Cape Peninsula University of Technology

LOW COST, ENERGY EFFICIENT, ROBUST AND MULTI-FUNCTIONAL SMART METER

By

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Declaration

I, Akindele Olufemi Abegunde, declare that the contents of this thesis represent my own unaided work and that the thesis has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

Signed Date

Abstract

The problem of assigning human operators to collect energy measurements from the conventional meters in the communities has become a great concern over the past decades. . Most times, the lives of these workers are in danger due to criminal activities within the communities, especially in this part of the world. During the collection process, data collected were inadequate due to factors such as bad weather, constant attacks on operators, inability to correct faults, and other factors that rendered the system highly inadequate. However, the rapid growth in population and industrial development has increased the demand for more human operators and longer working hours. The problem of disconnecting and reconnecting supply by utilities due to unpaid bills is considered problematic. In addition, the technology of metering has improved as research increases in the area of modifying old power grid into smart grid. Due to recent developments, old power grid is transformed into micro-grid, which makes all generating sources into one cluster cell. However, this cannot be achieved if there is no better way of metering; thus, the need for a smart meter becomes necessary. The smart meter is more reliable and efficient. It is an improved automatic meter reading (AMR) system.

This research demonstrated that a simple low cost, energy efficient, robust, and multifunctional smart meter can be achieved. The smart meter system has added features that enabled the utilities to recover the meter energy measurement data remotely such as Zig-bee, Wi-Max, and Wi-Fi, (GSM) based to mention a few. The system allows monitoring and transmission of energy consumed in real-time. It calculates the amount of energy consumed through the multiplication of voltage and current signals. This system considers the use of ATmega358 on Arduino Uno board as the controlling unit for the execution of control and monitoring of activities. A standard electrical measurement such as current, voltage, power and energy consumption will be displayed via liquid crystal display (LCD). The external communication device is required in the actualization of this project, in-conjunction with the control unit based on the existing mobile technology called “GSM”. This enhances accessibility of all sundries through effective measurement and collection of electric energy data generated with ATmega358 on Arduino Uno board. Therefore, GSM stands as intermediary between the nearby available utility station and consumers or end-users. In conclusion, LCD displays real-time based data for the end user to visualise. This proposed system consists of the energy meter called ATmega358 on Arduino Uno board programmed with “Arduino 1.8.7” as the program complier. The usage data billing is done within the interval of 30 seconds, stored and trans-received the process for data collection, storing and billing generation.

Keywords: Micro Controller, Smart meter, Evolution of Electricity meter, LCD, GSM.

Acknowledgement

I wish to use this medium to sincerely appreciate the Lord Almighty who made it possible for me to be able to complete this research in good health. May Your name be praised forever Amen. Similarly, I want to thank my late daddy Mr. H.I. Abegunde, of blessed memory, for guiding us through the right path. May you continue to rest in perfect peace. Thank you for always been our guiding angel. Your moral taughts will forever be part of us. Furthermore, I cannot thank my mother enough, Mrs. E. O. Abegunde who during the tough times never thought of forsaking us in every step of the way. She has always been a shining diamond to our dreams. You will continue to eat from the fruit of your labour in Jesus name. Amen.

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Dedication

I want to dedicate this work to the glory of God Almighty, for the privilege me to acquire the skill and knowledge to complete this research. For you alone, I will worship forever. Amen.

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List of abbreviations

AAM	Advanced asset management
AC	Alternating current
ADC	Analog to digital converter
ADO	Advanced distribution operation
AFE	Analog front end
AMI	Advanced meter infrastructure
AMR	Advanced meter reading
ATM	Automatic teller machine
ANSI	American national standard institute
ASIC	Application specified integrated circuit
BAS	Building automation system
CMU	Communication unit
CPUT	Cape Peninsula University of Technology
CS	Current sensor
CT	Current transformer
DMT	Digital micro technology
DSP	Digital signal processor
EADM	Electromechanical add-on digital meter
EEM	Electronic energy meter
EMF	Electromagnetic force
EMIC	Energy meter integrated circuit
EMS	Energy management system
ERT	Electronic receiver transmitter
FTDI	Future Technology Devices International
GPRS	General Packet radio service
HAN	Home area network

HLAN	Home local area networks
I(t)	Instantaneous current
ICT	Intelligent communication technology
IEC	International electro technical commission
IHD	In-home display
IT	Internet technology
Kva	Kilo volt ampere
Kvar	Kilo volt ampere reactive
MCU	Micro-controller unit
MDMS	Meter data management systems
PLC	Power line carrier
PLC	Power line communication
PS	Power supply
RF-Module	Radio frequency module
RTC	Real-time clock
SCADA	Supervisory control and data acquisition
SEEM	Static electronic energy meter
SMS	Short message service
SNR	Signal to noise ratio
SOC	System on chip
STS	Standard transfer specification
UK	United Kingdom
US	United States
V(t)	Instantaneous voltage
VPN	Virtual private network
VS	Voltage sensor
VT	Voltage transformer

WAN	Wide area network
WAP	Wireless application protocol
WIFI	Wireless fidelity
WIMAX	Worldwide interoperability for microwave

Chapter 1: Introduction

1.1 Chapter review

This chapter presented, itemised, and discussed previous work carried out on smart energy meter. Also, the chapter discusses rational/significance of the research, alignment to CPUT focus area, design for sustainability, research aim, research objectives, hypothesis, research design and methodology, research outcome and thesis layout.

1.2 Introduction

The power industries of the developing nations are confronted with many challenges. The energy power, billing, data collection from consumers, and transfer of data to the utility companies have been unyielding. Metering is a global issue to all the countries in the world, regardless of their developmental level. The era of conventional electromechanical meter has brought about a lot of inadequacy into metering. This system is incapacitated with its inabilities to communicate the generated energy data. Data collectors are then engaged in the quest to actively gather energy consumed. Thereby giving room for utility personnel to perform a house to house data collection exercise, at most, every two or three months. Then, communicate the collected information in bulk on a paper or through a hand-held data recorder to the designated utility headquarter for the generation of bills with monetary implications.

Actually, the utility representatives end up with the miniature result because meters are installed inside the house, which disallows access to metering. Moreover, collection of data during this exercise consumed time, as well placed the collectors in danger in the environment where the data are obtained (Depuru et al., 2011). Similarly, the quest to improve the efficiency and accuracy of electromechanical meter resulted in the development of solid-state electronic meters in meter reading. Yet, the developing nation’s power sector faces a lot of challenges when it comes to revenue collection, such challenges as energy thefts, failures to disconnect and reconnect consumers with the utility company.

Furthermore, Sabalza et al. (2014) discussed the difficulties encountered based on the conventional system adopted by measuring energy consumption (Maryori Sabalza et al., 2014). End users might not be in-doors when the meter readers arrive for data collection. Sometimes, the meter readers are persuaded by the customers and thereby discourage them from carrying out their obligations as directed. This effect, in many ways, has encouraged criminal activities across many developing nations such as meter by-pass, meter tampering, cable disengagement. All these criminal activities caused issues like inefficiency, outrageous billing, etc. Due to this effect, the design and development of a low cost, robust, efficient, and multifunctional smart meter for household consumption is required.

The aim of this study is to develop and establish a low cost, robust, energy efficient and multifunctional smart meter for household consumption use. This study will engage the use of simulation, circuit design, and PCD layout with the use of voltage sensor and current sensor as incorporated with the precise ATmega358 on Arduino Uno board. This approach is selected from the Application of Specified Integrated Circuit (ASIC) that maintains the international standard class 1 IEC 687/1036. The ATmega358 on Arduino Uno board stands as the Acquisition Module section of the smart energy meter. This is further interfaced with the sensors in-other to generate the multiplication effect of the instantaneous values. The Root-Mean-Square (RMS) value is therefore put together and controlled through the micro-controller to produce the energy meter parameters such as instantaneous voltage and current, power factor, power, and energy. The micro-controller board to be considered in this study is ATmega358 on Arduino Uno board, which serves as the energy metering parameter and displayed on the liquid crystal display (LCD). Invariably, all these parameters could be communicated without the help of a third party acting as an intermediary between the utility and the end-user (Maryori Sabalza et al., 2014). In addition, energy meters are classified relative to their structured hardware components and its software (Qiong-Fang et al., 2016). And these components are well coupled together.

