
Full Paper

DEVELOPMENT OF A SMART ELECTRICAL ENERGY METER FOR CONTROLLING POWER CONSUMPTION

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ABSTRACT

Smart meters being the state of the art in electrical energy metering possess a huge potential of being tools for better consumer side energy management. The aim of this work is to develop a smart meter capable of regulating power consumption via a priority-based load control system. Supply voltage and load current at the constituent units of the smart meter are measured with transformer-based voltage sensors and ACS-712 hall-effect current sensors interfaced to an ATmega32 microcontroller on-board an Arduino Nano development board. Software is developed with the Arduino integrated development environment (IDE) and programmed into the microcontroller to consistently compare the instantaneous power being consumed by the connected loads to a user defined threshold. The software also facilitates power consumption level regulation by controlling the loads in order of priority via relays while performing other standard smart meter functions. The development of the meter involved circuit design and simulation with Proteus, printed circuit board (PCB) development with PCB Wizard, PCB construction using the wet etching method on standard copper clad board (CCB) and assembly of the units of the smart meter in appropriate casing. The voltage and current response of the smart meter was tested and its output was compared to those of a standard voltmeter and ammeter, its ability to regulate loads to maintain specified power thresholds while being remotely monitored was also verified in the laboratory.

Keywords: Smart meter, Hall-Effect, Arduino, Threshold, Energy, Etching

1. INTRODUCTION

Smart meters are the state of the art in electrical energy metering. According to Horowitz (2010), smart meters are often promoted as a route for energy saving, real-time electricity pricing, automated energy usage data collection, reduction of labour costs

and instantaneous fault detection, resulting in a more efficient and reliable distribution network.

Smart meters operate with an assortment of sensors, actuators, microprocessors and other supporting hardware for effective operation such as the voltage and current sensing unit, power supply unit and communication system. Although there are different types of smart meter design and technology, there is a common overall process for data acquisition, processing and communication. Electricity usage is read and transmitted in regular intervals typically between 15 minutes and 1 hour to the utility. The data collected at the utility are used for a number of business purposes such as billing, network and service monitoring, profiling, prediction and planning (Damminda *et al.*, 2016).

Different types of tariff structures are commonly used for the billing of electrical energy use; the fixed, time-of-use and tiered or demand-based tariff structure. For the fixed tariff structure, a fixed rate is charged for energy use at all times while for the time-of-use plan, different rates are charged for energy use at different periods of the day, different days of the week or even different seasons of the year depending on the peak demand during that period (Gouri *et al.*, 2015). For the tiered or demand-based tariff structure, different rates are charged for energy use depending on the power demand of the consumer. Consumers with higher power demand are made to pay higher rates than those with lower power demand in an attempt to flatten peak demand and encourage consumers to lower their energy consumption during peak periods.

While older meters support only fixed or demand-based tariff structure depending on which it is designed for, smart meters typically support the use of one or more different tariff structures (Weranga, 2014).

Govinda (2015) designed a smart meter using Atmel 89S52 microcontroller and global system for mobile communication (GSM) modem. AT89S52 was chosen due to its faster programming and better memory advantage over the 8051 family. The microcontroller takes the reading from the energy meter via an opto-coupler, displays the reading on a Liquid Crystal Display (LCD) and sends same to the user through a GSM modem. The work focused only on periodic sending of warnings when a predefined energy level was exceeded.

Hu (2015) designed a smart meter system capable of supporting tiered electricity pricing using the ADE7755 power metering chip, SENS-01 power line carrier (PLC) communication module, C8051 microcontroller and other supporting hardware.

Test results indicated that the user could measure instantaneous power usage and it could be transferred to the district administrator. The downside to his work was the observed failure in signal communication whenever a transformer was encountered in the PLC transmission path.

Shubham et al. (2014) designed a smart meter using the AT91SAM3X8E microcontroller. The microcontroller provided the possibility of integrating with android devices, communicating with the web and other modules required for the efficient operation of the smart meter. They utilized the Allegro ACS712 chip which provides solution for alternating and direct current sensing. The energy meter was interfaced to a GSM module for bi-directional communication to the utility control center through Short Messaging Service (SMS). The data was also made available in a web portal wherein consumers may login with their account and access their usage logs. However, the cost of maintaining this system was considered a setback.

