UNIVERSITY OF EDUCATION WINNEBA, KUMASI CAMPUS

COLLEGE OF TECHNOLOGY EDUCATION – KUMASI

DESIGN OF A MICROPROCESSOR BASED PREPAID ENERGY METER WITH INBUILT COMMUNCATION TECHNOLOGY

Thesis submitted in partial fulfillment for the degree of

Masters in Technology (M.Tech.) in Electrical and Electronics Technology

BY

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DECLARATION

I hereby declare that except for specific references which have been properly acknowledged, this work is the result of my own research and it has not been submitted in part or whole for any other degree elsewhere.

Signature ………………………………….. Date ……………………………………

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ABSTRACT

This project presents a design of a microprocessor based prepaid energy meter which is equipped with GSM communication technology. This energy meter has features which conveniently addresses the above stated problems; thus, allowing consumers to comfortably purchase energy units remotely. It also has features that allow utilities to detect felonious tampering activities in real-time as well as transmit consumer notifications. This improved prepaid energy meter design is also proven to be of low-cost making it a suitable choice of replacement for most Ghanaian Utilities such as Electricity Company of Ghana (ECG) and Northern Electricity Distribution Company (NEDCo). Prepaid energy meter is a new concept in the measurement of electrical energy consumption on periodic basis. This method of measurement and data collection discards the conventional method of taking the meter reading manually. This project report presents a GSM based prepaid energy meter credit loading system comprising two microcontrollers, a single phase energy meter IC and a Global System for Mobile Communication (GSM) modem. The energy consumption is calculated using the output pulses of the energy meter chip and the internal counter of microcontroller (ATmega32). A microcontroller (ATtiny13) is used as a smart card and the numbers of units recharged by the consumers are written in it. A relay system has been used which either isolates or establishes the connection between the electrical load and energy meter through the supply mains depending upon the credit present in the smart card. Energy consumption (kWh), maximum demand (kW), total unit recharged(kWh) and rest of the units (kWh) are stored in the ATmega32 to ensure the accurate measurement even in the event of an electrical power outage that can be easily read from a (16x2) LCD. As soon as the supply is restored, energy meter restarts with the stored values. Cost analysis of the design resulted in GH₵264.00. Low power consumption, greater accuracy, greater convenience, easy maintenance and affordable cost were achieved by the design.

DEDICATION

I dedicate this project to my wife, Mrs Ganaku Gifty for her care, support and earnest contribution towards my education. Not for getting my uncle's; Mr Emmanuel Ganaku, Mr. Proper Ganaku and Mr. S.W.K Tsadidey (Principal). May God Almighty reward her abundantly.

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LIST OF ABBREVIATIONS

Abbreviation	Meaning
ALU	Arithmetic Logic Unit
AuC	Authentication Centre
BSC	Base Station Controller
BSS	Base Station System
BTS	Base Transceiver Station
CISC	Complex Instruction Set Computing
EIR	Equipment Identity Register
GSM	Global System for Mobile communication
HLR	Home Location Register
IMEI	International Mobile Equipment Identity
IMSI	International Mobile Subscriber Identity
ISDN	Integrated Service Digital Network
LCD	Liquid Crystal Display
LED	Light Emitting Diode
ME	Mobile Equipment
MS Visio	Microsoft Visio
MS	Mobile Station
OSS	Operation Support Subsystem

PIN	Personal Identity Number
PLMN	Public Land Mobile Network
PSTN	Public Switched Telephone Network
SIM	Subscriber Identity Module
SMS	Short Messaging System
SS	Switching Subsystem
UART	Universal Asynchronous Receiver Transmitter
USART	Universal Asynchronous Receiver/Transmitter
VLR	Visitor Location Register

CHAPTER ONE

INTRODUCTION

1.0 Background of the Study

Electricity has become ubiquitously known as the prime source of power for most homes and industries (Alan & Mohammed, 2007). There is basically very little work one can do without being connected to its power supply. As such, the efficient execution of the processes of generation, transmission and distribution of its electrical power is of keen interest to every community. A disruption in any of these activities could lead to curtailment in the benefits derived from electricity (IEC, 2007). Like most industries, the smooth rollout of the above-mentioned processes is heavily reliant on the provision of financial resources. It is important to note that the entire cost of all these processes is borne exclusively by the consumer (PEC, 2009). It is therefore imperative that revenue generated through the payment of electricity bills is done with little or no losses.

Electric energy meters are the only direct revenue interface between utilities and the consumers (TFEHP, 2011). They are installed on the customer's premise to measure the quantity of energy consumed over specific periods of time. In Ghana, these energy meters have undergone several advancements over the past decade. The prime areas of change in these meters have often been in the accuracy of measuring consumed energy and modes of payment; all targeted towards the overall goal of improving revenue collection (Boadi, 2013).

Modern trends have proven that there is a higher guarantee of revenue protection through the use of Prepaid Meters as compared to Post-paid Meters (Ahmed, Doug, Lisa & Adam, 2011). Not until recently, most homes in Ghana were installed with Post-paid meters. These meters are often associated with the following:

1. Periodic manual meter reading by trained utility personnel
2. Periodic printing and distribution of energy bills

3. Regular sensitization programs to educate customers to pay bills promptly to avoid being disconnected.
4. Disconnection of defaulting customers.
5. Reconnection charges and bad debts. (Dadzie, 2012)

Most of the above-mentioned characteristics raise privacy concerns for customers as well as increase administrative and operational cost of the utility (Ariel & Luciana, 2009). The post-paid nature of this meter, often requires that the utility puts in considerable effort before generating appreciable revenue. However, the Prepaid Meter is not associated with any of these characteristics. Due to its prepaid nature, there are no deficits or defaulting customers; energy is paid for before it is even consumed. According to Sheelasobanarani et al. (2015) consumers are also in control of their budget; they determine the frequency and the quantity of purchases. Also, the absence of additional operational and administrative cost may translate into lower tariffs. These advantages have been the driving factors behind the shift from post-paid to prepaid meters in Ghana.

1.1 Problem Statement

Despite the several advantages associated with the prepaid meters that have been installed in Ghana, their current standalone nature brings some level of inconvenience to the customer. With no connectivity to the utility or vending authority, consumers must endeavor to purchase energy units before vendor stores close. During weekends, holidays or late hours, when in dire need of energy units, they must be ready to travel long distances in search of operating vendors as well as be ready to join long waiting queues. It is also sad to mention that, because of this same lack of connectivity, the consumer must always make a return journey to his premise to load up purchased energy units, even when there are other scheduled pressing activities which need his/her attention.

Without detailed analysis of the effects of these inconveniences, one may be quick to say that these inconveniences only affect the consumer and may lead to nothing more than plainly what has been stated. As such, one may say that as long as the utility is guaranteed of its revenue there is no cause to worry. However, a critical analysis of these inconveniences would reveal that the utility in a long run would be affected.

In scenarios, such as described above, where the consumer is in dire need of energy units and has no other option but to suffer the loss of power for several hours, he/she may result to desperate measures – meter tampering. Consumer desperation has been identified as one of the major reasons behind meter tampering (Eisenbeiss, 2015). Desperate customers, despite knowing that tampering with meters can maim or kill them or get them prosecuted, may still venture this illegal activity. Armed with their desperation, they meddle with the meter's circuitry with the hope of getting it to provide them power for longer periods than expected (Sehar, 2014). When successful, they hardly would keep the "good news" of their hacking method to themselves but share it readily with others. This energy theft method would soon become public knowledge and the utility would stand the risk of losing revenue. The vision of protecting revenue through the prepayment method would soon be unattainable. The utility would be left with the only option of a wide-spread rollout of new energy meters with more secured features. As long as there are desperate consumers, this cycle may never end. In Ghana, there have been reports on such energy theft methods on the newly installed prepaid meters (Ghana web, 2012; Mensah, 2016).

Based on the discussion above it is evident that both utilities and customers are affected by the standalone nature of the prepaid metering system used in Ghana. This is the problem the research focuses on solving.

1.2 Research Objectives

The general objective of this research was design a microprocessor based prepaid energy meter with remote communication ability purposely for remote loading of purchased energy units. The research would use Ghana's Electrical Grid as its case study. The three specific research objectives were follows:

1. To design a microprocessor based prepaid energy meter with the basic functionality of accurately measuring consumption against purchased units.
2. Augment the design with an appropriate and cost effective two-way communication technology for energy unit top-up and acknowledgement.
3. Juxtapose the designed energy meter with existing prepaid metering systems to enumerate strengths and weaknesses.

1.3 Research Questions

The research was guided by the following research questions;

1. What microprocessor suit prepaid energy meter with basic functionality?
2. What are the appropriate technology for energy unit top-up and acknowledgement?
3. What are the weakness of the existing prepaid metering systems?

1.4 Significance of the Study

There is no doubt that the Prepaid energy meter has far more desirable advantages than the Post-paid energy meter (Sheelasobanarani, Raja, Dhanaraj, Manickam & Karthic, 2014). Ever since its inception, utilities in Ghana, such as Electricity Company of Ghana (ECG), have made drastic reductions in accrued debt from defaulting customers as well as a decrease in their overall administrative and operational cost (Mensah, 2016). The protection of their revenue has provided them with the necessary capital required to smoothly run the electric grid; thus, avoiding power shortages and carrying out more electrification projects (Gamor, 2014).

All the earlier mentioned advantages of the prepaid energy metering system seem to be more for the utility than for the customer. Even though the customer enjoys the benefit of being in control of his budget, the inconvenience that the new system brings far outweighs this benefit. Travelling to and fro vendor shops whenever energy units run out, is simply an inconvenience for the customer especially when he is the one paying for the service. The additional transportation expenses he has to incur, the time wasted waiting in long queues and the discomfort he has to experience when he has to endure nights, weekends and holidays without power because vendors are closed, are enough reasons to find an immediate remedy to the problem.

The post-paid system is not associated with any of these inconveniences. With the post-paid system, the customer uses power on credit and pays later. When payments are to be made, he/she pays at his/her own convenience; which in Ghana is usually within 28 days after the last bill is delivered. There is no need to return to his/her premise to activate his energy meter after payment has been made for energy. By simply comparing the two meters by these user experiences, it may seem as if the post-paid meter is more user-friendly.

Nevertheless, being convinced that the post-paid system cannot guarantee the utility of the needed revenue for its daily operation, it is imperative that the prepaid system be maintained. However, it should be altered to deal with the inconveniences described above. This study is therefore essential for the derivation of possible lasting solutions to these identified problems.

1.5 Limitations

The main challenges encountered during the course of this project included the following:

1. Unwillingness of Ghanaian utilities to release information on old and current prepaid metering systems.
2. Little or no documented information on some communication technologies in Ghana.

1.6 Organisation of the Study

The rest of the study is organized as follows:

In Chapter Two, existing literature on prepaid energy meters is reviewed with the focus of identifying possible drawbacks that need to be dealt with. Also, the essential features of prepaid meters has been discussed.

In Chapter Three, a research methodology is selected for the design of the proposed microprocessor based prepaid meter. In addition, details of the schematic design of the proposed meter would be presented.

In Chapter Four, results of the design, discussions and cost-savings analysis are presented.

Finally, Chapter Five summarizes the entire study, states the challenges encountered and makes recommendations for future study and implementation.

CHAPTER TWO

LITERATURE REVIEW

In this chapter, a discussion is made on the current nature of the prepaid energy metering system in Ghana. The discussion brings to light the benefits of this deployed system. Also, important drawbacks which stem from consumer inconveniences are highlighted with the aim of finding measures of addressing them. These measures are sought for by reviewing other prepaid energy meter designs found in literature. Also, the Ghanaian environment and electrical grid are studied to see if any of the reviewed solutions would be a best fit for addressing the identified inconveniences

2.1 Prepaid Energy Metering System in Ghana

As stated in the previous chapter, the mode of operation of the postpaid energy metering system has some inherent drawbacks which are highly undesirable to both the customer and the utility. These drawbacks include the invasion of consumer privacy, inaccurate meter reading leading to estimated bills, defaults in payment of bills and increase in the administrative and operational cost of utilities (Dadzie, 2012). As a consequence of these drawbacks, the prepaid energy metering system was introduced in Ghana in the year 1994 by the Electricity Company of Ghana (ECG) – the main power distribution company for the southern part of Ghana. This introduction started with a pilot installation of prepaid meters in some few towns and cities in Greater Accra and Central Regions. These meters were known as Electro-Cash 1 (ECG, 2010). Consumers who had their meters replaced were given smart programmable cards. These cards were to be used for loading purchased energy units onto the new meter. Whenever consumers needed energy units, they visited nearby vending points with their cards and purchased the quantity of energy they could afford. Vendors were equipped with special smart card programmers which they used in uploading the cards with the purchased units (ECG, 2010). An image of the Electro-Cash 1 prepaid energy meter in displayed in Figure 2.1.

Fig. 2.1: Electro-Cash 1 Prepaid Energy Meter (16)

Over the past two decades, the ECG has deployed seven (Dadzie, 2012) different prepaid meters; namely:

1. Electro-Cash 1
2. Electro-Cash 2
3. Electro-Cash 3
4. Smart G
5. SmartCash Bot
6. Kamstrup (Nuri) and
7. EnerSmart (Holley) (ECG, 2016)

The introduction and deployment of these different meters have been as a result of technological advancements. These advancements have often been in the area of accuracy of measuring energy consumption and the addition of other user-friendly features (ECG, 2016). These areas of advancement, though highly desired, have not been the major reason why ECG has often had to replace its energy meters (Brean & McGranaghan, 2010). The main cause for change has been the ever- recurring hacking of prepaid energy meters. After meters are installed on the consumer's premise, some consumers tamper with the system primarily to extend their period of consumption. When successful, they spread the word of how they tampered with these meters with little or no detection by the utility. After a period of time this method of energy theft becomes common knowledge and the utility is at the risk of losing revenue (Eisenbess, 2015) (Ghana Web, 2015). To mitigate this the utility is forced to replace all meters of this type with meters which are more difficult to hack – an expensive pursuit. The irony is that this cat-and-mouse game of meter tampering would never cease; as long as meters would be left unattended on the premises of consumers, consumers would always have the freedom to tamper with these meters. This almost-never-ending game is evidently seen from the number of meters that have had to be replaced over the past two decades (Eisenbess, 2015) (ECG, 2016).