1.3 Background

The system engaged by the electricity companies in some developing regions of the world, for example Africa, is an obsolete means of collecting data, basically with manual approach. It involves a couple of personnel who are assigned to monitor the energy meter and are familiar with the environment. These personnel are known as ‘meter readers’, in which their job description entails going around checking the installed energy meters by documenting the data in a book. For instance, in South Africa, the electricity company in charge developed an improved way through which energy consumption data are locally collected with ease. This process is attained by driving around the customers’ vicinities with a hand-held meter manually (Nit Warangal et al., 2012).

Nevertheless, the nomadic way of collecting and transferring information between the consumer and utility is frustrated by criminals, mostly in the area where crime is at its peak. For this reason, the utility company loses lots of money that could be used to improve the service of the organisation to the the populace (Toledo, 2013). Apart from this, the old system also enhances energy tapping which led to loss of revenue on the part of the company. According to Toledo (2013), this act is most common in Italy and Brazil (Toledo, 2013). This effect necessitates the development of the electronic meter. The electronic meter is referred to as automatic meter reading (AMR). It nullified the perpetual counting of the moving disc in the electromechanical meter, which results in wear and tear of its moving parts. Furthermore, the electronic energy meter has some features adapted to the old metering system. It has its ability to send information in one direction such as pre-paid energy meter. Pre-paid energy meter is an example of electronic meter, wherein bills and tokens for payment of electricity bills are carried out by recharging each consumers' identification numbers through rechargeable cards. The rechargeable card has encrypted codes; when loaded will power on the meter and restore energy for the house user. On the other hand, if exhausted the energy supplied is cut-off momentarily unless recharged.

Many times consumers travel far away from their various homes to purchase the recharge bills from appointed vendors. In that case, this act becomes tiring and this calls for the development of electronic banking. Ellenki et al.(2014) looks into the development of a prepaid electricity meter to avert human errors. This concept helps to control the payment of money through wireless technology by empowering the consumer with the ability to recharge from home. It was designed in a way that when power is consumed, the amount of bill to be paid is indicated. This is triggered by an alarm indicator when a used-up balance account signalised. This design enhances payment through identification card well synchronized Toledo,(2013). Although, it could only communicate in one direction.

Ajenikoko & Olaomi(2014) explained that smart meter enhances energy savings and automatic collection of data, and thereby eliminates human error through manual readings and reduces labour costs; thereby enhances instantaneous pricing and instant fault detection, which make it more efficient and reliable. According to Do Amaral & De Souza(2014) more flexible and well-structured smart meter has been developed, in which the aim is to collect and store data (electrical parameters) for further analysis. Furthermore, two micro-controllers were implemented in their research using the 8051 family micro-controllers for analog data acquisition and data computation into digital signals. One of the widely used micro-controller is ATmega358 on Arduino Uno board. This micro-controller can be used in the development of kits because of its low-cost value when used in the development of the smart metering system.

In smart energy meter, there are various sections. The first section models the voltage and current signal from its equivalent sensors directly from the power grid, while the other section stores and performs further signal processing by converting the analog input into digital output. The selection of the above-mentioned sensors was carefully carried out. In this case, the voltage sensor used was a voltage divider with five shunt resistors connected parallel to each other in a bid to reduce cost. Though the smart meter is composed of four key parts, which play significant role in the development of a smart meter Chandima(2014). Many previous researchers focussed on these components, which vary and avert excessive cost in design.

In addition, Klemenjak et al.(2016) presented the development of a smart meter with a low-cost design based on open hardware system and interfaced with a compatible Arduino product. Furthermore, the computation platform featured the use of Atmega 328 8bit micro-controller in the metering unit, which constitutes a measurement device called circuitry galvanic isolation, measurement hardware and signal conditioning Klemenjak(2014). This design was developed to fit in for all purposes, either commercial or industrial. Similarly, the YOMO/Arduino component stores and transmits the measured data to the interfaced graphical user connected to the server.

Another researcher, Jithin Jose et.al (2015) designed a smart energy meter which was aimed at reducing the human reader by making use of AMR approach through a GSM modem. The researcher incorporated this device with tamper proof to prevent illegal connection. This outcome bolster the utility from great loss of revenue due to nonpayment for energy consumption. This smart energy metering system has basic functional blocks like acquisition, computational and communication part. As part of these basic functional blocks, a voltage divider is used as voltage sensor and current transformer to sense the current in root mean square (RMS) value. The voltage sensor stands as the analog raw data stepped down to attain the conversion of analog to digital converter (ADC), which is integrated with the energy metering integrated circuit (IC). This serves as an inbuilt part of a selected micro-controller considered as a stand-alone integrated circuit (IC).

Mohammed(2016) developed an energy meter that solved the challenges confronting the consumers in calculating the amount of energy being consumed within their domestic domains. Also, the researcher discussed how to reduce energy related crimes by setting a precise standard value for his energy meter. However, if this standard value is exceeded, then malicious activities are detected. These activities sabotaged the resilient effort of the utility company. Nevertheless, the investigator could not provide detailed solution to this challenge. Furthermore, energy parameters such as line voltage, phase current, neutral current, active power, apparent power, power factor, and energy consumption computational data were displayed through the LCD unit, and transferred into the database of the utility company via a communication unit which was carefully selected in Zigbee

1.4 Rationale/significance of this research

The significances of this study are highlighted below:

- The development of the low-cost smart meter gives the consumers the fore knowledge about their bill of energy consumed.
- The smart energy meter validates the energy data without the influence of an operator, while ascertaining the correct information communicated between the utility and the consumer.

- The multi-functional smart meter facilitates the upgrade of the old power grid system, and it is suitable for the development of a sustainable energy in a smart grid system.
- The production of the proposed low-cost smart meter will contribute massively to the economy of a nation, wherein the product can strengthen inter-economic relationship between nations.
- The proposed low-cost smart meter generates data to be stored and transmitted between the utility and the energy consumers.
- The low-cost smart meter generates data on power quality and power outages with the assist of programmable software that requires periodical of updates.
- The low-cost smart meter characterises electronics digitalized meter used in smart/micro-grid and consumption, which could be for different purposes (Residential, Commercial, and Industrial).
- The data will empower the intellectual property agencies to create better awareness for the usage and initiatives on how environmental hazard can be checked.

1.5 Alignment to CPUT focus areas

Based on the information gathered from the ten blueprint focus areas of CPUT research innovation, the major areas in which the above research could easily fit in are highlighted below:

- Energy
- Climate change and the environment
- Economic growth and international competitiveness

1.5.1 Energy

The smart energy meter will help in supplying sufficient energy to the industrial sector and the domestic at a competitive price, if given access to poor households.

1.5.2 Climate change and environment

As smart energy meter among other smart grids will lower carbon consumption economy, which will contribute to the sustainance of environmental greenhouse effect with respect to the vision 2030 agenda.

1.5.3 Economic growth and international competitiveness

This aspect of smart energy meter has features that make it more attractive. The relevance of this device (product) has placed it as one of the required means of lessening revenue loss to energy theft within a community or entire nation at large. Therefore bolster the economic revenue growth of a nation by sustaining energy revenue across the entire nation.

1.5.4 Design for sustainability

The design of low-cost smart energy meter aids easy access to data and energy billing updates, without any need for printing papers. The design and production of this device is affordable to the public

1.6 Research aim

The aim of the study is to design and develop a robust, efficient, multifunctional, and low-cost smart energy meter.

1.7 Research objectives

The objective of this study is to understand and evaluate the design and development of a robust, efficient, multifunctional, and low-cost smart energy meter through the use of ATmega328P on Arduino Uno R3 board, as an open source micro-controller, which is also used for acquiring and generating energy parameter as a smart meter. The objectives of the study are given below:

- The development of the low-cost smart meter abolishes paper bill of energy consumed.
- To emphasize the advantage of a wireless smart meter over an electromechanical meter.
- The use of ATmega328P on Arduino Uno R3 board enhance the efficient development of a low-cost smart meter.
- To establish the development of low-cost digitalized smart meter consumption for Residential purposes.
- The impact of generating energy parameter information and power outage updates at low-cost.

