C# and then embedded on microcontroller. This was done in order to see how system circuit would work under real conditions. GSM modem was also connected via COM ports on PC in order to send commands to system circuit and study real-time simulation of energy meter. Simulation was set up to establish proper performance analysis and system circuit was evaluated to perform desired tasks.

After circuit components were soldered to VERO board, continuity tests were carried out. Setup was found to be properly working. Circuit board was further placed in casing and packaged. A registered SIM card was inserted into GSM modem. Design setup was connected to power source and then SMS command 'FASE UNIT 5000' was sent to SIM in GSM modem in order to load meter with 5000 mWh.

After system assembly and uploading code to microcontroller, GSM module was tested to assess its performance under real conditions.

D. GSM Module Test Results

In order to test GSM module, multiple SMS was sent to SIM card in GSM module, obtained result is shown in Table 1.

TABLE 1: GSM MODULETEST

Trials	Delay (sec)
1	5
2	7
3	10
4	4
5	4

From Table 1, average delay in reception by GSM module is:

$$\frac{5+7+10+4+4}{5} = \frac{30}{5} = 6 \text{ seconds.}$$

The average delay is 6 seconds which is an indication of reliable network strength of service provider. This is also an indication that GSM module is found to be in good working condition.

E. Meter Power Measurement Accuracy Test

When there is no load, power usage remained constant at 0 W. As a result, balance also stayed constant. These observation shows that no current is being drawn by external circuit. This is depicted in Plate 1.

Plate 1: Meter Reading with No Load

Plate 3 shows meter with one 60 W rated load connected to its external circuit, power usage fluctuated from 64 W to about 78 W. As a result of this, balance decreased.

Plate 2: Meter Reading with Two 60 W Rated Load

Plate 2 shows meter with two 60 W load connected in external circuit. As a result of this, instantaneous power usage fluctuates between 105 W to 118 W.

PIC18F4550 also plays an important role to this meter power measurement accuracy test as it: 1) controls all computational activities of the proposed system, 2) meets computational needs of task cost effectively and with less complexity, 3) possesses lightweight and efficient compiler, assemblers and debuggers, 4) has inbuilt enhanced flash program memory, 5) has computational performance with high endurance, and 6) is suitable for power sensitive applications due to pertinent design enhancements.

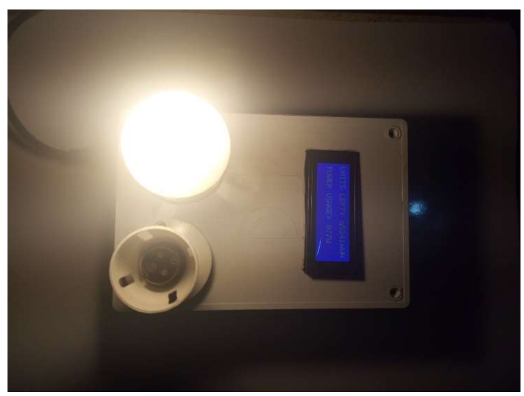

Plate 3: Meter Reading with Single 60 W Rated Load

TABLE 2: POWER USAGETEST ON A SINGLE 60 W RATED LOAD

Balance (mWh)	Time (sec)
1374	00:00
1086	15:39

Table 2 shows energy consumption rate of single 60 W bulb connected to external circuit. In order to determine energy measurement accuracy of proposed design, power consumption calculation is carried out as:

Average Power consumption (watt) = $\frac{watt-hour}{time\ in\ hours}$ = $\frac{(1374-1086)\times 3600}{16\times 1000}$ = 64.8 W

Percentage error on Single load = $\frac{64.8-60}{60} \times 100 = 6\%$

TABLE 3:POWER USAGETEST ON DOUBLE 60 W RATED LOAD

Balance (mWh)	Time (sec)
8570	00:00
7707	30:58

Table 3 shows rate of consumption of energy by two 60 W bulb connected to external circuit. Average rate of energy consumption is calculated as:

Average Power consumption (watt) = $\frac{watt-hour}{time\ in\ hours}$ = $\frac{(8570-7707)\times 3600}{30\times 1000}$ = 104 W

Percentage Error on double load = $\frac{120-104}{120} \times 100 = 13\%$

F. Discussion of Results

The designed system displayed satisfactory performance upon verification and testing. The energy measuring circuit interfaced with PIC18F4550 operated with minimal errors of 6% and 13% for single and double load respectively. The LED of SIM800L module blinked uninterruptedly every three seconds which is an indication of reliable operation under good network reception. The relay switch module executed load shedding function instantaneously for a threshold of 500 mWh. The implementation and operation of the designed system was relatively cheap and simple making it satisfy the core objectives of this research.

The designed system successfully performed remote recharge without the need for a manual operation via SMS command which makes the proposed system very easily manageable, simple and portable. The designed system also exhibited satisfactory GSM Module network reception result as the network strength displayed good performance for user and meter location with regards to strength of service of network provider.

IV. CONCLUSIONS

In Nigeria, prepaid energy meters were proffered as solution to the deficiencies of traditional metering system. The continuous wave of GSM revolution, digital automation and ICT-based digitization has facilitated this gradual transition to remote monitoring and control of electrical systems. As a result of these advancements, the overhead costs, complexities and delays associated with traditional metering is curtailed. Therefore, it avoids human intervention, provides remote recharging and improved energy conservation. The power consumption is and remaining balance is displayed on an LCD. However, the current prepaid meters are fraught with challenges tied to recharge issues, systemic faults and payment bottle-necks. These challenges necessitate immediate action and urgent shift from the status quo to an alternative innova-tive solution that will minimize metering errors, reduce technical faults and automate the control of these meters. This research addresses these challenges by developing a low-cost low-complexity energy-efficient controller with remote recharge and load shedding capabilities for pre-paid meters. The designed system displayed satisfactory performance upon verification and testing. The energy measuring circuit interfaced with PIC18F4550 operated with minimal errors of 6% and 13% for single and double load respectively according to the calculations in section III. The LED of SIM800L module blinked uninterruptedly every three seconds which is an indication of reliable operation under good network reception. The relay switch module executed load shedding function instantaneously for a threshold of 500 mWh. The implementation and operation of the designed system was relatively cheap and simple making it satisfy the core objectives of this research.

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