Andres et al. (2012) developed a privacy-preserving smart meter with a low cost MSP430 microcontroller. The advantage of their method is its cost minimization. Their work focused only on privacy-preservation using data encryption techniques.

Ryan (2012) worked on an AVRmega8 and ZigBee RF230 based smart electricity metering system for greenhouse-conscious homes. The metering system was in two parts; the transmitter and receiver module. The transmitter module consists of operational amplifiers, an AVRmega8 microcontroller with inbuilt Analog to Digital Converter (ADC) and ZigBee RF230 for communication. Voltage and current signals to be measured are interfaced with the ADC using transformers and operational amplifiers. The Receiver module consists of a ZigBee RF230, AVRmega8, MAX232 and it was interfaced with a computer for data logging and user interfacing. The AVRmega8 and ZigBee RF230 make a two-way communication via a serial peripheral interface (SPI) bus on both modules, the AVRmega8 on the receiver module sends signals to the MAX232 while the MAX232 sends signals to the computer using RS232 interface. MATLAB was used for the graphical user interface for the software design with a provision for logging of data. The advantage of his method is its ability to communicate with remote monitoring devices wirelessly, however, the design is costly due to relatively large component parts, it does not make provision for utility company side monitoring and control.

Koay et al. (2003) designed and implemented a Bluetooth-based energy meter where several meters in close proximity communicated wirelessly with a master computer. Operating distance was a major setback for this system because Bluetooth communication works effectively only at close range.

The objectives of this work are to design a smart electrical energy meter capable of regulating power consumption to a user defined range, construct a prototype of the meter and evaluate its performance.

2. METHODOLOGY

2.1. System Overview

The system consists of three units; the smart meter, load controller and remote user interface unit. The smart meter unit performs meter functions such as energy metering, billing and communication with the utility while the load controller performs priority-based load control. The remote user interface provides a means for the user to recharge as well as query energy usage, power demand and credit balance from the meter. The block diagram of the smart meter is shown in Figure 1.

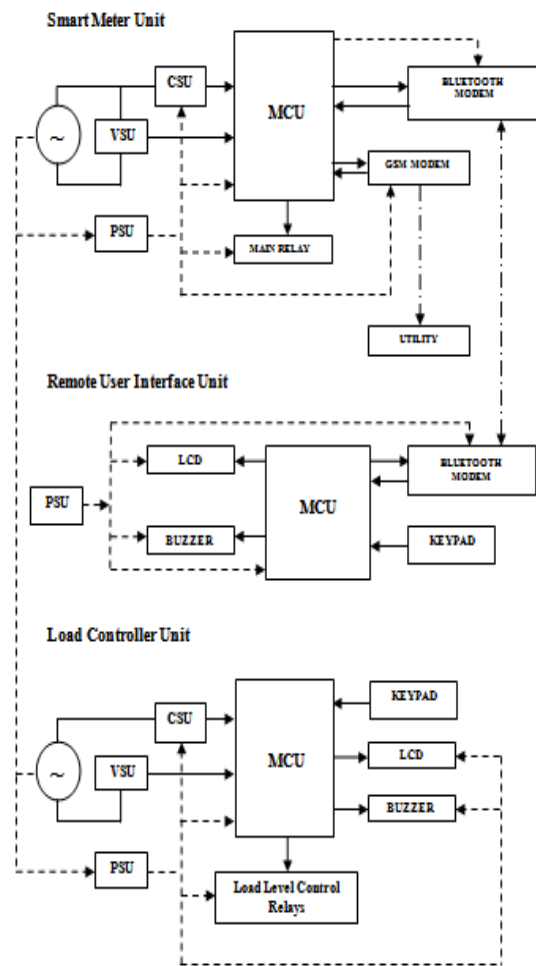


Figure 1 System block diagram

2.2. System Design:

Power Supply Unit: Identical power supply units (PSU) consisting of 220-12V step-down transformer with maximum 1A secondary current was used to provide the required power for the smart meter unit and load controller unit. The remote user interface unit was powered with a rechargeable 7.4V 1800mAh Lithium Polymer (LiPo) battery which can be recharged with an external 12V DC adapter. A battery charging and monitoring circuit was integrated into the remote to prevent overcharging the battery.

The Current Sensing Unit: An ACS-712 linear hall-effect current sensing module with 0-30A current range was used to measure the AC current drawn by the load(s) on both the load controller and smart meter units. The module gives an output voltage directly proportional to the load current. Figure 2 shows the circuit diagram of the connection between the current sensor and the microcontroller.