1.8 Hypothesis

Currently, smart energy meter is an integral part of smart grid. Smart energy meter helps to document the amount of energy parameter consumed. While the smart grid system is designed simply for power generation. Nonetheless, a greater understanding of smart energy meter and smart grid helps to solve hypothesis questions. The study helps address smart energy meter impact on smart grid and the consumers. Due to this effect, the performance rate of the smart energy meter requires a practical evaluation and analysis to determine its efficiency, and the need to present it at affordable rate to the consumers.

The research questions formulated in this study cut across in-depth understanding of the device's performance, and the significance of knowing the consumption rate of energy across households by end-users. Therefore, the questions formulated are given as:

1. What are smart energy meter technologies?
2. What are the impacts of smart energy meter on the smart grid?
3. To what extent is smart energy meter embraced by the end-users?
4. Is smart energy meter affordable?

The KICAD (5.0.1) for 64-bit windows and "Arduino 1.8.7" are electrical engineering software used in designing and programming the smart energy meter as a system test case. In this study, KICAD (5.0.1) for 64-bit windows and "Arduino 1.8.7" were used to address the raising concerns of designing an affordable smart energy meter for the end-users.

1.9 Research design and methodology

Case Study 1: this case study will look into the use of KICAD (5.0.1) for 64-bit windows and "Arduino 1.8.7 for the modelling a low-cost smart energy meter that stands as a functional part of smart grid. The purpose is to come up with a more robust and highly efficient energy meter that has the capacity to communicate in two-ways. And the device is tested via simulation to validate its workability.

Case Study 2: this case study introduces the practical actualization of the smart energy meter assembled. The device is coupled together in the laboratory after a full analysis of all the suitable components selected after hardware cost reduction estimates.

1.10 Research outcome

The use of ATmega328P on Arduino Uno R3 Arduino Uno board in the design and development of the smart energy meter is to attain a low-cost efficient multifunctional smart meter that possesses market value. This research is mainly targeted towards domestic and commercial uses subjected to future review to pave way for further research. The significances of the research are highlighted below:

- The smart energy meter design will enhance co-operate organizations' partnership with the school; thereby facilitate a centre for more production of the smart meter on a large market scale. This will promote another means of enhancing the revenue of an academic environment, community, and country.
- The product will eradicate the perpetual use of traditional meter. Although, in the case of this product, it is more flexible, effectual, and easy to regulate to renewable energy system such as wind energy technology and solar energy technology.

- The product has the capacity to keep intelligent information to enable the consumer know the rate of energy consumed via a display unit.
- In terms of its accuracy: it is far more accurate in comparison with the conventional meter and holds the historical data about the past energy usage.
- It stores both new and old data for future need; therefore, enhancing billing estimation of the energy consumption.
- The data collected by this product will enable governments and interested parties to create initiatives forum aimed at limiting the environmental impact of energy consumption.
- The market for the product is expected to boost the economy of the community or the entire nation.

Chapter 2: Literature review of smart energy meter

2.1 Chapter review

This chapter presents the literature review, evolution of energy meter, and the development of smart energy meter in Africa, South Africa, and the whole world. This chapter further discusses the definition of smart energy meter as analysed by various authors. Furthermore, it distinguishes between AMI and ARM in relation to the major components that constitute them.

2.2 Introduction

The energy utility company has been operating with the use of electronic meters for over fifteen years which was greatly successfully Edison Electrical Institute and AEIC Meter Committees(2011)This technology is used by the commercial, industrial, and domestic customers to collect detailed billing data. AMI is used in the electronic meters to communicate and collect data, including control and monitoring purposes Weranga et al (2014). Unlike AMI, AMR is described as an energy metering system (EMS) that employs one-way communication for data collection. Notably, to develop the old power grid into a smart grid, a systematic smart meter ideology has to be imbibed into the electricity metering. Moreover, Edison Electrical Institute and AEIC Meter Committees (2011) reported that the word “smart grid (SG)” was introduced in 2005 by Wollenberg and Amin.

Similarly, the Energy Independence and Security Act (EISA), in 2007 officially defined SG as a future electricity network. In that case, no particular definition was developed for SG, it is considered as a next generation electrical power system that combines information and communication technology system. Actually, the transmission and distribution equipment used in the old system are obsolete, they required replacement. In essence, problems like huge cost in the consumed energy, very low efficiency, depleted fault detector, polluted atmosphere (incessant release of carbon monoxide), lack of proper interface between the consumer and the utility are associated with the old grid system.

Moreover, the application of research and development enhanced the discovery and development of SG. Zheng et al (2013) stated that grid is an electrical system that performs functions like energy generation, energy transmission, energy distribution and energy consumption. While performing these functions a dependable communication link is established all over the grid system, through the integration of modern telecommunication technology to aid better monitoring and control of power usage within the system.

Understandably, a smart meter is one of the components used in SG. To support the statement, Ahmed et al (2016) said that energy generation, energy transmission, and energy distribution are categorised under the SG. These functions aid the delivery of electricity from the energy suppliers to the consumers. The distribution or consumption of energy could be practically monitored or quantified through the development and implementation of a digital technology. This device will facilitate the efficiency of energy consumption, consistency of energy distribution, reduction in the cost of design and affordable metering. Klemenjak et al (2016) designed a low-cost smart meter, with its fundamentals based on the open source hardware components available.

2.2.1 Evolution of electricity meter

The first patent of electricity meter was introduced in 1870, and the device was made of a gas meter but not robust, and it lacked accurate metering. In view of inventions, Thomas Alva Edison developed the first direct current (DC) meter, which was recorded as ampere-hour meter in the 1881. The device was deployed into New York City as watt hour meter. Reechniewoki and Meylan (1886), as reported by Toledo and Fabio(2013), built watt-hour meter for measuring DC and AC (alternate current) circuit 1886. During this period, AC was built for residential and industrial purposes, while DC was designed as electrochemical meter known as reason Meter whose specific application electrolytic cell for summing-up the chemical consumption Tsado et al.(2014).

In the 1889, Elihu Thompson developed a measuring meter that allowed both AC and DC to work together. Similarly, Oliver B. Shallenberger built a watt-hour meter, an upgraded version of an ampere-hour meter. Despite these inventions, meters energy consumption demand is documented for residential use in Kwh and for industrial use in Kvar and Kva. Nonetheless, only two basic kinds of meter technology are manufactured and made available in the market, which are the induction electromechanical meter and the electronic meter Toledo (2013). The electronic meter has digital meter, upgraded mechanical meter, remote read meters, and pre-pay.

Furthermore, Toledo (2013) explained that utilities and manufacturing companies came together with the idea of designing various energy meters to satisfy customers' needs. Chandima (2014) said that smart meter possesses numerous functions to accomplish the end-user loads, and to reduce the electricity bill along with the energy conservation.

2.2.2 Traditional meters for electricity

Vadda & Seelam (2013) described the traditional electrical meter as a device where reading done manually. During operation, the meter readers carried out a monthly collection of energy data to deter data accumulation. This type meter has an aluminium disc plate that displayed the basic operation process. There are four types of meter classified under the traditional meters, such meters as single-phase induction meter, DC watt hour meter, motor meter, and electrolytic meter Vadda & Seelam (2013).

2.2.2.1 Single-phase induction meter

In the process of selecting a suitable energy current for households, AC was selected over DC because it was discovered that DC is a none changing current, which makes it difficult to be considered Toledo (2013). Afterwards, it was problematic to measure the availble AC energy in the current supply to the households. This problem led to the development of an energy meter to address the problem Goyal (2017). In view of this, the rotating field in the AC meter is generated alternating ampere-hour meter. However, the meter lacked voltage element that accounts for the power factor in the system. This disapproves the suitability of the meter for commercial and household uses. The induction meter, as presented in Figure 2.1[1], replaced the alternating ampere-meter. This device is a metallic-like rotating disc controlled by two magnetic fields in phase against each other, which was fixed on a wood plate Goyal (2017).