A close study of the various prepaid meters that have been deployed over the past few decades, revealed that their basic mode of operation has not changed much. The consumers are still equipped with tokens; either programmable smart cards or radio frequency identification (RFID) cards, which they use to load their meters with purchased energy units (ECG, 2016). Purchase of energy units are still done at vending stations, consumers still have to queue to purchase units and round trips always have to be done whenever one needs to purchase energy units – from the consumer's premise to the vending point and back to the premise to load the purchased energy units. Consumers are also sometimes forced to endure periods without power especially during late hours, weekends and holidays when vendors are closed. All these, to a large extent, cause great inconvenience to consumers (Dadzie, 2012; ECG, 2016).

Research has proven that root cause of meter tampering is consumer desperation and anxiety. Desperate consumers have a higher proclivity of tampering with meters with the aim of satisfying their anxieties (Eisenbess, 2015). The uncomfortable experiences described in the paragraph above are enough to influence some consumers into the practice of energy theft. Whenever they are unable to accommodate the idea of staying for hours without power, mainly because vending points are not in close proximity or have closed, they tend to use desperate measures to access extra energy units.

As stated earlier, these acts of energy theft have lasting ripple negative effects on the utility and eventually consumers. These effects start off with a reduction in the utility's revenue. With a reduction in revenue, the utility is unable to smoothly carry out its operations and this eventually would lead to customer dissatisfaction. After the utility realizes the shortage in operational capital, they are forced to increase tariffs in order to generate the needed capital (Alan & Mohammed, 2007). A typical example was seen in 2013, after ECG realized that the utility required 4 Billion USD to effectively run their operations, they increased energy tariffs by 78% (Appiah, 2013; Ghanaian Times, 2014 ; PURC, 2013). In other words, the remaining loyal and law-abiding customers were being forced to pay more for electricity. These increases only cause more customers to become desperate thus increasing the percentage of customers who dabble with meter tampering (Eisenbess, 2015). It is for such reasons that in Ghana the constant increase in tariffs has been almost equally matched by a persistent increase in non-technical losses (energy theft) (PURC, 2013). Having understood that the electrical grid is run by financial resources, reduction in these financial resources usually leads to extended seasons of power shortages – energy crisis (Deloitte, 2011; ESI Africa, 2014). Based on this premise, one can understand why Ghana has experienced energy crises for the past ten years.

Having realized the negative ripple effects of these inconveniences, this research is aimed at suggesting measures of dealing effectively with the root cause of these problems. In the next section, literature on prepaid metering systems are reviewed in order to bring to light how other authors have attempted to curtail these inconveniences.

2.2. Existing Method of Dealing with the Inconveniences

From the above section, it is clear that the current mode of operation of prepaid metering systems in Ghana brings about the following key inconveniences:

1. Round trips done each time energy units are to be purchased; to the vending station and back to the consumer's premise, thus wasting the consumer's precious time.
2. In areas where there are few vending points, consumers may have to wait in long queues before being attended to by vendors – another major contributor to wasted time.
3. The unavailability of vending stations during late night hours, weekends and holidays

– causes consumers to endure periods without electricity. Also, businesses which run during such hours are brought to a halt when such situations occur.

These inconveniences were non-existent in the previous postpaid metering system, thus creating the notion that the postpaid system is better than the prepaid system (Dadzie, 2012). However, a critical look of the inherent drawbacks of the postpaid system still makes the prepaid metering system a preferable choice for both the consumer and the utility.

In trying to deal with the above-mentioned inconveniences, et al (Preeti Parmar 2014) designed a prepaid meter which had the ability to provide the consumer with extra energy units during emergencies (Parmar et al. 2014). In other words, consumers who run out of credit during late night hours, weekends or holidays could use these extra energy units over such periods till they finally get access to vendors. The quantum of energy units credited to the customer in such situations is often the prerogative of the utility. The extra (borrowed) energy units are deducted after the next purchase is made.

A discussion paper on prepaid meters deployed in some Australian jurisdictions indicated that in order to avoid consumer desperations, customers experiencing financial difficulties must be protected by a number of provisions which include the following (EWO, 2014):

1. Prepaid meters should only be allowed to self-disconnect during weekdays and only during hours when vending shops are still operational

2. Meters should be credited with a quantum of energy units equivalent to the average cost of 3 days of electricity

Per these stipulated provisions, each type of energy prepaid meter had the emergency units feature. For most jurisdictions discussed, the quantum of emergency units available for consumers ranged between 5 – 18 USD. These units were to be accessible each time a consumer runs out of his/her purchased energy units (EWO, 2014).

It is clear that the provision of emergency units helped to deal with the inconvenience of running out of energy units whenever vendors are unavailable – during late hours, weekends or holidays. However, it is important to note that just as seen in the Australian jurisdictions, these emergency units are a specific finite quantity. As such there is no guarantee that these units are copious enough to last during the entire period when vendors are unavailable. It is impossible for the utility to know ahead of time the specific quantity of energy units each consumer would need for such periods of time. Also, the duration of such periods cannot be predetermined by the utility. It is also important to note that this measure does not deal with the inconvenience of time wasting. It is therefore imperative that other measures are sought for to amply tackle these inconveniences. Reduan, Tanzim, Sreeram & Herbert (2010), proposed a prepaid metering model that leveraged the benefits of Worldwide Interoperability for Microwave Access (WiMAX) communication technology (Reduan, et al., 2010). In this model, prepaid meters were equipped with two-way communication ability, allowing for the transfer of data to and from utilities. With this ability, purchased energy units from vendor stations were wirelessly transferred via WiMAX to the meter without the consumer necessarily making a return trip to activate his/her meter. As such the issue of round trips which often wastes consumers' precious time was efficiently dealt with. The nature of this model did not require the use tokens as a means of transferring purchased units from the vending point to the meter. Equipped with this wireless technology, cashless payment methods were adopted for the purchase of energy units. Some of these payment methods included the use of online payment platforms, direct debit transfers and mobile payment platforms. While using these payment platforms, the consumer could buy energy units without the inconvenience of waiting in long queues or even coming to the vending store. It is therefore evident that the inclusion of a communication technology in this prepaid metering model efficiently dealt with the identified inconveniences (Reduan et at., 2010).

S. Arun et al also researched on a similar prepaid energy meter which was equipped with ZigBee communication technology (Arun, Krishnamoorthy & Rao, 2011). This technology allowed it to deal effectively with the above-mentioned inconveniences by providing wireless means of purchasing and loading energy units just as was done in Reduan H. Khan's research (Reduan, et at., 2010; Arun et al,. 2011). However, the WiMAX technology used in the former allowed it to communicate over longer distances than the later. Data to be transferred over beyond 100 meters required that data be sent to concentrators or retransmitted by connected neighbouring meters. However, it required less power and therefore was ideal for this application area which had limited power resources (Chung & Shiang, 2010).

Mart´ınez-Cruz and Carlos Eugenio also designed a low-cost Wi-Fi based electric energy prepaid meter (Cruz & Carlos, 2014). This meter performed the basic functionality of calculating power consumption and electric energy demand using a suitable microcontroller. Similar to the previous two designs, their design was also equipped with two-way communication ability. Through the use of Wi-Fi, it was capable of sending and receiving meter data to and from utilities. The use of this communication technology required the installation of Wi-Fi routers in areas where these meters were deployed. These routers were only accessible by meters within a 100-meter proximity (29). This required that the utility carefully positioned these routers in order not to lose any transmitted data. Also, because this wireless communication technology has the inherent flaw of poor penetration through concrete walls, it was important that the utility circumspectly placed these meters in consumers' premises (ERI, 2013).

From the above reviewed literature, it is discernible that different communication technologies have been applied to provide the solutions to earlier mentioned inconveniences. All the different approaches solve the problem amply (Parmar et al, 2014; EWO, 2014; Reduan et al., 2010; Arun et al., 2011, Chung et al, 2010; Cruz & Carlos, 2010). However, it is important to carefully ascertain whether these approaches are feasible in te Ghanaian setting. These different communication technologies require different initial conditions before these approaches can be a success. For example, the Wi-Fi based prepaid meters required the installation of Wi-Fi routers to facilitate the transmission of data (Cruz & Carlos, 2014). Also, Reduan H. Khan's WiMAX based prepaid metering model required the enabling WiMAX network infrastructure (Reduan, 2010). Utilities in Ghana could select any of these approaches, however the enabling communication infrastructure must be installed before deploying the prepaid meters. This process would both require financial resources and time. It is therefore important that the utility selects an approach which would require the least resources and setup time – a low-cost quick implementation scheme. In the next section, the research discusses various wireless communication technologies in an attempt to settle on one which would require the least investment of financial resources and setup time.

2.3 Wireless Communication Technologies in Ghana

The benefits of communication technologies to an economy are enormous; leading to sustainable socioeconomic development and social inclusion (Pikas, 2006). It is for these reasons that Ghana together with many Ghana have taken several initiatives to set up communication technologies to link up all areas of their nations. These initiatives have undoubtedly led to an increase in penetration rate of internet (Wikipedia, 2016). These communication technologies can be described as either being wired or wireless in nature. Wired communication technologies in Ghana include Powerline Communication (PLC) and Landline. Examples of wireless communication technologies deployed in Ghana include Wi-Fi, WiMAX, CDMA and GSM (ERI, 2015; Wikipedia, 2015).

Currently in Ghana and the rest of Africa, wireless communications have higher penetration than wired ones (Bruijin, 2009). For example, in 2012, statistics show that Ghana had only 285,000 landline users as against 25,600,000 mobile cellular users (Wikipedia, 2015). In other words, the landline density was just 1% as against 99% for mobile cellular user, thus showing the preferred choice of most Ghanaians. This low penetration rate could possibly have resulted from the high expenses one has to incur to own a landline as well as the immobile nature of the technology (ERI, 2015). Power line communication has also suffered such poor market penetration in Ghana and some of other Ghana because of its lack of interoperability and nonuse of open standards as well as its poor tolerance to noise (ERI, 2015).

Despite the fact that wireless communication technologies are most preferred not all are widely deployed in Ghana. Currently in Ghana the most pervasive wireless communication technology is GSM (GSM, 2015). It covers more than 70% of the nation's population, thus making it highly available. It has been around for more the three decades and as such it enjoys the benefits of long term use. This long-term use can be reinterpreted as being tested and tried to reliably transmit data wirelessly. Also as a result of keen competition among providers its service, cost of communication has been fast-dropping (Parmar, 2014). All these advantages cannot be said about the other three aforementioned wireless communication technologies – Wi-Fi, WiMAX and CDMA (ERI, 2015; NFC, 2015). These wireless communications, though deployed in Ghana, do not have high market penetration. For example, in Ghana there is only one Mobile Network Operator (MNO) that provides communication over CDMA (Expresso Telecom, 2016). It is also important to mention that this MNO has the least number of mobile subscribers (Mubarik, 2016). CDMA's suitability for only short bursts of data as well as its incomplete area coverage are part of the reasons behind its low market penetration. WiMAX and Wi-Fi on the other hand, have not been widely deployed in most areas in Ghana (Mirjam, 2009) (Ken et al. 2006; Su & West, 2012). As such, they also have limited coverage over the entire Ghanaian population. With very few providers of their communication service, data rates are still more expensive than using GSM (Mirjam, 2009). The ground work for the deployment of ZigBee communication infrastructure in Ghana is still being done, hence there is very scanty data concerning its usage (Smartgrid, 2015). It can therefore be said that it has also suffers from low market penetration.

The communication based solutions proposed in the reviewed literature for tackling the earlier identified inconveniences of the current prepaid metering systems in Ghana used either ZigBee, Wi-Fi or WiMAX (Parmar et al, 2014; EWO, 2014; Reduan et al., 2010; Arun et al., 2011, Chung et al, 2010; Cruz & Carlos, 2010). From the above discussions, it is clear that these communication technologies are not widely deployed in Ghana and therefore it would be difficult, if not impossible, for a utility to deploy any of these proposed solutions nationwide. To do so would require considerable effort, financial resources and time to install the enabling communication infrastructure before deploying their proposed prepaid meter designs. A low-cost quick adoption scheme would be to use an existing communication technology which spans over a larger percentage of the nation's population. Doing so would require less effort, less financial investments and time. In the earlier paragraph, it was established that GSM is the most pervasive communication technology in Ghana (Smartgrid, 2016; GSM, 2015). As such designing prepaid metering systems that communicate via GSM would not only effectively deal with the inconveniences of the current system, but also be a cost-effective solution. Therefore, the research would incorporate GSM communication technology in its proposed prepaid meter design.

SUMMARY

In this chapter, the benefits of prepaid metering systems over postpaid meters are revisited. Also, the inconveniences associated with the current deployed prepaid metering system in Ghana is discussed. Literature is reviewed in an attempt to find possible solutions to these inconveniences. It is observed that the addition of communication technology to a prepaid metering system could solve the identified challenges. Finally, a discussion is made for the choice of communication technology that would be a best fit for Ghanaian utilities.

CHAPTER THREE

RESEARCH METHODOLOGY

This chapter presents guidelines of a Design Science Research Methodology (DSRM) which is adopted for this research. Section 3.1 introduces the prescribed steps of DSRM. Sections 3.2 to 3.4 discusses the system analysis and design stages of the adopted methodology. Also, justification is made for the selection of various components used in the system design.

3.1 Design Methodology

The Design Science Research Methodology (DSRM) is one of the most preferred methodologies in research areas that border on Information Technology (Ken et al. 2006). Its overall objective is to provide essential principles for guiding the design of technology based artifacts which have improved performance, user-friendliness and additional functions over other existing artifacts. The artifacts designed by these guidelines have addon features which the existing artifacts do not have (Ken et al. 2006). Since the objective of this research is to improve the existing prepaid energy meter; similar to the overall objective of the DSRM, this methodology has been adopted for the design of the proposed system.

The prescribed guidelines of DSRM are outlined below:

1. Relevance Identification
2. Comparative System Analysis
3. Design and Development
4. Comparative Evaluation
5. Communication

A brief introduction of how each of these guidelines is followed in this research is provided in the following subsections.