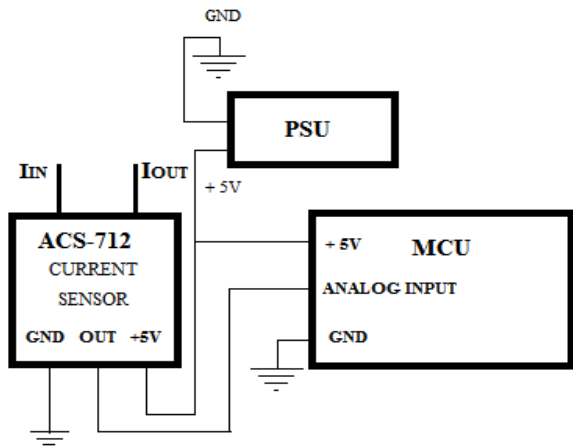


Figure 2 Current Sensing Unit Interfacing

The Voltage Sensing Unit: The voltage sensing unit is shown in Figure 3. A 220-9V transformer was used to step-down the input voltage to 9V rms. This voltage was further attenuated by a 100 kΩ potentiometer which also provides a means of adjusting the output voltage of the voltage sensing unit. The output voltage at this stage is sinusoidal and its magnitude varies below ground level (0V). In order to restrict the voltage to a range of 0 – 5V which can be measured by the microcontroller, a DC offset of 2.5V was added by two 470kΩ resistors connected in potential divider configuration. The 10µF 25V electrolytic capacitor provides a low impedance path to ground for the AC signal.

By measuring the output voltage between the wiper of the potentiometer and ground, the input voltage was determined.

The Microcontroller: An ATmega32 microcontroller onboard an Arduino Nano module was used for computation and control in the smart meter, load controller and remote user interface units. A 4x4 keypad is interfaced to the microcontroller on the load controller and remote user interface units to accept user input and a 16*2 LCD is also used to display information to the user.

12V relays with 30A contact rating are used in the smart meter and load controller units to control load. It is interfaced with the microcontroller via a relay driver consisting of a 4N-35 optocoupler IC, BC547 NPN transistor and other supporting circuit components as shown in Figure 4.

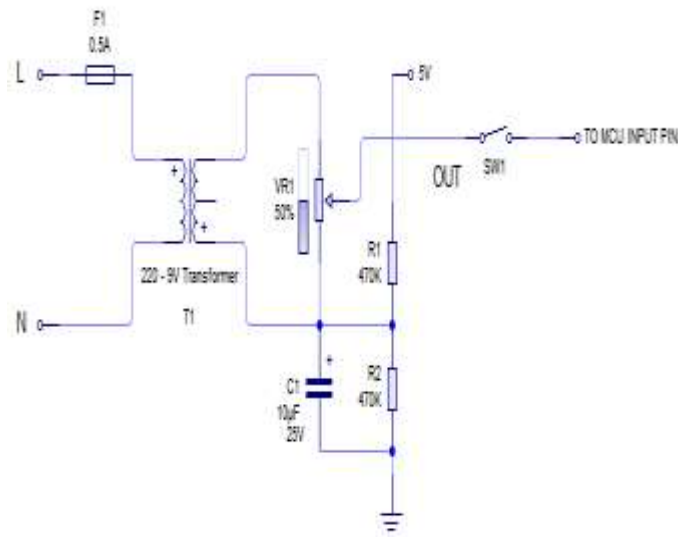


Figure 3 The Voltage Sensing Unit.