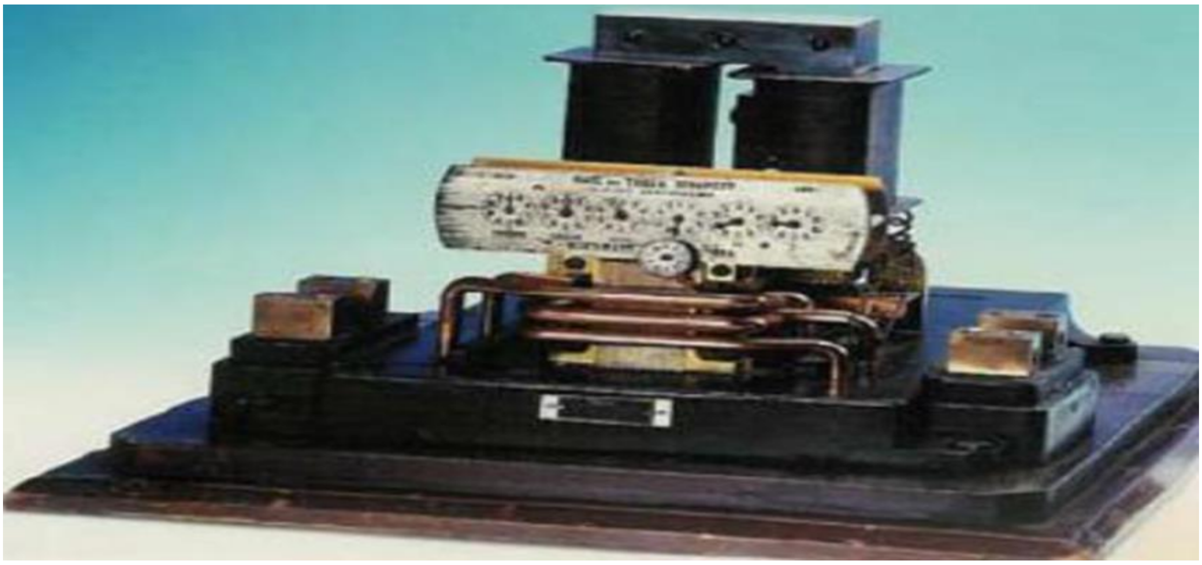

Figure 2.1: Induction motor

2.2.2.2 DC watt hour meter

This model meter is mostly used for heavy current circuit where the temperature coefficient is at its peak. Also, for indication purposes, a separate time switch is used.

2.2.2.3 Motor meter

This is a meter developed with the use of motor. This meter has a load with a driving torque and braking torque. The driving torque is directly proportional to the load, while the braking torque helps to control the speed of the rotor in the system. This happens only when the torque

[1]The picture was adapted from R. K. Goyal (2017)

is in the same state. Elihu Thompson, an American inventor, who came into limelight 1853-1937 developed an iron-less motor as a meter Toledo (2013). The meter has the stator and rotor parts. Both the stator and rotor is energised either by voltage or current via a Commutator Goyal (2017). This process propagates a driving force which is proportional to the product of the energised voltage and current. There is also an aluminium disc which is attached to the rotor, and a permanent magnet acts upon this disc to initiate counting through the help of the generated torque Gopinath et al (2013). Although, this approach is specific for DC only. In that case, commutator poses a great disadvantage in achieving an accurate result.

2.2.2.4 Electrolytic meter

Between 1841-1931, Thomas Alva Edison was the first to develop an electrolytic meter for distribution systems designed for DC Oliveira et al (2016). The electrolytic cell has a coiled copper placed at the beginning of every billing period Goyal (, 2017). The meter operates in a way that electric current is allowed to pass through the electrolyte with a quantity of copper deposited at the end of the billing process Mnati et al.(2017). Furthermore, the copper is coiled with different amount of electricity consumed. The meter is measured in cubic feet, and the disadvantage of using this meter is load congestions between the utility and consumers Goyal (2017). The operational illustration of the meter is demonstrated in Figure 2.2[2].

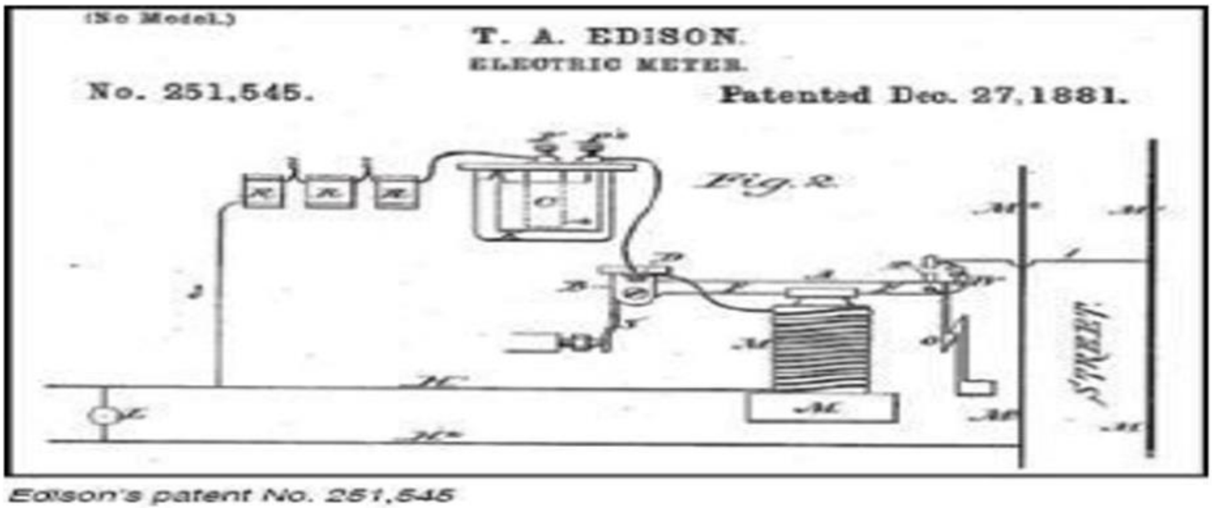

Figure 2.2: Edison electrolyte meter

2.3 Electromechanical energy meter operational principles

Electromechanical meter is based on Ferrari's principle Cetina et al (2017). In 1885, Galileo Ferrari discovered that when a solid disc is introduced within a magnetic field, then the disc rotates in proportional to the flow of the electrical energy in the coils as generated by AC phase Sharma & Mohan Saini & Hossain et al (2015; 2013). This operation is based on the principle

[2] The picture was adapted from R. K. Goyal (2017)

of electromechanical energy meters. Whenever the armature rotates in the magnetic field, a counter is initiated to detect the number of revolutions per disc EGyanKosh (2018). Figure 2.3 below[3] shows a clear picture of the electromechanical induction meter.