3.1.1 Relevance Identification

In identifying the relevance of this research, sufficient justification has been provided in the preceding chapters. These chapters covered the significance of the study by identifying the gap in literature that the research attempts to address. Also, the benefits that consumers and utilities stand to achieve from this research have been clearly established.

3.1.2 System Analysis

This guideline requires that the existing system to be improved be studied and juxtaposed to the final artifact to be produced. This is done in order to identify sub-units, functions and algorithms in the existing system which would require improvement. Going by this guideline, a wide range of existing standalone digital prepaid energy meters that are currently deployed in Ghana would be studied. The functions and sub-units of these meters would be compiled.

3.1.3 Design and Development

In this step, an improved artifact is designed comprising the identified sub-units and functions that are missing in the existing standalone prepaid energy meter. A critical process which greatly influences the design of the improved prepaid energy meter is the method of embedding the identified necessary additional functions. As stated earlier, this research seeks to provide an efficient communication technology solution based on GSM. It is therefore important that this feature addition deals effectively with the problems identified without negatively affecting the standard functions of the prepaid energy meter – which is basically to accurately measure energy consumption. However, this method should not significantly increase the cost of producing the new improved meter.

3.1.4 Comparative Evaluation

This guideline suggests that the newly improved system should be compared with a standardized prepaid meter in terms of performance. This is to verify if the design process achieved the set objectives. In this research, it is important that these tests are done in the light of the identified gaps in literature in order to ascertain if these gaps have been sufficiently addressed.

3.1.5 Communication

In this step, the problem the improved system solves, its significance, design and development process and results from comparative evaluation must be communicated to a relevant audience.

3.2 Existing System Analysis

As mentioned above, the relevance for the research has already has been well established. As such, the next guideline from the DSRM to be tackled is the analysis of the existing standalone prepaid energy meter. In order to achieve this, four kinds of prepaid standalone energy meters which were deployed to homes and industries by Electricity Company of Ghana (ECG), the main electricity distribution company for southern Ghana, were critically studied. These meters provided the following basic functions:

1. Measurement of energy consumption in kilowatt-hours and in currency.
2. Periodic measurement of power quality (e.g. Voltage, Phase Angle, Current, etc.)
3. Automatic (dis)connection of power based on the amount of energy units left
4. Display of energy consumption in kilowatt-hours and in Ghanaian currency
5. Display of power quality measurements

Figure 3.1 shows the prepaid standalone industrial and residential meters which were understudied.

Figure 3.1: Standalone Prepaid Energy Meters Deployed by ECG

From the above listed functions, it is clear that these existing prepaid meters have no communication abilities, the bane of the earlier identified problems.

3.4 System Design And Development

Adhering to the guidelines of DSRM, after having established the functions and features of the existing standalone prepaid energy meter, the next step is to design and develop the proposed improved energy meter. In the subsections that follow the stages of design and development are presented.

3.4.1 Requirement Specification

To have a clearer definition of the improved meter's basic functional requirements, use cases are employed in eliciting these requirements. These help to present in natural language (unambiguous terms) the expectations, goals and benefits of the system to the major actors/stakeholders, namely consumers and utilities (Distributing Companies and Power Generating Stations). These use cases are presented in Figures 3.2 and 3.3.

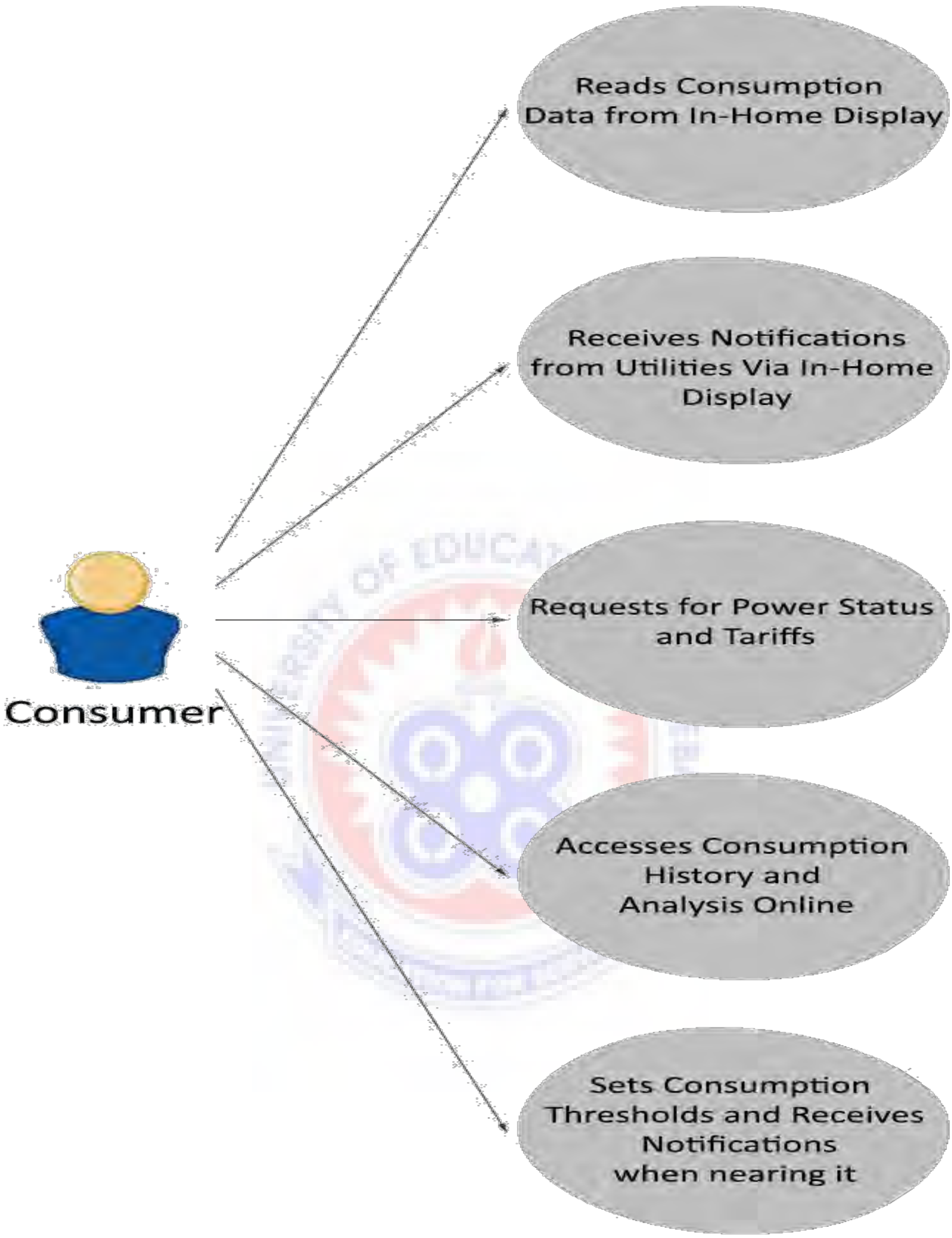


Figure 3.2 Consumer Use Case

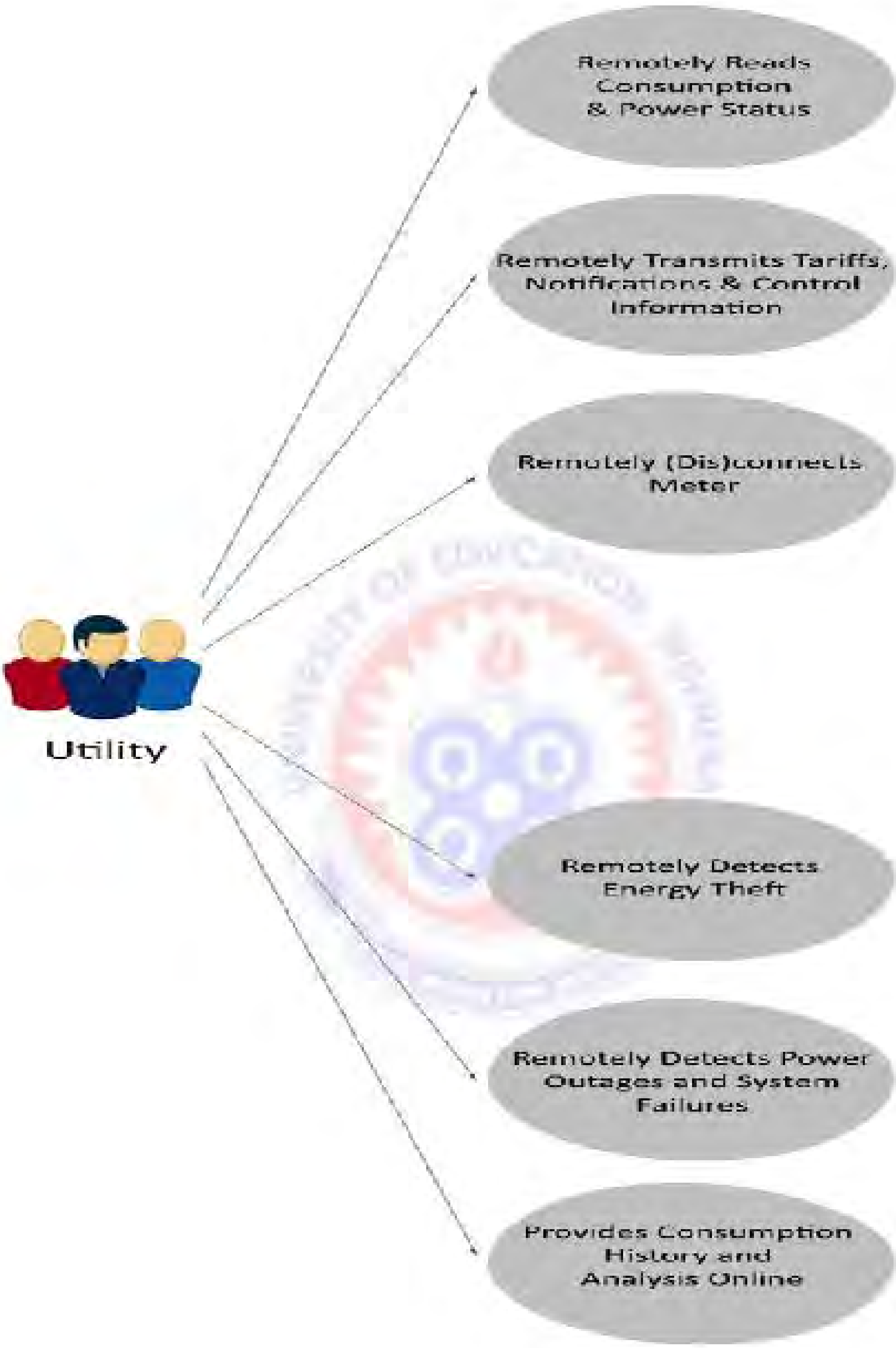


Figure 3.3 Utility Use Case

Based on the use cases provided above, the functional requirements of the improved energy meter can be summarized as follows:

1. Measurement and display of accurate consumption data in kWh and currency via in-home display.
2. Measurement and display of accurate power quality characteristics.
3. Real-time remote transfer of purchased units via mobile and web platforms
4. Reception and display of utility transmitted notifications and control information.
5. Real-time transmission of accurate consumption data and power quality measurements to utilities.
6. Real-time detection and remote reporting of meter tamper.
7. Remote disconnection and reconnection of power supply by authorized stakeholders.

The requirements provided above give an idea of the necessary building blocks of the improved prepaid energy meter. Also, a careful look at these functional requirements reveals the inclusion of essential remote utility services. These features and services, such as the remote and real-time detection of meter tamper and transmission of consumer notifications, are feasible by virtue of the addition of an efficient communication technology.

3.4.2 Building Blocks of the Improved Meter Design

From the above functional requirements and research objectives, the following components described in Table 3.1 have been identified as essential building blocks of the improved energy meter design. These would embellish the existing prepaid meter with the necessary features needed to achieve a feasible solution for the identified problem. Figure 3.4 shows a diagram of the basic interconnections between the selected components

Table 3.1 Building Blocks of Proposed improved prepaid energy meter

No.	Name	Function
1.	GSM/GPRS Communication Module	Provides reception and transmission of data messages to/from utilities.
2.	Liquid Crystal Display (LCD)	Displays consumption data, tariffs, power measurements, utility transmitted notifications and control information.
3.	Relay	Remote disconnection/reconnection of meter from/to power supply.
4.	Microcontroller	Programmed to handle all arithmetic and logical processes.
5.	Ball Rolling Switch (Tilt Sensor)	Energy Theft Detection Mechanism: Detects physical tamper of meter.
6.	Triple Axis Accelerometer	Energy Theft Detection Mechanism: Detects motion and shock.
7.	Hall Effect Sensor	Energy Theft Detection Mechanism: Detects external magnetic fields.
8	Current Sensor	Energy Theft Detection Mechanism: Detects meter bypass. Also required to carry out power quality measurements.
9.	Data Logger	Registers measurements from sensors at set intervals. Also keeps track of time.
10.	Speaker	Sounds an alarm to prompt user.
11.	Rechargeable Battery	Provides power to the proposed improved prepaid energy meter even during power outages.