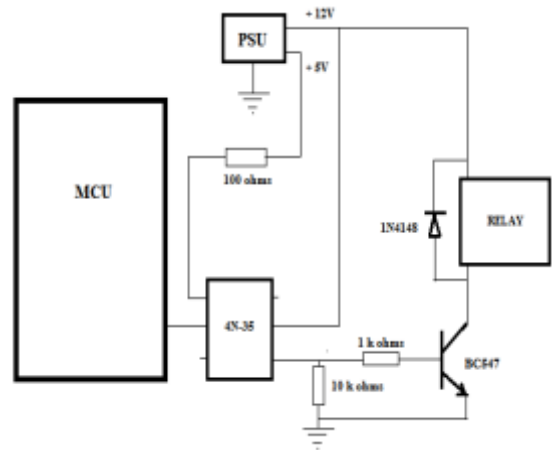


Figure 4 Interfacing diagram of the relay to the microcontroller

Communication: HC-05 and HC-06 modems were used for data transmission between the smart meter and remote user interface unit. HC-05 was used as the master device that initiates connection requests and it was interfaced with the microcontroller on the remote user interface. HC-06 was used as the slave device and it was interfaced with the microcontroller on the smart meter unit. The HC-06 was configured to connect to the HC-05 master device whenever it was in range. Both devices operate on the Bluetooth 2.0 protocol with maximum data transfer speeds of 3 Mbps and default baud rate of 9600 bps. Data transmission between the modems is via low-power UHF radio waves at a frequency of between 2.402 GHz and 2.480 GHz and communication range is approximately 10 meters.

A quad-band SIM800L GSM modem was used to send energy usage information from the smart meter to the utility hourly.

2.3. Circuit Development

The development of the circuit layout of the smart meter design was done with Proteus8 Design Suite. Proteus is a highly versatile electronic development software for circuit designing and testing. The schematic capture option of the software was used to develop the circuit of the units of the smart meter. Selection of circuit components were made from the software's robust integrated component library which features the circuit components needed from the ACS-712 current sensor down to the basic resistors.

2.4. Software Development

The software for the smart meter was developed with Arduino IDE. Two distinct software layers can be identified in the software development process for each unit of the meter; the driver layer and the application layer. The driver layer consists of routines for communication between the ATmega32 microcontroller on the Arduino and the interfaced devices such as the LCD, keypad, voltage and current sensors. The driver layer is mainly in the form of open-source software (libraries) obtained and modified to suite the objectives of this work. The Application Layer is the main system software. It consists of routines written to perform metrology, load control, general system coordination and communication.

2.5. Simulation

Sequel to hardware construction, simulation was carried out in Proteus in order to observe the performance of the developed circuit and software.

Voltage and current were measured by connecting sinusoidal voltage sources with different voltage magnitude and phase angle equivalent to the expected output of the voltage and current sensing units to two Arduino Uno analogue pins. Arduino Uno was used instead of Nano due to the unavailability of the Nano on Proteus. The specifications of both boards were checked and verified to be equivalent but for fewer number of pins on the Uno and some other differences in the construction of the board. These differences did not compromise the purpose of the simulation.

The voltage, current and power factor measurement of the smart meter was taken and compared with the applied input. Also, the instantaneous power consumption of the load was computed per second and summed over a one-hour period to obtain the energy consumed by the load in kWh. Credit deduction accuracy was monitored by comparing the hourly deductions with the energy usage of the load based on input voltage and current draw.

Serial communication between the various units of the smart meter was monitored with Virtual Terminal on Proteus to verify the operation of the remote user interface unit to smart meter and smart meter to utility communications. The Load control capability of the system was checked by monitoring the state of the microcontroller pins controlling the load control relays with a logic probe for different values of preset power threshold and power demand.

2.6. PCB Construction

A PCB layout of the circuit diagram for the various units of the smart meter was created with PCB Wizard. The layout was printed on a Heat Transfer (HT) paper using a laser-jet printer. The surface of the HT paper where the layout to be transferred was printed was placed face down to the copper side of the CCB. The circuit layout was then transferred from the heat transfer paper to the CCB using a 1000W electric iron heated to a temperature of about 200°C. The hot electric iron was used to press the entire circuit layout area with slight pressure to the CCB for about 2 minutes. Thereafter, the CCB was immersed in Ferric Chloride solution for about 3 minutes under close monitoring to ensure complete etching of the circuit layout.

After etching, the PCB was removed from the Ferric Chloride solution, rinsed in water and dried. Thereafter, the surface of the PCB was sanded with fine sand paper to remove the toner and ink layer on the copper tracks. Holes were drilled for the mounting of circuit components on PCB and the circuit components were mounted and soldered. The circuit boards were mounted in suitable plastic casings and electrical connections were made to the other components of the smart meter units with appropriate cables.

3. RESULTS AND DISCUSSION

3.1. Simulation

Figure 5 shows the circuit of the smart meter during simulation in Proteus. The output of the meter was compared to computed values based on the input voltage, load current and power factor. The results are presented in Table 1. The percentage error in the reading of the smart meter was observed to increase as power factor reduces. This was due to imprecision in the timing of Proteus since power factor was computed by measuring the difference in zero-crossing time between the voltage and current signals.