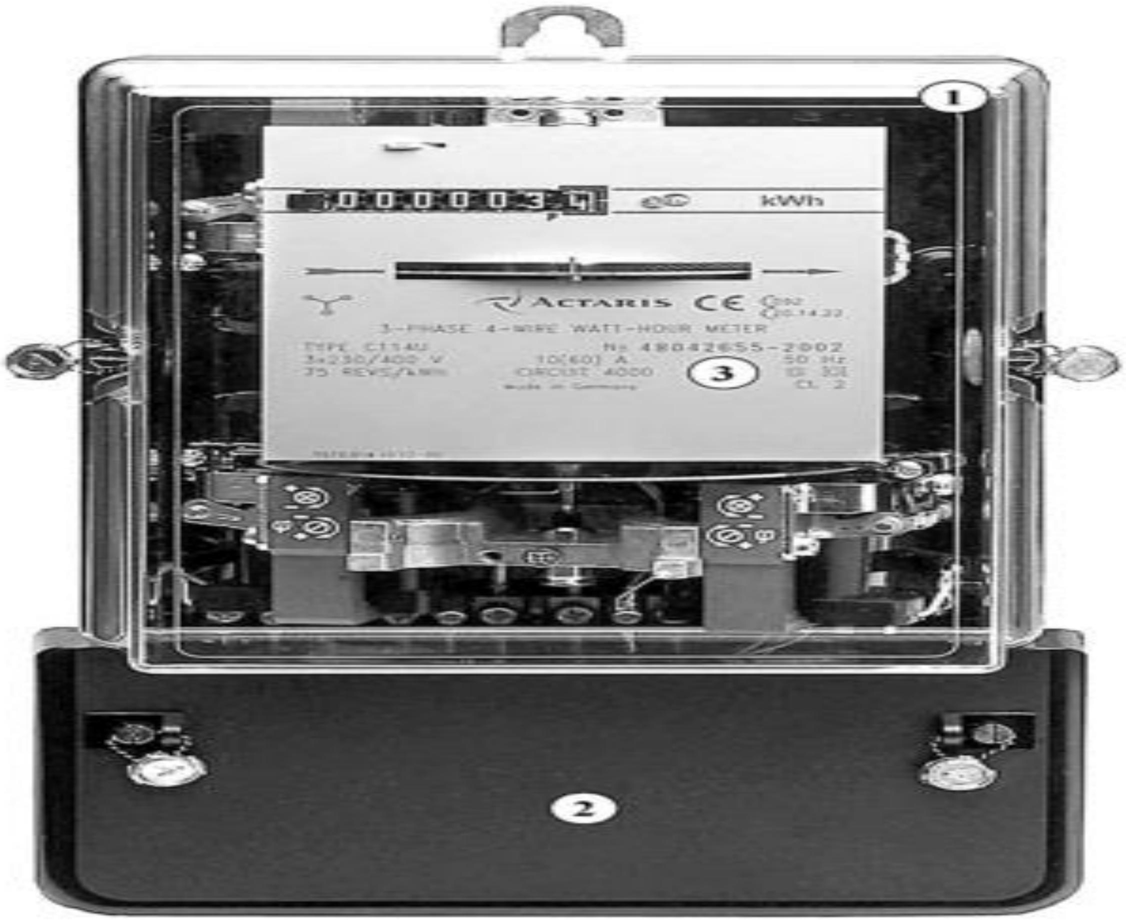

Figure 2.3: Electromechanical energy meter external part

Electromechanical induction meter comprises of 10 components as numerically indicated in the Figure 2.3 and Figure 2.4 below[4].

- 1 – Base meter compartment
- 2 – Terminal connection and cover
- 3 – Display board
- 4 – Stator
- 5 – Voltage circuit
- 6 – Current circuit

[3] The picture was adapted from Tsado et al. (2014) and EGyanKosh (2018)
[4] The picture was adapted from Toledo (2013)

- 7 – Rotor disk
- 8 – Magnetic brake rotor
- 9 – Pivot and spindle connected to the register
- 10 – Calibration elements

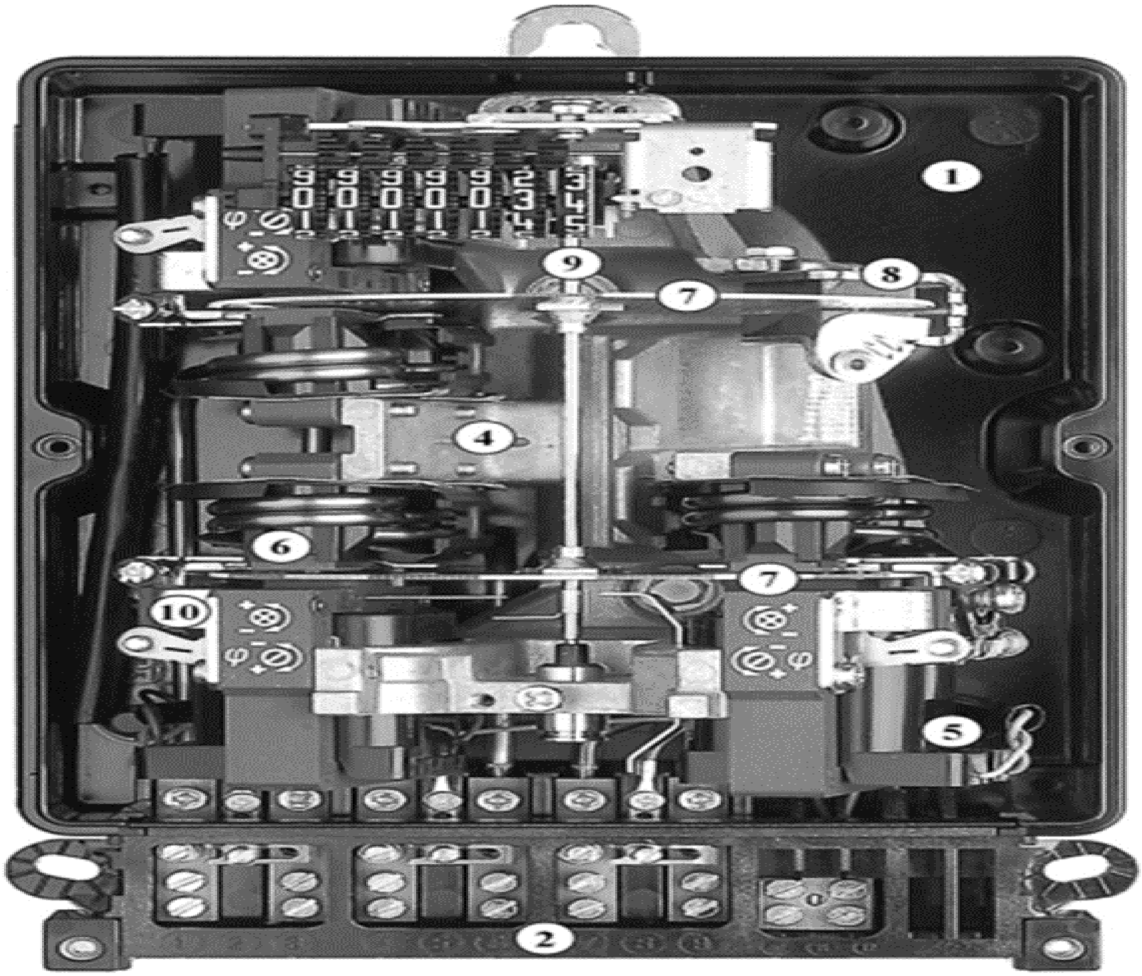

Figure 2.4: Electromechanical energy meter internal build-up

The energy meter is designed in association with four salient systems, which are:

- Driving system - it has two electromagnets.
- Moving system - it is composed of an aluminium disc.
- Breaking system - a permanent magnet is attached as a breaking device.
- Registering system - both gear train and counter make up this system (Chandima, 2014).

Measurement composition for energy meters is basically composed of the two circuits highlighted below.

1. Voltage circuit.

2. Current circuit.

The voltage circuit: - this circuit is made up of a coil connected to the main supply circuit. Current reference is actualised through current flowing within the current

The voltage coil receives the voltage reference from the line, while the current reference is acquired from the current flowing within the current coil Chandima (2014). Hence, this makes the meter performs similarly to the induction engine Toledo (2013). During this process, the voltage across the voltage coil generates an electromagnetic field proportional to the amount of voltage supplied and the current that flows through the meter. The aluminium disc is positioned on the rigid axis. The magnetic force exerted on the disc generates an eddy current to power or rotate the aluminium disc Effah Emmanuel & Owusu (2014). The operation includes rotation of the pivot and the spindle, which power the gears in proportion to energy consumption. The speed of the disc is registered by the counter. The register display is composed of sub counters, with corresponding number of digits.

More so, an opposite force is produced by the magnetic brake rotor to control the speed of the disc in relation to the used energy. The base of the meter and its compartment are glued or screwed together. The connection terminal concealments are normally sealed to avoid illegal connections and for the safety purposes. As part of the safety procedures, an identification tag with necessary information is attached to the meter to guide the users or operators about the installation of the meter Toledo (, 2013). The information simply contains the drawing, identity and features needed to comprehend before the installation is executed. Also, other significant processes indicated an alternating flux generated through the current coil proportional to the load phase. On the other hand, the voltage coil conveys the current proportional to the voltage supplied. The flux is not in phase with the supplied voltage, and thereby lag by 90^0 with the supply voltage Toledo (, 2013).