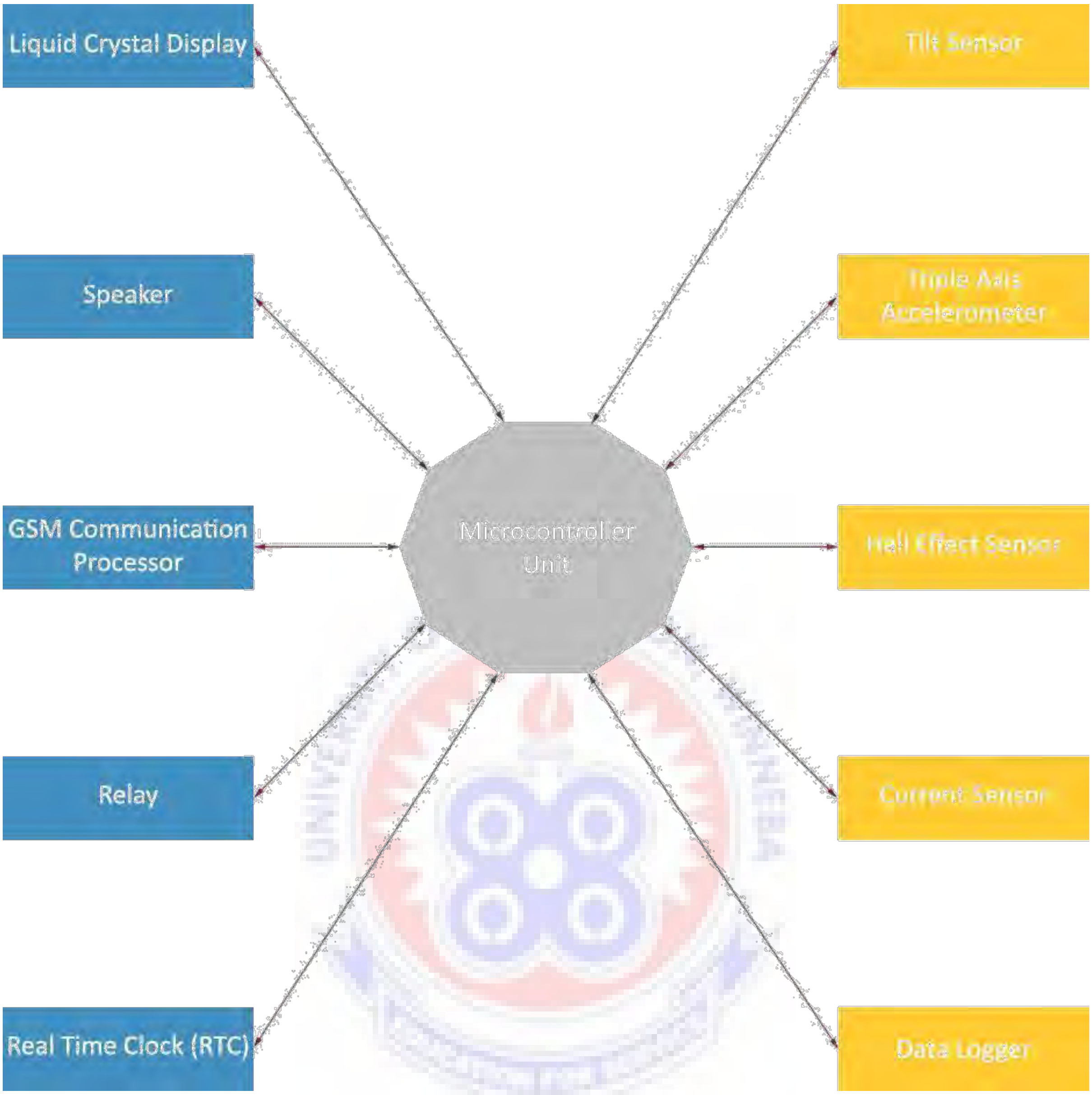


Figure 3.4 A Basic Block Diagram of Interconnecting Components

3.4.3 System Modelling

This section focuses on modeling the improved prepaid energy meter using flow chart diagrams to provide a structured representation of the system's essential functions and features. These representations are used to elicit the workflow of important system processes/services. These processes have been categorized into two groups; non-preemptive and preemptive processes.

The non-preemptive processes are high priority tasks which when scheduled to take place, execute without fail or interruption. If at the scheduled time of execution, a process of a low priority is being executed, it is interrupted briefly for the high priority task to execute. The only time a non-preemptive process is interrupted is when another non-preemptive process of a higher priority than the current process has been scheduled to run. In other words, non-preemptive tasks have different classes of priority. Preemptive tasks on the other hand can always be interrupted and resumed later, where need be.

On most microcontrollers, there are a number of digital pins that can be assigned to non-preemptive tasks. It is important to identify the total number of non-preemptive functions in this application area in order to select a suitable microcontroller which allows for that number of interrupt service routines (ISR). After critical analysis of the improved prepaid energy meter functional requirements, detection of energy consumption and energy theft have been identified as essential non-preemptive processes. Table 4.7 presents the list of identified non-preemptive functions and their level of priority.

Table 3.2 Interrupt Allocation Table

	Function	**Level of Priority**
1	Detection of energy consumption in kWh	0
2	Detection of motion and shock with Triple Axis Accelerometer	1
3	Detection of external magnetic fields with Hall Effect Sensor	2
4	Detection of physical tamper of meter with Ball Rolling Switch	3

So, from Table 3.2 it is evident that the detection of drawn out current in order to ascertain consumption is deemed the most important task of the proposed improved prepaid energy meter. Three of the energy theft detection mechanisms are also assigned other interrupt pins. However, a fourth energy theft detection mechanism which uses the Current Sensors to detect meter bypass has not been included. This is because this mechanism requires some computation and comparison of current readings measured from the live and neutral lines before ascertaining if there has been a bypass or not. When the readings are approximately the same no bypass is detected, as such this mechanism cannot be assigned to interrupt each time readings are to be taken.

Power quality measurements and processing of received control information and notifications from the utility have been identified as preemptive tasks/processes. Figure 3.5 illustrates the basic workflow of the improved prepaid energy meter in performing these categorized tasks/processes.

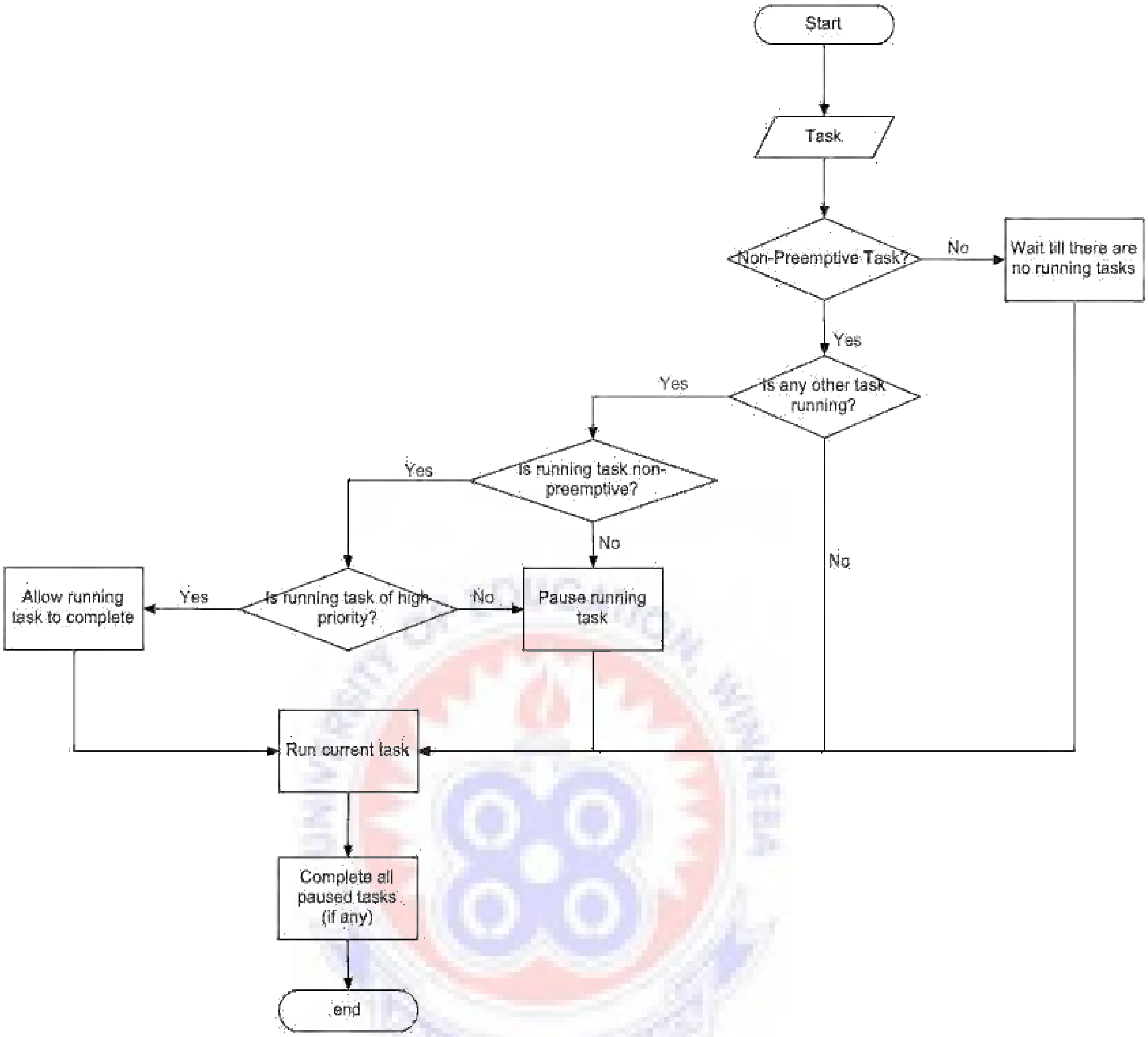


Figure 3.5: Task Execution Workflow

The workflow of each of these identified system functions are illustrated in Figures 3.6 to 3.8.