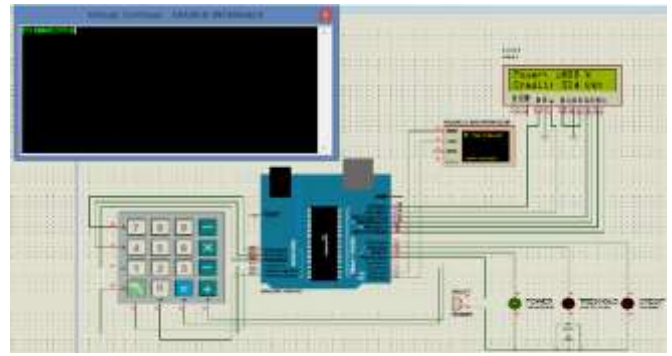


Figure 5 Smart meter simulation in Proteus

Table 1 Smart Meter Output vs. Calculated Power for various values of voltage, current and power factor

Voltage(V)	Current (A)	Power Factor	Smart meter Value (W)	Calculated Value (W)	% Error
240	60	1.00	14388.27	14400.00	0.0815%
240	30	1.00	7198.32	7200.00	0.0233%
240	15	1.00	3596.53	3600.00	0.0964%
220	60	1.00	13203.43	13200.00	0.0260%
200	60	1.00	11996.61	12000.00	0.0283%
180	60	1.00	10793.68	10800.00	0.0585%
240	60	0.97	13779.40	13968.00	1.3502%
240	60	0.93	13222.98	13392.00	1.2621%
240	60	0.87	12294.37	12528.00	1.8649%
240	60	0.83	11685.66	11952.00	2.2284%

3.2. Test and Calibration Results

The smart meter and its constituent units were tested and its voltage and current measurement was compared to that of a voltmeter and ammeter while connected to a resistive load rated 480W, 240V. The calibration constants were adjusted in software until satisfactory results were obtained. The energy metering and credit deduction of the meter was tested by subjecting the meter to the same load for a total period of six hours, three hours each on different days. The results of the test are shown in Table 2. The energy readings accumulate continuously per second as time progressed. The readings were found to be accurate with respect to the connected load. The load control capability of the load controller was tested by connecting 160W, 240V loads to the output of each priority level and testing the ability of the meter to regulate load level to different preset power threshold values. The time duration for automatic regulation was also noted and presented in Table 3.

The unit was able to regulate load level. It was observed that the response time of the meter is dependent on the priority level of the load. At the final stage of the test when the preset value was lower than the power consumption of the loads connected to the high priority output, an audible warning was generated at the response time recorded. Figure 8 shows the smart meter being tested in the laboratory.



Table 2 Energy measurement test results

Measured/Calculated Values				Smart Meter Readings			
Voltage (V)	Current (A)	Apparatus Power (VA)	Energy (kWh)	Initial Reading (kWh)	Energy after 1 st hour (kWh)	Energy after 2 nd hour (kWh)	Energy after 3 rd hour (kWh)
220	2.05	451	0.45	0.00	0.45	0.90	1.35
220	2.10	462	0.46	1.35	1.81	2.27	2.73

Table 3 Load level response test results

Threshold (W)	High Priority Loads	Medium Priority Loads	Low Priority Loads	Total Load (W)	Response time (sec)
400	ON	ON	OFF	320	2.51
200	ON	OFF	OFF	160	5.69
100	ON*	OFF	OFF	160	8.86



Figure 8 Smart meter being tested in the laboratory

3.3. Comparison of the developed meter with reviewed works

This work focused on the development of a meter through which a user may regulate his power consumption to a desired threshold by switching off loads deemed non-critical during peak periods while performing other standard smart meter functions. Other works reviewed developed smart meters using various microcontrollers, communication protocols and supporting different tariff plans.

4. CONCLUSION

A smart electrical energy meter with the capability of automatically regulating load level was developed in this work. The results of the study revealed that the meter was able to regulate load level to a predefined threshold. The results also showed that the response time of the meter is dependent on the priority level of the loads that need to be switched off in order to regulate power consumption. The meter transmitted usage information to the utility via GSM communication. This may be logged and used for power system planning and maintenance by the utility. Also, a Bluetooth-based remote device was used to communicate with the meter to check necessary parameters and load credit. This project provided an enhanced smart meter capable of improving consumer side energy management.

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