2.4 Electronic energy meter (EEM)

In electromechanical meter, energy consumption can be interpreted and documented but existing accumulated information barrier between the consumers and the utility company frustrated and rendered the process ineffective Zivic et al (2016). Due to this effect, EMR technology was developed to solve the problem for both parties BioInitiatives & Zivic et al (2012;2016b). This development eradicates the meter reading challenges associated with collection of energy consumption data.

This digital technology is designed to capture and document parameters attributed to the electricity consumption rate, such parameters as power quality, apparent power, reactive power, active power; and other parameters like power factor, frequency, phase voltage, and phase current Chandima & Muzafar Imad Ali Ahmed (2014; 2013). The device has a display unit known as the LCD or light emitter display (LED), together with the radio frequency (RF) purposely for data transfer as shown in Figure 2.5[5]. Although, this picture

Figure 2.5: The electronic energy meter

is only displaying a replica of the EEM. This receiver is a handheld device or radio base network installed in a mobile car for the collection and transfer of energy consumption data, through a wireless means such as ZigBee Zivic et al (2016a).

2.5 Electronic energy meter (EEM) operating principle

This form of energy meter has no moving or driving parts compare to the conventional energy meter counterpart. it is preferred to the conventional type because of its ability to operate automatically (dmohankumar, 2011). The device operates based on the application of electronic receiver transmitter (ERT), which is known as static electronic energy meter (SEEM) Toledo (, 2013). Therefore, this operation is made possible with the installation of application specified integrated circuit (ASIC). This is a built application primarily in embedded system used for the development of EEM Michal et al (2014).

ASIC is mostly installed in other devices such as digital camera, washing machines, automobiles, air conditions, and many other appliances. As part of the components, EEM contains voltage and current transformers that operate as the sensors and analogue circuits Thomas et al (2015). The data received or collected from both transformers are referred to as voltage and current measurements Himawan et al (2016). These measurements are

[5] The picture above was adapted from Visiontek (2019)

mathematically generated within the analogue digital converter (ADC) existing in the ASIC, and therefore convert the digitalised data generated into average values (mean values).

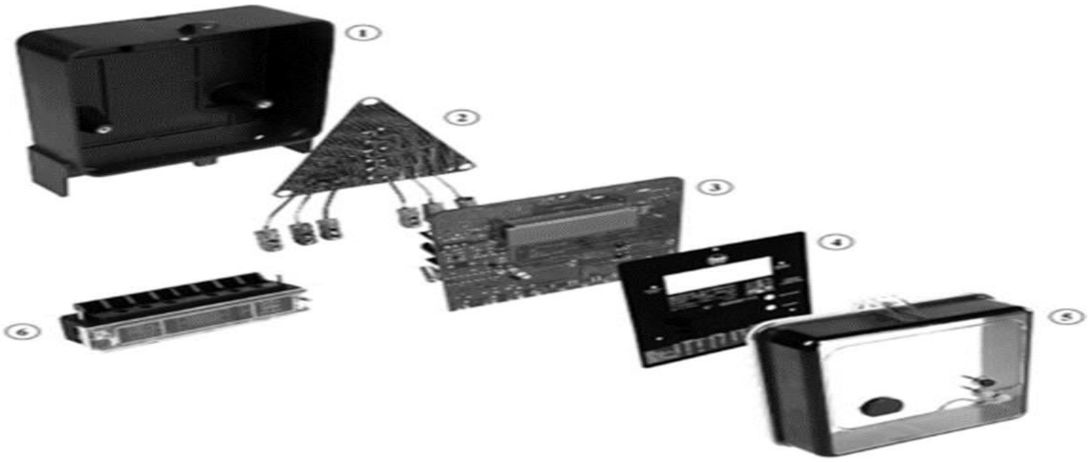

Figure 2.6: The explosive display of electronic energy meter (EEM) components

Average value (mean value) is the measuring unit power Male et al (2014). The resulted output is displayed on LED. These pulses equivalent to the average kilo watt hour (Kwh/unit) (Ali et al (2012). In this case, ASICs generate pulses ranging from 800 pulse/Kwh to 3600 pulse/Kwh. Most of the EEMs installed by the Kerala State Electricity Board (KSEB) have pulses ranging from 3200 pulse/Kwh, which drives the stepper motor that indicates on LED through the rotation of digitals embossed wheels. The most common ASIC company deal in the manufacturing of analogy device where ADE7757 and ADE7755 are largely used in the design and implementation of EEMs. The energy meter can be classified into two phases, which are single and polyphase. The explosive display of the components that constituted the electronic energy meter is presented in the Figure 2.6[6] above.

The explosive display of the components is numerically indicated as follows:

1. Base compartment.
2. Acquisition and measurement board.
3. Computational circuit board.
4. Display board.
5. Main concealment.
6. Terminal connectors and cover.

However, EEMs can also be likened to electromechanical add-on digital meters (EADMs)

[6] The explosive picture above was adapted from Toledo (2013)

2.6 Electromechanical add-on digital meter (EADM)

EADM is designed with the integration of electronic add-on module with electromechanical mechanism inside the meter box (see Figure 2.7[7]). The integration of these two processes generate vital information for both consumers and utility company. The production cost of the device is affordable, and commonly found in India. Further study shows that the electronic add-on module was designed particularly to sense the black or red strip existing on the rotation disc, by engaging an infrared (IR) sensor that converts the energy consumption into digital meter readings. The IR sensor IC could be OPB706A and LM324 comparator, designed to count the number of turns made by the rotor subject to the amount of energy consumption rate captured by the meter, and displayed through the digital display unit (Prudhvi et al., 2012).

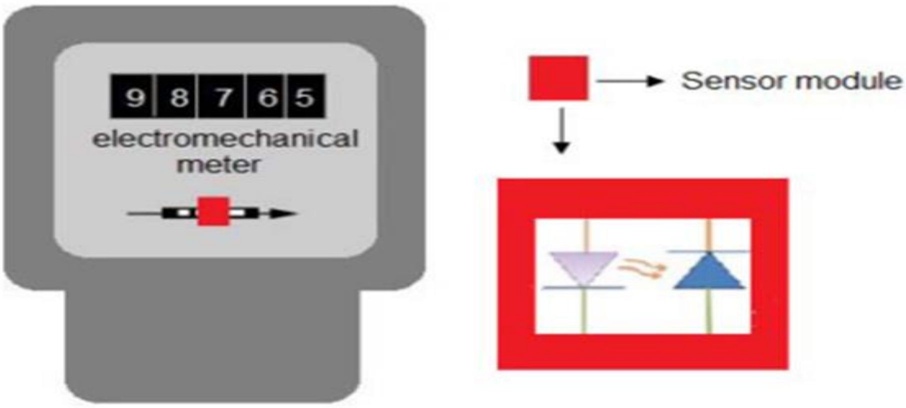

Figure 2.7: Electromechanical add-on module

2.7 Types of electronic meters

The electronic meter comes in various forms which are categorized into:

1. Traditional meter,
2. Modular meter, and
3. Pre-pay electricity meter.

2.7.1 Traditional meter

This a type of electronic meter designed with a single module and a seal that gives no room for embedded component upgrade. The seal was added as a protective measure to prevent any form of interfering. For future upgrading, the device undergoes a complete replacement of all the components irrespective of any identified outdated components (see Figure 2.8[8]).