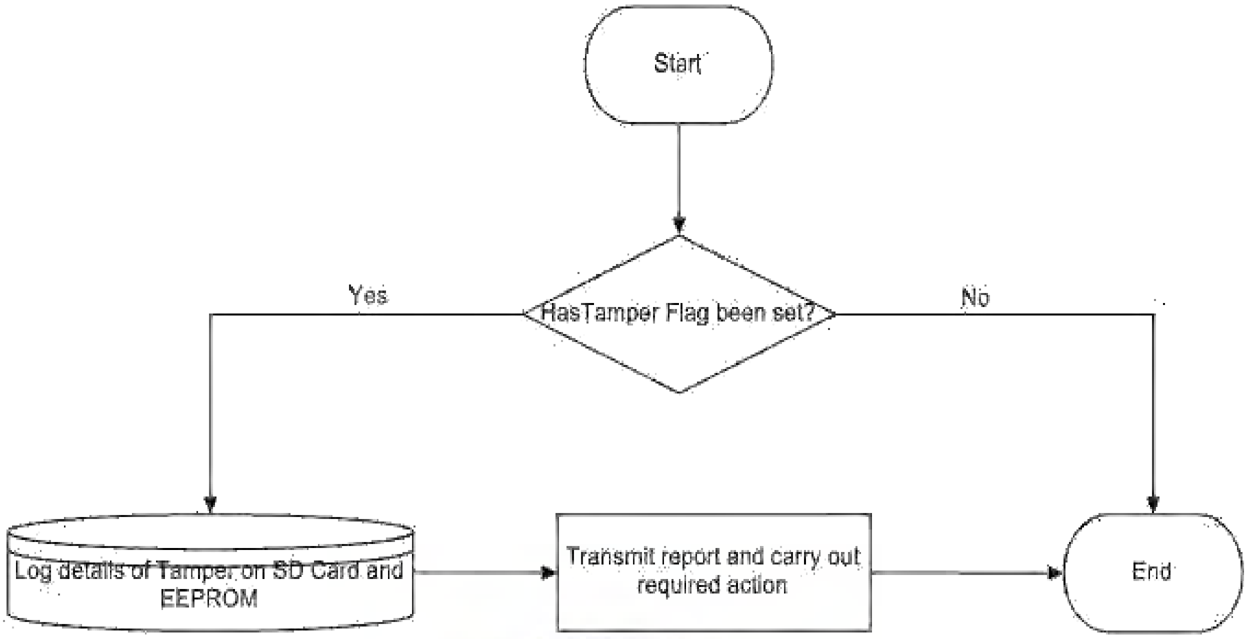


Figure 3.6: Energy Theft Detection

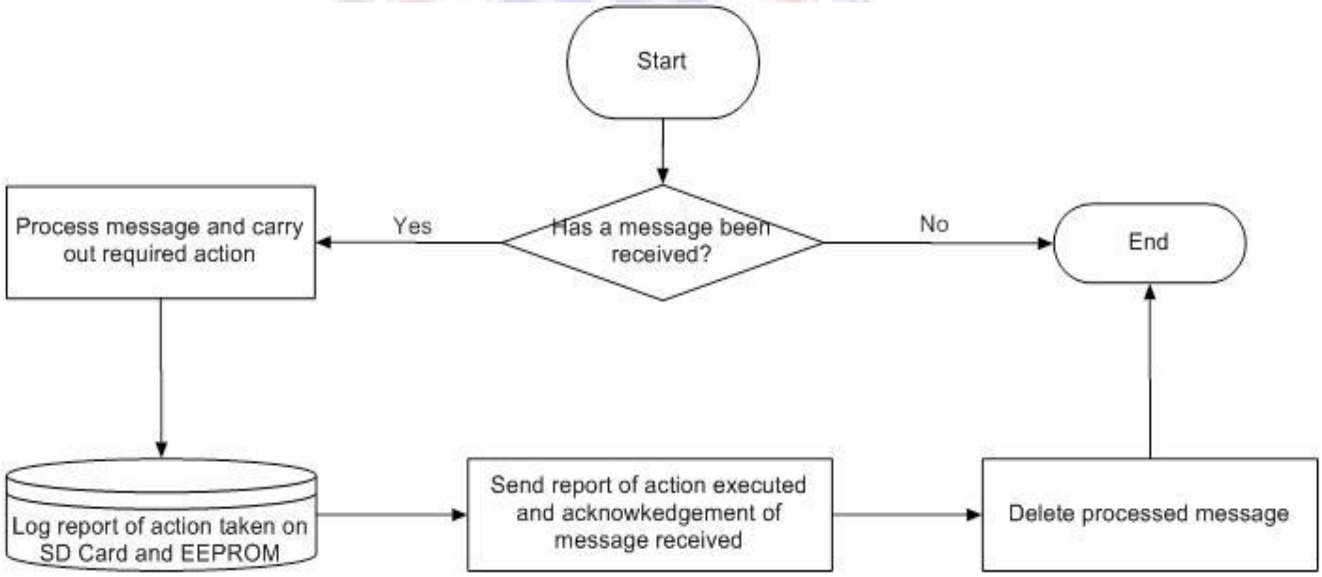


Figure 3.7 Processing of Transmitted Utility Messages/Notifications

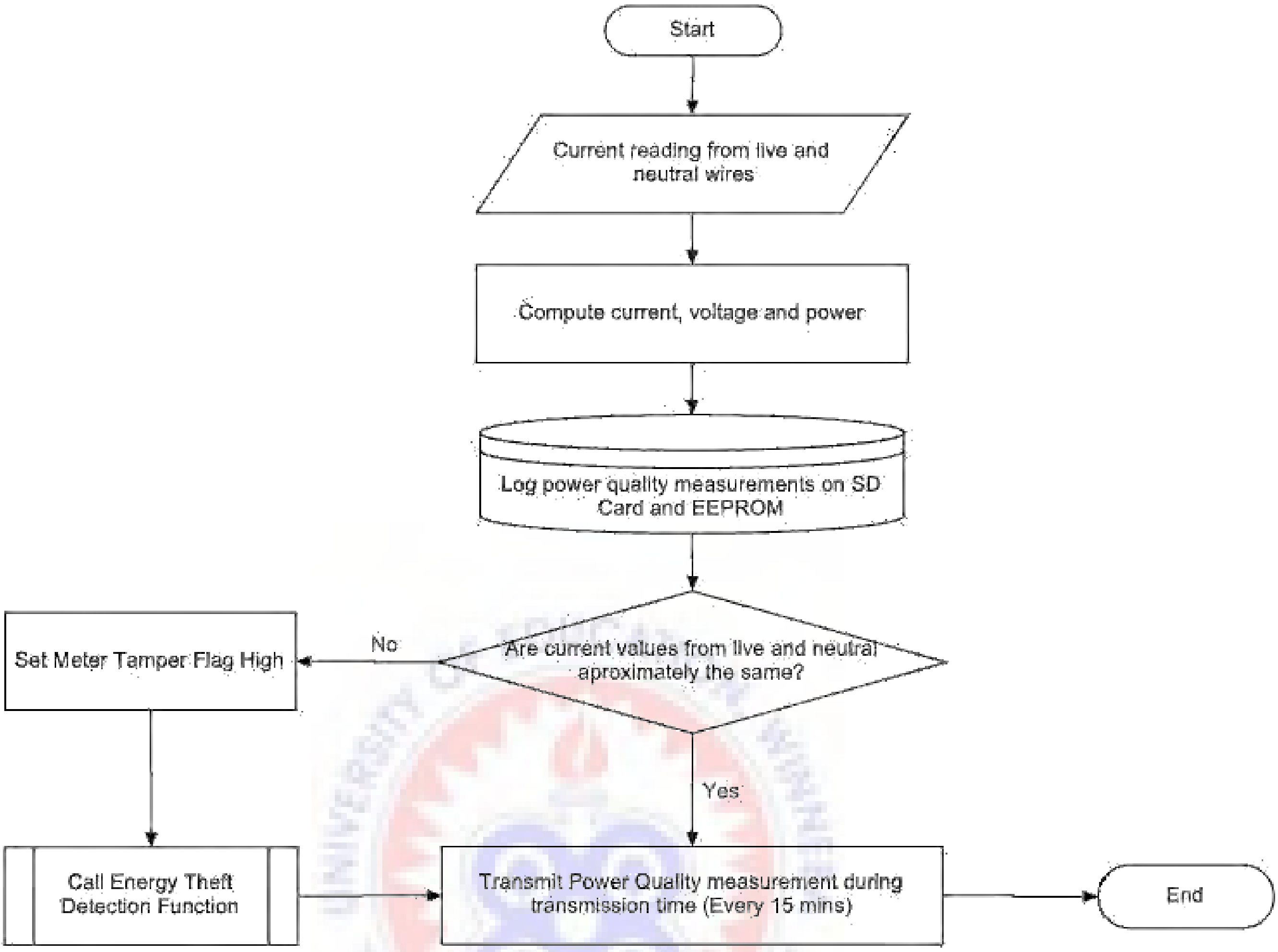


Figure 3.8: Power Quality Measurements

The above workflows serve as an essential guide in modeling the improved prepaid energy meter. Based on these workflows the appropriate system code, simulation and schematics are developed and presented in the sections that follow.

3.4.4 Component Selection

The list of suggested components presented in the previous chapter for the implementation of the proposed improved prepaid energy meter design, were more general than specific. In this section, specific components are selected for the design of the proposed improved prepaid energy meter. Similar to the selection process used during the interface design, these components have been carefully selected on the basis of performance-to-cost ratio, availability, mode of operation and robustness. Additional justification is provided in the subsections below to buttress their suitability.

3.4.4.1 GSM/GPRS Communication Module

A key function of the proposed meter is the transmission of meter data and the reception of control information from its designated utility. This control information includes the purchased energy units remotely transmitted to top-up the energy units of the meter. These operations require the incorporation of a two-way communication ability into the system design. The choice of the communication technology to be used for the proposed improved prepaid energy meter has been based on the comparisons made in Chapter Two on the various plausible communication technologies for prepaid energy meter deployment in Ghana. From the comparisons, it was quite obvious that the features of GSM made it a more likely option for implementing the proposed improved prepaid energy meter. It is highly available, highly reliable and cost effective.

Based on these favourable features, a GSM/GPRS communication module is sought for in the implementation of the proposed improved prepaid energy meter. A wide range of such modules exist. Common among these include: Sim300, Sim800 and Sim900 GSM/GPRS Communication modules. Of these three, Sim900 is the most recent module and has upgraded features which are superior to the other two modules. Some of these features include:

1. Support for GSM/GPRS/EDGE Quad band (850/900/1800/1900 MHz)
2. Low Power Consumption (1mA during sleep mode)
3. GPRS (data) downlink rate of 85.6 Kbps
4. Support for Packet Broadcast Control Channel (PBCCH)

Based on these desirable features, a GSM/GPRS TTL UART Sim900 Communication module was selected for the proposed improved prepaid energy meter implementation. To further justify the selection of this component, diagnostic tests were carried out on this module using an online browser based AT Command Tester, accessible via the uniform resource locater http://m2msupport.net/m2msupport/module-tester/. Using standard AT commands, various tests were carried out with the module to ascertain the following:

1. Network Registration status
2. Signal Strength
3. Hypertext Transfer Protocol (HTTP) GET and POST

All conducted tests were successful and produced desirable results. These results are presented Figures 3.9 – 3.10.

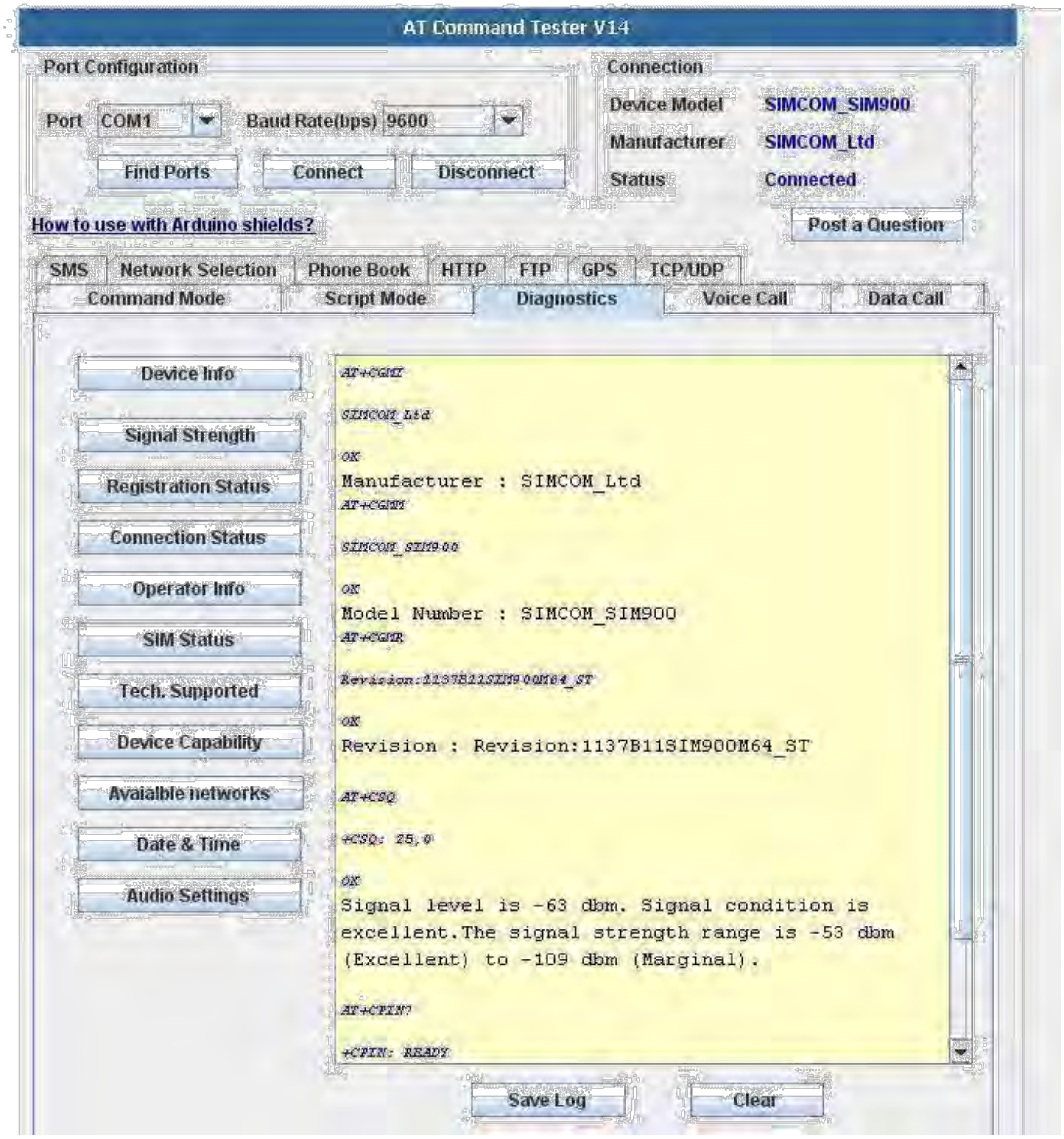


Figure 3.9 Diagnostic Test to Ascertain Signal Strength and Registration Status

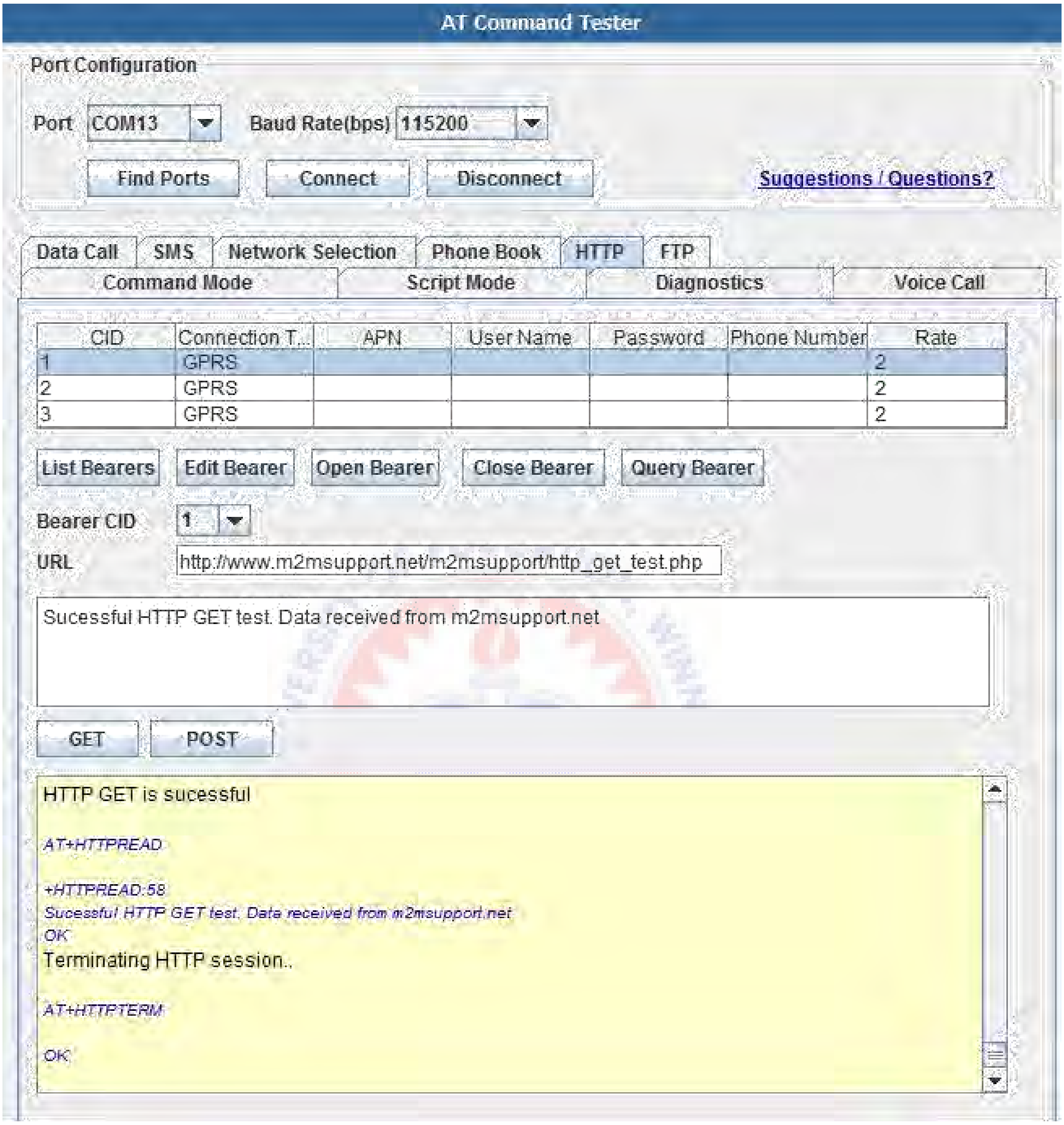


Figure 3.10 Diagnostic Test to Test for HTTP functionality

These results justify the selection of this Sim900 module for the implementation of two-way communication in the proposed improved prepaid energy meter.

3.4.4.2 Liquid Crystal Display (LCD)

This component is responsible for displaying consumption data both in kWh and currency as well as tariffs, utility transmitted notifications and power quality measurements. This in-home display is essential in providing the consumer with direct feedback necessary for consumption behavioural change. The following LCDs are options for the provision of this function in the proposed improved prepaid energy meter:

1. 16x2 Character Display
2. 20x4 Character Display
3. 128x64 Graphic Display

The above-mentioned displays are listed in order of increasing size (display area) and cost. Among the three, it is only the 128x64 Graphic Display which is capable of displaying graphics of sizes greater than 5x7 pixels. The other two displays are more suitable for displaying text and small icons. Considering the nature of information presented here, displaying of graphics is not a priority; as such a Character Display would do. The 16x2 Character display can only present 32 characters at any point in time while the 20x4 displays a maximum of 80 characters. Thus, the latter can present more information at a go than the former. Since it is more convenient to present consumer notifications on a single page than in multiple pages the 20x4 is preferred for the proposed improved prepaid energy meter design.

The specific 20x4 Character Display selected for the design is the Xiamen Ocular GDM2004D LCD model. It has the following features:

1. LED Backlight to illuminate screen especially in darkness
2. +5 volts power supply

3. Expected lifetime of ~50,000 hours
4. Adjustable contrast
5. Operational Temperature range of 0~+50 ºC

Its low input voltage can be supplied by a microcontroller; thus, not requiring the addition of any external power source. Also, it illuminates brightly in the dark which makes its displayed characters legible for consumers. These features justify the selection of this LCD for the implementation of the proposed improved prepaid energy meter in-home display.

3.4.4.3 Relay

In the proposed improved prepaid energy meter design a relay is included to handle remote requests from the utility to either disconnect or reconnect the meter to power supply. Utilities could also allow consumers to request such services. Two types of relays are capable of this function. They are

1. Solid-State Relays (SSRs) and
2. Electromechanical Relays (EMRs).

SSRs are made of non-moving electronic parts and as such usually have longer lifespans than EMRs; hence they are mostly preferred in applications where switching would be done often – more than 10,000 times. Unlike EMRs, they are silent in their operation and consume very small power. Also, they do not produce any sparks when they switch; thus, making them ideal in highly flammable applications. Despite their several advantages, they suffer the disadvantage of not being able to completely switch off or on. In either state, there is always some amount of resistance present in the semiconductor. This makes them to easily heat up thus requiring the addition of active or passive heat sinks. The on-state resistance can cause some measure of voltage drops, which is highly undesirable in voltage critical applications.

Also, the off-state resistance causes more current than required, also known as leakage current, to flow to the connected load. This would add to the user's consumption; which is very undesirable in this application area.

For EMRs, their contacts would get stuck together or get oxidized if they are connected to loads higher than their power requirement. This can be avoided if the right EMR is selected to match the connected load. Based on their mode of operation, EMRs may cause some little electromagnetic interference if there are any perforations in their casing. This is however not a major problem if these devices are properly covered and distanced from likely affected components.

From the comparisons made above, EMRs are more ideal in this application area hence are included in the proposed improved prepaid energy meter design. The specific EMR model used in the design is the Songle Single Channel 5V 30A High Power Relay Module. It has the following key features:

1. Can switch 220 volts AC loads
2. 5 - 12 V transistor-to-transistor logic (TTL) control
3. Maximum Switching Current of 30A

This component also has a low input voltage hence can be easily connected directly to the centralized microcontroller. Its ability to switch high power AC loads makes it a viable choice for switching the power mains connected to either a single-phase or three-phase energy meter.

3.4.4.4 Microcontroller Unit (MCU)

As described in previous sections, the microcontroller unit is the centralized hub for all logic and arithmetic operations. It serves primarily as the main processing engine of the proposed improved prepaid energy meter; processing all data that comes from the interconnecting components. Therefore the selection of a microcontroller was influenced mainly by the anticipated processing power requirements, number of interconnecting digital and analog components, total number of non-preemptive processes and memory requirements. The following MCUs were identified as plausible options for the design of the proposed improved prepaid energy meter:

1. PICAXE
2. Arduino
3. Raspberry Pi
4. BeagleBone

The list provided above is in increasing order of cost, computation power and size. Although PICAXE is the least expensive it is limited in so many areas. For example, of all the MCUs presented it requires the inclusion of a lot more hardware for any basic setup. It also has the least online support and libraries; thus, requiring more effort from the user and reducing its versatility.

Arduino and Raspberry Pi have the largest online support and libraries. They are also the most used because they are relatively cheaper than BeagleBone which is 3 times the price of an Arduino. Raspberry Pi and BeagleBone run on Linux Operating System (OS) and are equipped with a 700 Megahertz (MHz) processor; these make them fully fledged computers.

Arduino's Integrated Development Environment (IDE) and 16MHz processor however do not give it such functionality. However, its low computational speed implies that low power is required; which is highly desirable for battery powered systems such as the proposed improved prepaid energy meter. In addition, unlike Raspberry Pi, Arduino has analogue input ports which are a basic requirement for operating some of the energy theft detection sensors. So in short, Arduino is the most ideal MCU for the proposed improved prepaid energy meter design. The Arduino board used in the proposed improved prepaid energy meter design is the Arduino Mega 2560 Revision 3 model. It has the following features:

1. 54 digital input/output ports
2. 16 analog input ports
3. 4 Universal Asynchronous Receiver/Transmitter (UART) ports
4. 16 MHz Crystal Oscillator
5. Operating Voltage of 5V
6. 4 kilobyte EEPROM
7. 6 External Interrupt
8. Resistance of Hazardous Substances (RoHS) Compliant

These features are copious enough to facilitate the implementation of the proposed improved prepaid energy meter. The four earlier identified non-preemptive processes can be assigned to any of the six external interrupt pins. The remaining two unassigned interrupt pins as well as all other unused digital and analog pins are available for future upgrades. Table 3.3 presents a list of the available interrupt pins, their assigned non-preemptive processes and level of priority.

Table 3.3 Interrupt Allocation Table

Function	Pin Number	Level of Priority
Detection of energy consumption with current sensor	2	0
Not Assigned	3	1
Detection of motion and shock with Accelerometer	21	2
Detection of external magnetic fields with Hall Effect Sensor	20	3
Detection of physical tamper of meter with Tilt Sensor	19	4
Not Assigned	18	5

Alluding to standard identified methods of energy theft, the next few subsections describe sensors which have been carefully selected to detect these felonious activities whenever they occur.

3.4.4.5 Tilt Sensor

The tilt sensor's main function is to detect energy theft by physical tamper of the meter. It triggers the MCU when an attempt is made to move a part or the whole meter. The MCU would then transmit a tamper report to the utility via the GSM/GPRS communication module.

It was discovered that a simple ball rolling switches can implement this function. This switch contains a steel coated ball which closes a switch whenever it is tilted. An AT407 Ball Rolling Switch was therefore incorporated into the proposed improved prepaid energy meter's design. It was selected because it has very low input voltage of 5V and low operating current of 6mA; hence can be connected directly to the MCU.

3.4.4.6 Triple Axis Accelerometer

Magnetometers, Gyroscopes and Triple Axis Accelerometers are all capable of detecting changes in acceleration or shock, hence can be used to detect meter tamper. However, the gyroscope and magnetometer have some inherent flaws or limitations. Since the magnetometer detects motion based on its relative position from the earth's true magnetic north its readings are susceptible to errors when magnets are brought into its field. Also, gyroscopes are only accurate when used over very short periods of time. The Triple Axis Accelerometer is however not affected by these limitations. As such, the ADXL337 Triple Axis Accelerometer was included in the proposed improved prepaid energy meter's design to also detect physical meter tamper. It has the following attributes:

1. Ultralow Power
2. Operating Current of 300 micro amps (μA)
3. High Resolution
4. Wide voltage range (1.6~3.5 V)

These features, which are similar to the earlier selected components, are desirable for MCU applications. They can be easily attached to the MCU without the addition of external power sources or processors.

3.4.4.7 Hall Effect Sensor

This sensor is needed to detect energy theft caused by criminals who use strong earth magnets to cause electromagnetic devices in the meter to malfunction. It detects the presence of such strong magnets, triggers the MCU which in turn report to the utility via the communication module. A reed sensor is also capable of providing this functionality. However, it is often limited by its glass container and miniature size. The Hall Effect Sensor selected for the proposed improved prepaid energy meter design is the US1881 Hall Effect Sensor. It has the following features:

1. Ultralow power consumption
2. Reverse polarity protection

3. Wide Range Operational voltage (3.5~24 V)

4. Temperature compensation

3.4.4.8 Current Sensor

This sensor is required to measure the current in the live and neutral wires. Any significant difference in their values indicates the possibility of a meter bypass. Also, current measurements are necessary to evaluate the quality of supplied power. An ACS715 Hall Effect Based Linear Current Sensor is employed for this purpose in the proposed improved prepaid energy meter design. It has the following key features

1. 2100 V root mean squared (VRMS) isolation voltage

2. Operates at 5V

3. Capable of measuring up to 30A of current

4. Operational temperature of -40~150 ºC

5. Little or no magnetic hysteresis

This current sensor is a viable current measuring component for the proposed improved prepaid energy meter because it is capable of measuring high currents even at high voltages while operating at a low input voltage.

3.4.4.9 Data Logger

This electronic device records data such as consumption data, meter tamper data, power quality measurement and tariffs unto a local storage medium. Equipped with a real-time clock (RTC), each data entry is time stamped. This serves as a contingency plan for utilities; in case there is a communication failure meter data is stored locally and retransmitted later after the problem has been resolved. The following electronic devices are capable of providing this function:

1. SparkFun OpenLog
2. Adafruit Data Logging Shield

Although they are both capable of performing the same function, the latter is less expensive and requires addition of less hardware. It is also easier to assemble and customize to meet different installation requirements. Unlike the former, it has a slot for Secure Digital (SD) storage card as well as a battery which keeps the RTC running even after power is disconnected. These are the reasons why the Adafruit Data Logging Shield was included in the proposed improved prepaid energy meter's design. It has the following key attributes:

1. Saves data to a formatted File Allocation Table 16/32 (FAT16/32) storage SD card
2. Support for a majority of the Arduino boards
3. Onboard 3.3 V regulator safeguards SD cards from power surges

3.4.4.10 Speaker

This alerts a consumer by sounding an alarm when new notifications have been received from the utility, measured power quality is below standard or a user is about reaching his set threshold. There are a wide range of speakers that could be used in the proposed improved prepaid energy meter design. However, a Piezo Speaker was incorporated in the proposed improved prepaid energy meter design because of its compact size, low cost and ultralow power requirements. It has the following features:

1. Operational voltage: 3.5-5 V
2. Maximum current rating: 35 mA

3. Diameter: 12 millimeters
4. Operates in 2.048 kHz audible range
5. Sound output: 95 A-weighted decibels (dBA)

3.4.4.11 Backup Battery and Charger

A rechargeable backup battery is needed to supply the proposed improved prepaid energy meter with power at all times; especially during power outages. Without this battery, the proposed improved prepaid energy meter would fail to perform its function during such periods. Critical functions such as meter tamper and outage detections are to be recognized and reported in real-time to the utility and as such require perpetual supply of power to the proposed improved prepaid energy meter.

The following battery options are considered for the proposed improved prepaid energy meter design:

1. Lithium Polymer Ion (LiPo/ LiIon)
2. Nickel Metal Hydride (NiMH)
3. Coin Cell
4. Alkaline

From the list of batteries presented, LiPo batteries have the highest energy densities; most compact and having the highest capacity. They last longer than the others because they have an ultralow discharge rate. They are the most available and most used battery supply for electronic devices. Most LiPos are equipped with an internal circuitry to safeguard the battery from depleting below a certain threshold. They can be recharged with several low-cost chargers.

Based on these attributes a 6,600-milliamp-hour (mAh) Lithium Polymer Ion Battery fitted with a charger is included in the proposed improved prepaid energy meter design. This unit has the following features:

1. Nominal Voltage of 3.7 V
2. Maximum charging rate of 3A
3. Maximum depletion rate of 6A

After having described and justified the above components, Table 3.4 summarizes the selected components and their basic performing functions.

Table 3.4 Major Components for Proposed improved prepaid energy meter Implementation

No.	Name	Function
1.	Sim900 GSM/GPRS Communication Module	Provides reception and transmission of data messages to/from utilities.
2.	Xiamen Ocular GDM2004D 20x4 Liquid Crystal Display (LCD)	Displays consumption data, tariffs, power measurements, utility transmitted notifications and control information.
3.	Keyes 5V Electromechanical Relay Module	Remote disconnection/reconnection of meter from/to power supply.
4.	Arduino Mega 2560 Revision 3 model	Programmed Microcontroller to handle all arithmetic and logical processes.
5.	AT407 Ball Rolling Switch (Tilt Sensor)	Energy Theft Detection Mechanism: Detects physical tamper of meter.
6.	ADXL337 Triple Axis Accelerometer	Energy Theft Detection Mechanism: Detects motion and shock.
7.	US1881 Hall Effect Sensor	Energy Theft Detection Mechanism: Detects external magnetic fields.
8	ACS715 Hall Effect Based Linear Current Sensor	Energy Theft Detection Mechanism: Detects meter bypass. Also required to carry out power quality measurements.
9.	Adafruit Data Logging Shield	Registers measurements from sensors at set intervals. Also keeps track of time.
10.	Piezo Speaker	Sounds an alarm to prompt user.
11.	6,600 milliamp hour (mAh) Lithium Polymer Ion Rechargeable Battery	Provides power to the proposed improved prepaid energy meter even during power outages.

Detailed datasheet specifications of each of these components are obtainable from trusted online stores such as Adafruit, Digikey, Mouser and SparkFun.

3.5 SUMMARY

In this chapter guidelines are suggested for the design and development of an improved prepaid energy meter for Ghana. This improved meter has features that make it communicable as well as capable of detecting energy theft. Copious justification has also been provided for the selection of components required for the design of this meter.