[7] The above picture was adapted from Prudhvi et al. (2012)
[8] The pictures displayed in Figure 2.8 and Figure 2.9 were adapted from Toledo (2013)

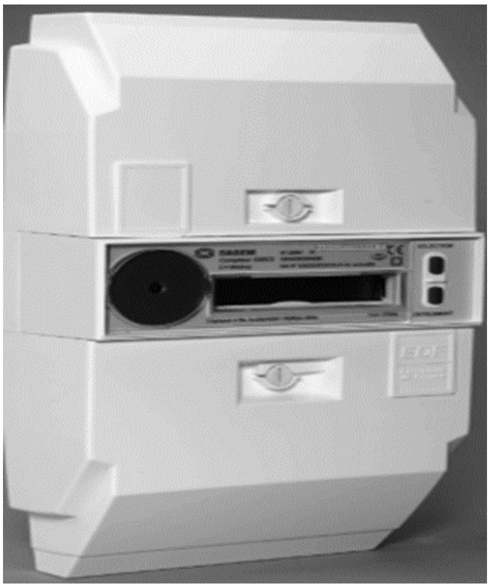

Figure 2.8: Traditional meter

2.7.2 Modular meter

This is a form of energy meter that can be easily upgraded. The design of modular meter aids components upgrades because lifespan of components differs. Among the installed components, only communication technological module and switches are mostly replaced to reduce cost of field operations (Toledo, 2013). The picture of the modular meter displayed in the Figure 2.9 below.

Figure 2.9: Modular meter

2.7.3 Pre-pay electricity meters

Pre-pay electricity meter is developed to relieve the customers from the debt suffered (Jack & Smith, 2016). In addition, the device is perceived as a good veritable tool for low income earners because it assists them in off-setting their outrageous bills and reduces exorbitant use of electricity by consumers Effah Emmanuel & Owusu; Franek et al (2014; 2013). The device is generally adopted by many developing countries in some part of the world such as Africa, Asia, and Latin America. Thus, the process involved entails the purchase of electricity units by consumers from approved vendors or utility company and input the electricity units in the control box of the meter Muzafar Imad Ali Ahmed(2013).

Concisely, if the electricity units inputted is valid then electric current is supplied into the household. Otherwise, no electric current is supplied to the households while the remaining amount of electricity unit is indicated or displayed in Kwh on the control box of the meter. The display process is demonstrated by three different light blinking stages, which varies from ≥1000 units (green light), and blinks yellow light at 500 to 50 units extending to red light, which blinks at ≤20 units.

Furthermore, it is a system that is branded as "pay-as-you-use" Nagarale, Gulhane (2017). Compare to post-paid metering, consumers are tasked to monitor the usage of their electricity unit. In that case, the bills are attributed to monthly or periodical reading of the electricity unit from the meter. The depletion of the electricity unit suggests another payment for energy consumption at the end of use. Effah & Owusu (2014) emphasised that post-paid metering system is used by many African countries to increase revenue. But in some cases, is another means of extorting consumers through skyrocketed bills to be paid. Despite the fact that electricity is never supplied to some regions, however, they are still billed unfairly.

2.8 Classes of pre-payment systems

There are various pre-payment technologies used today that user friendly to the customer. The use of pre-paid meter has aided the customer's ability to stabilise his/her credit generation, credit management, and customer management processes.

2.8.1 Coin meter

Coin meter is found to be used at the end of 19th century in the United Kingdom. Nevertheless, some utility companies around the world still adopt the use of mechanically operated meters (see Figure 2.10). It works by inserting coins in proportion to the amount of energy needed. Furthermore, the coins inserted is collected by the authorised utility agents. Interestingly, similar method is used in some countries as a money collection and saving mechanism.

Figure 2.10: Coin meter

2.8.1.1 Disadvantages

The disadvantages of adopting coin meter are highlighted below:

- Mechanical fault–which could encourage criminal activities,
- Inability to perform payment control and credit management, and
- Obsolete technology.

2.8.2 Token meter

Token meter is generally used around the world. It is a type of energy payment meter practically developed from the idea of payphone principle (refer to Figure 2.11[9]). The energy credit is loaded on it as indicated on the meter. It is mostly measured in Kilowatt hours or monetary values. Hence, the energy credit cards could be of two basic forms, which are: 1) Customised energy meter. 2) Non customised energy meter

Figure 2.11: Token meter

[9] The picture displayed in Figure 2.11 was adapted from Muzafar Imad Ali Ahmed (2013)

2.8.3 Customised energy meter-credit

The customised energy meter-credit operates by using a card writing machine to encode a specific or desired amount of energy credit on a card purchased at any pay point location.

2.8.4 Non-customised energy meter-credit

This type of energy meter-credit does not operate based on the use of a card writing machine to encode energy credit on a card, but it does operate only when the card writing machine is programmed with energy credit that will be inserted in the meter.

2.8.5 Advantages

The advantages of adopting both the customised and non-customised energy meter-credit are highlighted below:

- Access to the purchase of customised credit card at authorised dealers' shops such places as gas station, supermarket, etc.
- Emergency credit availability.
- Affordable costs despite the cost implication of procuring disposable cards.

These types of energy meter-credit systems are predominantly used in countries like South Africa, United Kingdom and Australia. There is a specific system used in generating these tokens or credits. This system is called standard transfer specification (STS) or international electrotechnical commission (IEC) and produced largely by many manufacturers of meter.

2.8.6 Smart card meter

The development of smart card meters was through the feasibility study performed on the token meters. It operates very similar to the token but particularly designed for specific type of meters (refer to Figure 2.12[10] below). Customers are mandated to always carry their smart card

Figure 2.12: Smart card meter

[10] The pictures displayed in Figure 2.12, Figure 2.13 and Figure 2.14 were adapted from Toledo (2013)

with them to avoid stress whenever there is any need of purchasing energy credit from any pay point location. After loading the energy credit on the smart card, then the card is inserted into the meter in order to load the credit on the smart card meter to discharge power and display customer's energy consumption rate per use in Kwh.

2.8.6.1 Advantages

- It prevents fraud by operating an open policy.
- It enhances ease resolve of debt management and fixed charges.
- It improves automated disconnection of non-credited meters.

2.8.6.2 Disadvantages

- Possibility of behavioural misconducts during credit purchase.
- Sometimes customer must travel far to purchase credit.
- Inability of customers to locate a neighbouring authorised credit dealer.
- Lost, damaged, or stolen smart card can deter customer's right to credit purchase.

This technology is commonly used in Europe and Africa.

2.8.7 Key meter

Key meter is another type of energy meter that uses a similar method of loading digitalised energy credit to initiate energy supply into households (see Figure 2.13). This meter is designed with a chip embedded to store and transfer energy data across energy management institutions.

Figure 2.13: Key meter

2.8.7.1 Disadvantages

- Customers can switch from one energy providers to another and allowed to retain the old key for use.

- Credits lost is tantamount to keys lost.

Hence, it is deployed and used in the United Kingdom and sparsely in other countries.

2.8.8 Keypad meter

Keypad meter is another metering system with a set of buttons used to encrypt credit codes on the meter (see Figure 2.14), and it is perceived to be reliable more than the previously discussed energy meters. In addition, credit purchased by customer is loaded on the meter with the use of this set of buttons (keypad). The machine decodes the codes entered and actively converts them into credit for power supply generation or increment. This process is elevated with energy communication devices like low power radio frequency (LPRF) and general packet radio services (GPRS).

Figure 2.14: Keypad meter

Furthermore, STS and IEC are the open standards that define the code. In the process of purchasing credit, customer is instructed to present his/her allocated meter number to generate an allotted credit codes about the amount of energy to be purchased. Once the IT system receives the payment rate and meter number, then allotted credit codes is generated in sequence with the house meter number or credited to the customer's account. The net energy credit is converted and measured in Kwh.

2.8.9 Forms of procurement methods used in keypad meter

The forms of procurement methods used in keypad metering are sub-divided into scratch card, mobile phone, through wireless application protocol (WAP), Automatic Profile and Automatic teller Machine and others as seen in the section 2.8.9.1 through 2.8.9.9.

2.8.9.1 Scratch card

Use of scratch card is perceived as one of the methods of generating energy credits as printed on the cards. This is purchased or obtained from the authorised utility vendors such sale points as supermarkets, gas station, etc. The unique experience about this method is that the credit imprinted on the cards is not allotted yet to a specific household meter until when the codes is scratched off the card and sent to the authorised utility agent in form of text messages through the internet and/or dialling call centre for codes conversion into credit. Short Message Service (SMS) is received by customer that contain the converted credit and input into the meter to generate energy.