CHAPTER FOUR
SIMULATION RESULTS, DISCUSSIONS AND COST ANALYSIS

4.0 This chapter presents the final schematic design of the proposed improved prepaid energy meter with communication and tamper detection abilities.

4.1 Simulation Of Improved Energy Meter

After having keyed out the specific components required for the implementation of the improved prepaid energy meter, the research progressed with circuit simulations. These simulations were done using ISIS Professional Software version 7.9 Service Pack 1. These simulations were carried out primarily to imitate the functions of the selected interconnecting components. This step is important in verifying the established functional requirements of the improved prepaid energy meter. It is however important to note that a few of the specified components were not available in the chosen circuit simulator. As such, suitable replacements were used to achieve the same functionality. The schematic of the circuit simulation is presented in Figure 4.1.

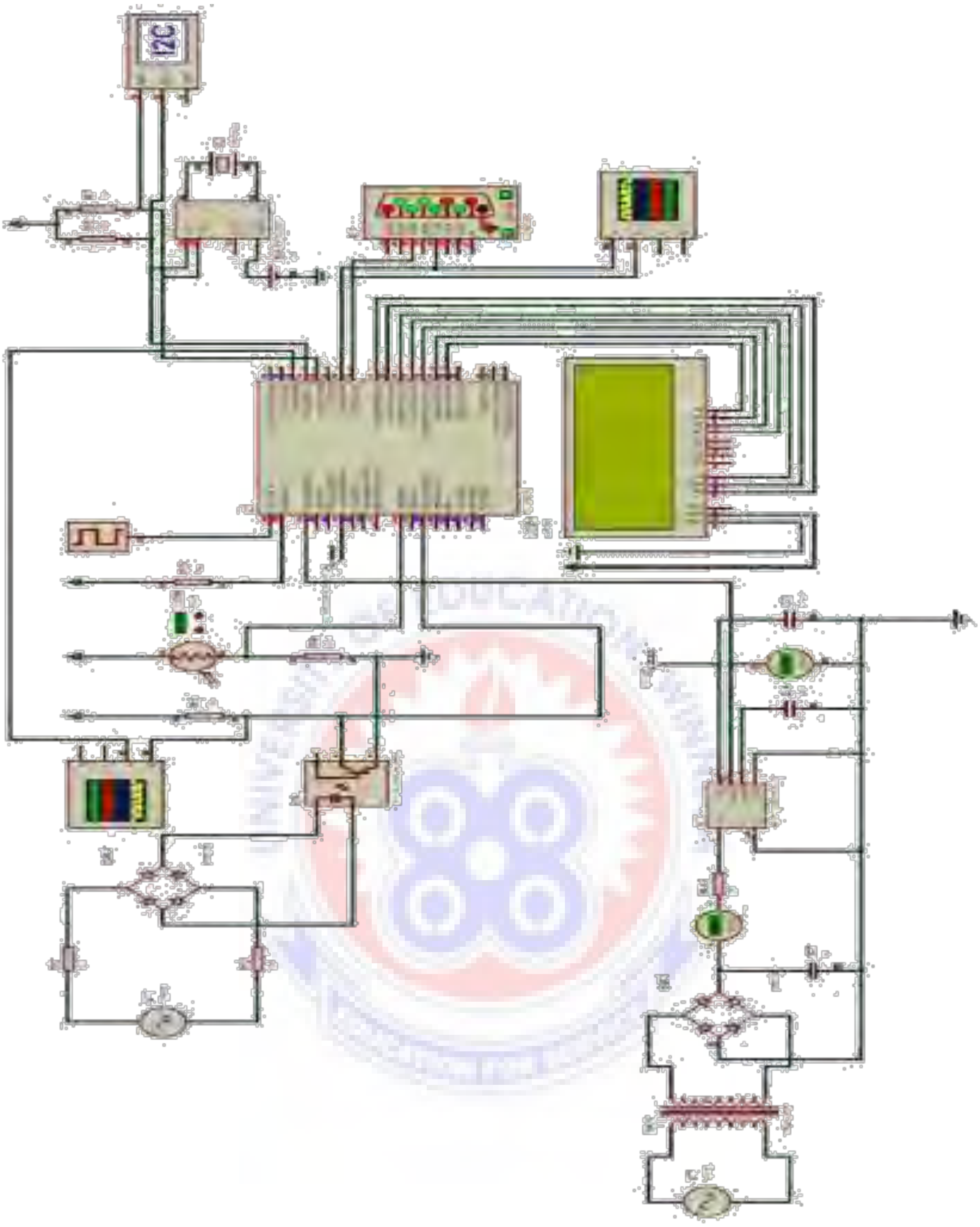


Figure 4.1 Schematic of Improved prepaid energy meter Circuit Simulation

During the circuit simulation, a program was written for the centralized microcontroller unit (MCU) to perform the required system processes. This program was written in C and compiled using a CCS C Compiler, Version 4.093. After compiling the code, a hex file was generated and loaded unto the centralized MCU. The written program is presented in Appendix A.

The simulation environment was designed to mimic features that pertain to the current electrical grid in Ghana. Key among the features includes:

1. A voltage supply of AC220 volts ±10%
2. Voltage signal supplied at a frequency of 50Hz
3. Power factor ranging between 0 and 0.9

The key performance indicators (KPIs) for this simulation are implicitly given as the basic functional requirements of the improved prepaid energy meter. These requirements were elicited in the previous chapter and are summarized below.

1. Display of accurate consumption data in kWh and currency via in-home display.
2. Reception and display of utility transmitted notifications and control information (including purchased energy units).
3. Real-time transmission of accurate consumption data and power quality measurements to utilities.
4. Real-time detection and remote reporting of meter tamper.
5. Remote disconnection and reconnection of power supply.

After having run the simulation over a period of time; providing it with input from the various connected components, the following observations were made:

1. The improved prepaid energy meter gathers consumption data by measuring the amount of current drawn using the ACS715 Current Sensor
2. Energy consumption is computed in kWh and stored in the MCU's EEPROM and logged on the SD Card

3. At the end of specific time periods; such as hour, day, week, month and year, the MCU computes the average consumption over the period and stores results in its EEPROM

4. Power quality measurements (voltage, current and active power) are taken using the ACS715 Hall Effect Based Linear Current Sensor.

5. The MCU stores the measured value and does various checks to find out if power supplied to the meter is of good quality. The MCU also checks to see if current measured on live and neutral lines have no significant difference. If they do, a meter tamper flag is set high and stored on the SD Card and EEPROM.

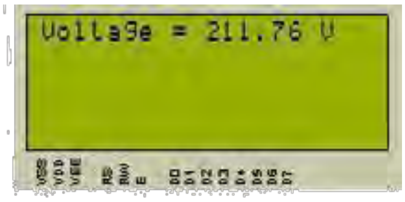
6. All the other connected sensors; Hall Effect, Accelerometer and Tilt sensors, interrupt the MCU when there is a significant change in state. The MCU then sets the tamper flag high on the SD Card and EEPROM.

7. All stored data are transmitted to the utility every 15 minutes via the GSM/GPRS module. However, registered tamper flags and poor power quality measurements are transmitted instantaneously.

8. The GSM/GPRS module alerts the MCU each time a message is received from the utility or customer. The MCU processes the message and carries out the required action. For example, upon request of a top-up of energy units the meter adds the purchased units to the already existing energy units.

9. The LCD displays computed consumption data, tariffs and notifications in turns as depicted in Figure 5.4.

Consumption at present time both in kWh and in currency



Voltage Measurement

Average Consumption per hour

Consumption of the previous hour

Figure 4.2 LCD displaying consumption data and power measurements

The above observations gave a clear indication that the earlier stated functional specifications of the improved prepaid meter have been met.

4.2 Final Meter Design

After consistent desirable results were gathered from the system's simulations; some of which are depicted in Figure 4.2, a final schematic diagram was developed using Fritzing Software version 0.92b; an advanced and comprehensive tool for open source hardware circuit design. This circuit diagram depicts the underlying circuitry and interconnections of the earlier mentioned building blocks and other enabling components. The schematic diagram is presented in Figure 4.3.

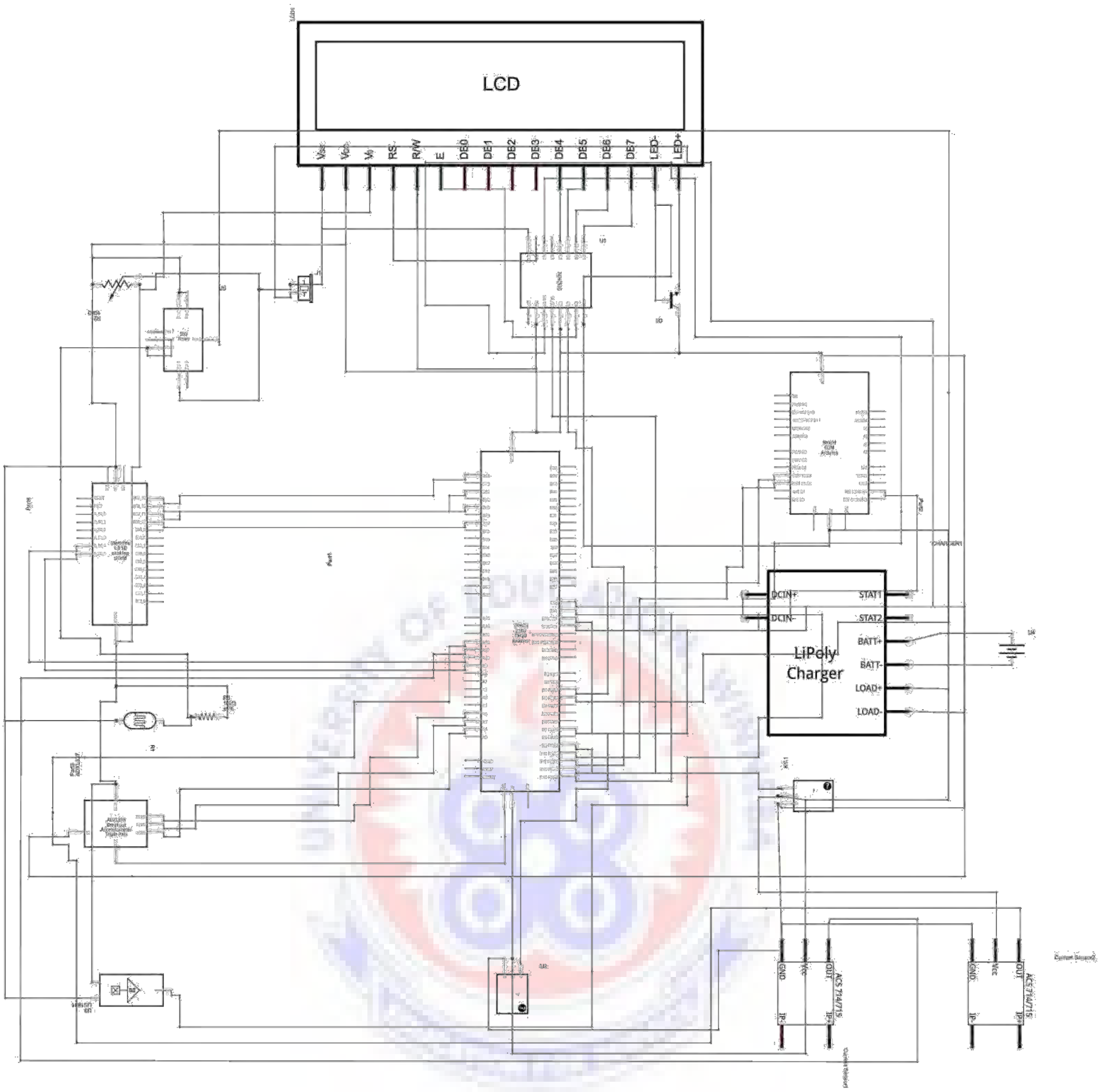


Figure 4.3 Schematic Diagram of an Improved Prepaid Energy Meter Design

A high-level breadboard presentation of this schematic design is presented in Figure 4.4.

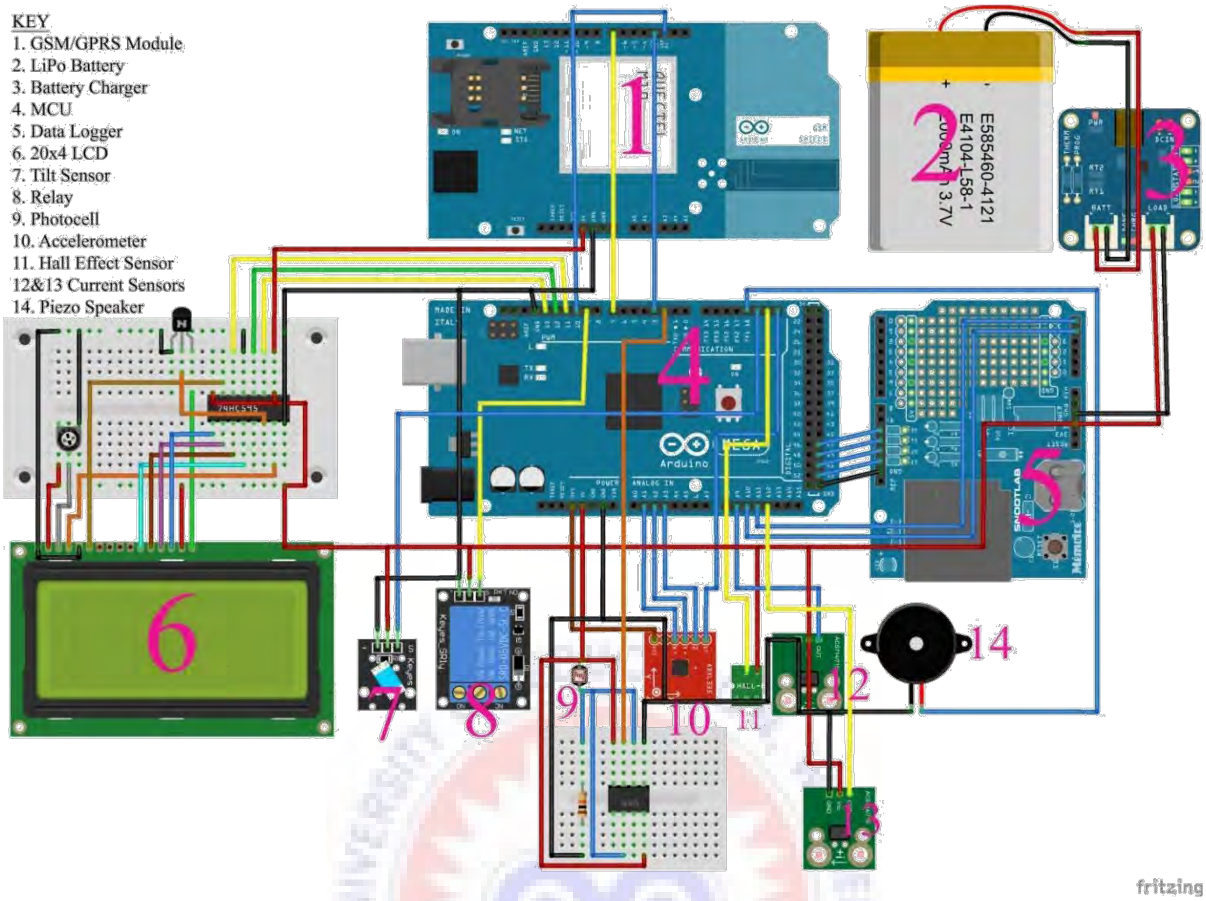


Figure 4.4 Breadboard Schematic Diagram of an Improved Prepaid Energy Meter Design

4.3 Cost Analysis

From a research conducted by Siemens, the average cost of most deployed prepaid energy meters is 221 USD (39). Also inferring from a recent massive deployment of 15,257,931 prepaid energy meters with communication technologies in the United States of America under a Smart Grid Investment Grant (SGIG) program, the total cost of the meters was 2,545,320,027 USD. This brings the average cost of each prepaid meter to 166.82 USD (740).

In this research, the cost-benefit analysis is done by gathering prices of all the above-mentioned components of the improved prepaid energy meter from trusted online stores such as SparkFun, Adafruit and Mouser. These stores were selected because they are among the few that allow retail and bulk purchases of components. Table 4.1 shows the prices displayed on their sites.

Table 4.1 Prices of Components

Name of Component	Quantity	Price (USD)
Sim900 GSM Communication Module	1-9	69.95
	10-24	66.45
	25-99	62.96
	100+	59.46
Xiamen Ocular GDM2004D 20x4 LCD	1-24	17.95
	25-99	17.05
	100+	16.16
Keyes 5V Electromagnetic Relay	1-2	2.52
	3-5	2.23
	6-9	2.22
	10+	2.21
Arduino Mega 2560 Revision 3	1-10	45.95
	10-99	44.95
	100+	44.45
AT407 Ball Rolling Switch	1-24	1.95
	25-99	1.85
	100+	1.76
ADXL337 Triple Axis Accelerometer	1-9	9.95
	10-24	9.45
	25-99	8.96
	100+	8.46
US1881 Hall Effect Sensor	1-24	0.95
	25-99	0.90
	100+	0.86
ACS715 Linear Current Sensor	1-9	7.95
	10-24	7.55
	25-99	7.16
	100+	6.76
Adafruit Data Logging Shield	1-9	19.95
	10-99	17.96
	100+	15.96
Piezo Speaker	1-24	1.95
	25-99	1.85
	100+	1.76
Lithium Ion Battery Pack - 3.7V 6600mAh	1-9	29.50
	10-99	26.55
	100+	23.60
USB LiIon/LiPoly charger - v1.2	1-9	12.50
	10-99	11.25
	100+	10.00

From Table 4.1 it is evident that the prices of these components decrease as their quantities increase. Bearing in mind that utilities usually have client bases that span from hundreds of thousands to millions, it is important to obtain the cost of these components when producing for such volumes. As such logarithmic extrapolations were done using the prices displayed in Table 4.2. Table 4.3 shows the logarithmic equations obtained for each of the components.

Table 4.2 Logarithmic Extrapolation of Cost of Component

Component	**Equation**
GSM/GPRS Communication Module	-3.386*ln(x) + 69.299
Liquid Crystal Display (LCD)	-0.893*ln(x) + 17.907
Relay	-0.183*ln(x) + 2.4557
Microcontroller (MCU)	-0.359*ln(x) + 45.567
Tilt Sensor	-0.096*ln(x) + 1.9435
Triple Axis Accelerometer	-0.479*ln(x) + 9.8559
Hall Effect Sensors	0.046*ln(x)+0.9458
Current Sensor	-0.382*ln(x) + 7.8745
Data Logger	-0.861*ln(x) + 19.329
Piezo Speaker	-0.096*ln(x) + 1.9435
LiPo Battery	-1.274*ln(x) + 28.577
LiPo Charger	-0.54*ln(x) + 12.109

In the table “ln” represents the natural log function, “*” represents multiplication and “x” represents the purchased quantity of the component. After computing these equations for quantities spanning from hundred thousand to one million, Figure 4.5 and Table 4.3 were obtained.

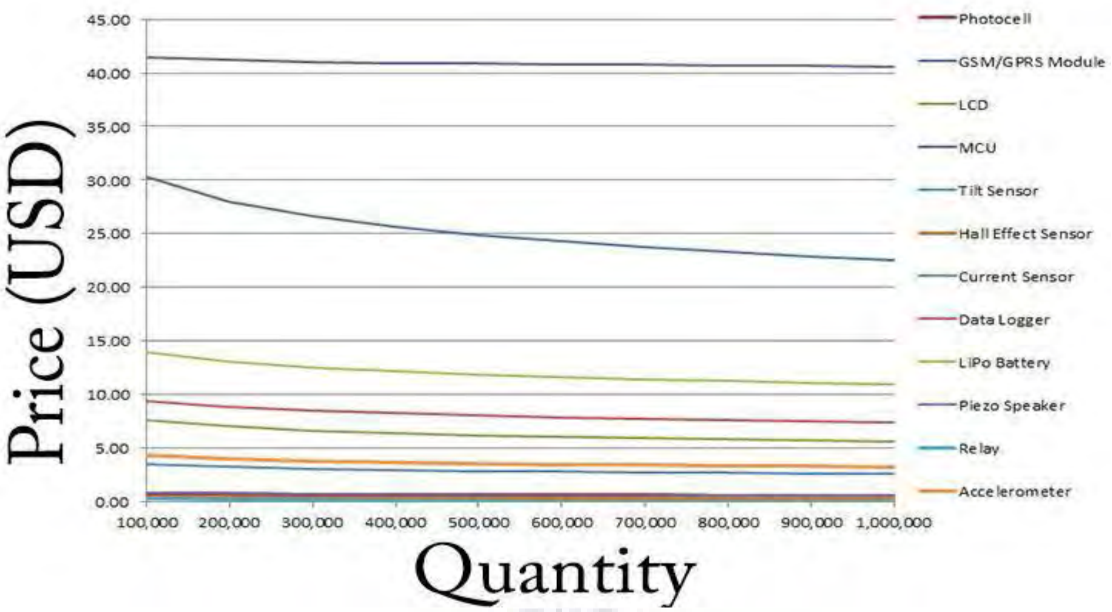


Figure 4.5 Logarithmic extrapolation of cost of component

Table 4.3 Logarithmic extrapolation of Component Cost (USD)

Quantity	Photocell	GSM/GPRS Module	LCD	Relay	MCU	Tilt Sensor	Hall Effect Sensor	Current Sensor	Data Logger
100,000	0.65	30.32	7.63	0.35	41.43	0.84	0.42	3.48	9.42
200,000	0.60	27.97	7.01	0.22	41.19	0.77	0.38	3.21	8.82
300,000	0.57	26.60	6.64	0.15	41.04	0.73	0.37	3.06	8.47
400,000	0.54	25.62	6.39	0.10	40.94	0.71	0.35	2.95	8.22
500,000	0.53	24.87	6.19	0.05	40.86	0.68	0.34	2.86	8.03
600,000	0.51	24.25	6.03	0.02	40.79	0.67	0.33	2.79	7.87
700,000	0.50	23.73	5.89	0.02	40.74	0.65	0.33	2.73	7.74
800,000	0.49	23.28	5.77	0.02	40.69	0.64	0.32	2.68	7.63
900,000	0.48	22.88	5.66	0.02	40.65	0.63	0.32	2.64	7.52
1,000,000	0.48	22.52	5.57	0.02	40.61	0.62	0.31	2.60	7.43

Quantity	LiPo Battery	LiPo Charger	Piezo Speaker	Accelerometer	TOTAL 1	TOTAL 2	TOTAL 3	TOTAL 4
100,000	13.91	5.89	0.84	4.34	119.50	143.40	179.25	239.00
200,000	13.03	5.52	0.77	4.01	113.49	136.19	170.24	226.98
300,000	12.51	5.30	0.73	3.81	109.98	131.97	164.95	219.95
400,000	12.14	5.14	0.71	3.68	107.48	128.98	161.22	214.96
500,000	11.86	5.02	0.68	3.57	105.55	126.66	158.33	211.10
600,000	11.63	4.92	0.67	3.48	103.97	124.76	155.95	207.93
700,000	11.43	4.84	0.65	3.41	102.66	123.19	153.99	205.32
800,000	11.26	4.77	0.64	3.35	101.52	121.83	152.28	203.05
900,000	11.11	4.71	0.63	3.29	100.53	120.63	150.79	201.05
1,000,000	10.98	4.65	0.62	3.24	99.63	119.56	149.45	199.26

In Table 4.3 there are four totals presented, namely Total 1, Total 2, Total 3 and Total 4. Their differences are explained as follows:

1. Total 1 represents the unit cost of improved prepaid energy meter when manufacturing at the specified volume without any miscellaneous cost.
2. Total 2 represents the unit cost of improved prepaid energy meter when manufacturing at the specified volume in addition to a 20% miscellaneous cost.
3. Total 3 represents the unit cost of improved prepaid energy meter when manufacturing at the specified volume in addition to a 50% miscellaneous cost.
4. Total 4 represents the unit cost of improved prepaid energy meter when manufacturing at the specified volume in addition to a 100% miscellaneous cost.

The miscellaneous cost was added to take care of any additional cost that may be incurred during the manufacture of the improved prepaid energy meter. Since this cost often comes as a percentage of the unit cost of the improved prepaid energy meter, the above-mentioned percentages were provided just to give an idea of what the final cost of the improved prepaid energy meter would be. To verify how cost efficient this meter design is, Table 4.4 compares the unit cost of the proposed meter design with that of the average unit cost of the prepaid meter deployed in the SGIG program (40). The unit cost of the improved prepaid energy meter is the logarithmic extrapolated value when manufacturing for a volume of 15,257,931; which is the same as the quantity of meters deployed in the SGIG program.

Table 4.4 Cost-Benefit Analysis: Comparison between proposed prepaid meter and SGIG Deployed Meter

SGIG Meter	Proposed Prepaid Meter			
	TOTAL 1	TOTAL 2	TOTAL 3	TOTAL 4
166.82 USD	76.51 USD	91.81 USD	114.76 USD	153.01 USD
	Percentage of Cost Savings			
	54.14%	44.96%	31.21%	8.28%

The same comparison is done with the average unit cost of 221 USD, as quoted as the average unit cost of prepaid energy meters by Siemens (39). This is presented in Table 4.5.

Table 4.5 Cost-Benefit Analysis: Comparison between improved prepaid energy meter and Siemens Meter

Siemens Meter	Proposed Prepaid Meter			
	TOTAL 1	TOTAL 2	TOTAL 3	TOTAL 4
221.00 USD	76.51 USD	91.81 USD	114.76 USD	153.01 USD
	Percentage of Cost Savings			
	65.38%	58.46%	48.07%	30.76%

From Tables 4.6 and 4.7, it is evident that the improved prepaid energy meter is of a low cost than the other deployed prepaid meters. Its cost savings ranges between 8.28% and 65.38%. Utilities in Ghana with low budges are therefore likely to spend less in adopting this low cost improved prepaid energy meter; thus, reducing the wait time between saving for deployment and deployment. Also, the process of deployment is further expedited and its cost reduced via the use of the already existing GSM/GPRS communication infrastructure.

CHAPTER FIVE

SUMMARY, CONCLUSION AND RECOMMENDATION

This project brought to light the inconveniences of the current prepaid metering systems deployed in Ghana. It proposed the addition of a cost-effective communication technology to the prepaid meter design in order to deal effectively with the identified inconveniences.

5.1 Summary and Conclusion

After detailed analysis of various communication technologies, it settled on GSM as the best fit for Ghana. This decision was made mainly because of the pervasiveness of GSM in Ghana, its reliability and low rates of communication.

The inclusion of GSM in the design adds to the basic functionality of the prepaid meter important benefits such as

1. Wireless purchase of energy units/credits. Thus, eliminating the need to visit vendor points as well as nullifying the need to wait in long queues to purchase energy units.
2. Wireless loading of energy units/credits. This also eliminates the need for the consumer to always return to his/her premise before loading purchased energy units.
3. Energy units can be purchased at all times. This is especially needed during holidays, weekends and late hours of the night when consumers run out of energy units.
4. Utilities are also able to detect felonious acts that result in energy theft in (near) real-time
5. Utilities are also able to disseminate consumer notifications to be displayed on the in-home display

With these inconveniences efficiently addressed, there is a high probability that there would be higher customer satisfaction and comfort, thus eliminating the desperation and anxieties that usually lead to meter tampering and energy theft. This would go a long way to increase revenue and eliminate the frequent need for utilities to change tampered meters.

5.2 Recommendation

The design is simple to use, cost effective, user friendly and of high benefits to the consumer and utility. Based on the aforementioned it should therefore be implemented to replace the existing system. Utilities in Ghana such as Northern Electricity Distribution Company (NEDCo) and Electricity Company of Ghana (ECG) should adopt this system for a reliable and effective operation.

Also, it would be necessary that in future the system would be augmented to be able to function as a fully-fledged smart energy metering system.

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