2.8.9.2 Mobile phone

Another way of producing or acquiring energy credit is by using a mobile phone as a pre-paid payment communication technology (refer to Figure 2.15[11]). This method requires pre-paid payment in exchange for energy credit, in which an SMS is received to confirm the conversion.

Figure 2.15: Payment via mobile phone

2.8.9.3 *Wireless application protocol (WAP)*

This system engages the use of identification number and password used by the customer to access credit card information stored in the IT system.

2.8.9.4 Telecommunication

This system employs the use of the existing telecommunication has been a platform adopted by Smart Energy Meter manufacturer for transceiver bidirectionally. The concept is built upon the existing mobile telecommunication technology. It is found appropriate for rural, urban and developing areas of the world. The concept facilitated the use of GSM modem as interfaced

[11] The pictures displayed in Figure 2.15 and Figure 2.16 are adapted from Muzafar Imad Ali Ahmed (2013)

with microcontroller unit within a particular design (refer to Figure 4.1 below and Figure 2.22 below).

2.8.9.5 Automatic profile

This is like WAP system wherein credits are automatically purchased periodically.

2.8.9.6 *Automatic teller machine (ATM)*

This system involves purchasing of energy credit from a designated automated cash dispensing and depositing machine, which automatically debited your bank account in exchange for energy credit purchased. The meter is loaded with exact amount of energy credit purchased in customer's correct details. This process loads energy credit on the meter automatically.

2.8.9.7 *Barcodes*

This is another system of purchasing energy credit. The system involves the decrypting of encrypted codes obtained through a pay point payment with the use of a mobile phone and then the payment is made at the bank or by cash (see Figure 2.16).

Figure 2.16: Barcodes meter

2.8.9.8 *Automatic call centre*

This system provides the customer with the code via voice message on the phone through automatic call centre.

2.8.9.9 *GPRS terminals*

These systems are made available at most strategic points for credit purchase purposes such places as gas stations.

2.8.9.10 *Virtual private network (VPN)*

This system is installed and implemented at energy credit purchase points by the utility company and authorised energy dealers to enable easy purchasing of credits.

2.8.10 Split meter

This type of meter is designed with separate boxes comprised of the meter and display unit. The design enables the meter to be placed anywhere around the household, while the display unit is installed within the household. Thus, it is referred to as "in-home-display". The common communication networks used are low power radio frequency (LPRF) and power line carrier (PLC).[12]

2.8.11 Remotely managed meter

This type of energy meter emerged from the feasibility study carried out on the keypad meter. It is a debit meter with a communication device network called wide area network (WAN). Update on energy credits reflects automatically on the meter (see Figure 2.17[13]). In this case, physical keypads are provided to deter communication breakdown. In this system, the prepayment and credit data are executed locally or remotely.

Figure 2.17: Remotely managed meters

[12]The picture displayed in Figure 2.16 was adapted from Frost & Sullivan &Jean-Noël Georges (2011)
[13] The picture displayed in Figure 2.17 was adapted from Toledo (Toledo, 2013)

2.8.11.1 In locally debit meter

This meter aids the management through energy acquisition activities involving taxes or fees relating to monetary credits.

2.8.11.2 Remotely via IT system

In contrast, this meter operates through a fixed connection to the server in an online mode. Both data and credit management is executed remotely by the IT system and frequently displayed in the meter.

2.9 Advance metering infrastructure

Most utilities in the world today have utilised any of the meter discussed in this study, such meters as electromechanical, electronics, automatic meter reader, and pre-pay meter. Although, with the wider use of these meters around, they still lack the sensing and accurate measurement capabilities to fast-track much information concerning the usage of energy, quality of energy and impudence to bear multiple rates of forms. Therefore, advanced metering infrastructure system is considered better.

Apart from the deficiency mentioned above, these meters were unable to yield more comprehensive and appropriate information to instruct customer on the use of energy credit or electricity, and lack of provision for excellent ways of using the energy to gain cost reduction. This could be actualised in a smart metering system with communication and data processing abilities called meter data management (MDM) system. The combination of these two processes formed a system called advance metering infrastructure (AMI). Actually, metering system is no longer a device that measures and records consumption rate of electricity, but it is nowadays seen as an entryway for control and communication amongst utility (grid), customer, and load.

Evidently, AMI system boosts customer's choice of attractive reimbursements (refer to Table 0.1 below for the tabularised functions of AMI). This idea is believed to guide the customer's on decision-making process when it comes to the prudent usage of their energy credits. In return, it will foster the utility efficiency in gathering data and delivering customer service through AMI data and asset management process. The smart grids have four major parameters which are:

- Advanced transmission operation (ATO).
- Advanced distribution operation (ADO).
- Advance metering infrastructure (AMI).
- Advanced asset management (AAM).

Figure 2.18[14] presents the diagrammatical relationship of the AMI systems.

Figure 2.18: Graphical relationship of the AMI system

Table 0.1: The function of AMI

Main function	Optional function
Reads in real-time daily	Customer interaction
Takes record of consumption and data profile data	Interact via home area network (HAN)
Active, reactive, energy demand, voltage, current and others	Capacity to communicate with programmable communicating thermostat
Reads remotely	Energy management system (EMS)
Pre-payment operation	Building automation system (BAS)
Import / export of meters	In-home display (IHD)
Tamper detection	
Remote time clock stamping	Remote connection/disconnection
Communication and data Security	Load control
Quality of supply and another event recording	Pre-payment option
Plug and play devise commissioning	
Remote software firmware upgrade	

[14] The diagram displayed in Figure 2.18 was adapted from Goyal (2017)

From the diagram, it is simply illustrated that smart meter is the central component to assist in the reduction of design cost of the multi-functional capabilities with regard to its robustness.

Although, from the smallest components to the biggest components, all are seen as vital in creating and aiding data management through local transaction of information between the utility company and the customers.

The components that constitute the technological framework of AMI are highlighted below as:

- Smart meter.
- Home local area networks (HLAN).
- Communication infrastructure.
- Meter data management systems (MDMS).

2.9.1 Smart metering system

Smart metering system could be described as an energy system that executes measuring consumption of energy, data collection, data creation and energy billing activities (Halder, 2014; Waghchaure & Tated, 2016; Chandima, 2014; Bhagawati et al., 2017; Babu Babel, President, 2015; Depuru et al., 2011). Phair (2017) simply defines smart meters as the device built and installed around a home or business with the intention of measuring real time consumption rate of electric, gas, and water used to envisage the improvement required for the accuracy, reliability and efficiency enhancement of the outdated or/and overburden electrical, water and gas grids. Jason Scotty (2009) categorically stated that that smart energy meter is an electrical device that tracks energy usage, and instantaneously communicate the outcome with the energy supplier.

Figure 2.19: Smart energy meter

Understandably, process initiated in transferring the energy captured, recorded, and stored at the electricity distributors through wireless network takes ≤30 seconds to deliver. Khan & Khan et al. (2014) described the impact smart meter energy has in enhancing the challenges of energy efficiency through a concept called intelligent energy network. This concept comprises energy meter device and intelligent communication technology (ICT). Intelligent energy networking was pointed out as the ultimate energy device needed in achieving smart energy metering system (see Figure 2.19[15]). This device makes it possible to monitor and control energy data exchange between the utility and the consumers effectively. This process is performed in two-way directionally between meters to meters with regard to the networking type imbibed.

Chakra borty et al. (2016) mentioned the significance of smart metering as an antidote to a more energy efficient and metering system that gives accurate meter reading and billing system. Although, smart metering has related working principles with the conventional meter in arrangement and calculation of physical quantities, but differs in the computational aspect of the process. Smart metering computes less period of energy consumption rate either in hourly or in seconds rather than in monthly. Phair (2017) said that smart energy meter operates in two formats, such as AMR and AMI. AMR, as discussed in section 2.2, communicates and collects data for the utility company just in one direction. In the same section, AMI was described as electronic meter that communicate between the energy provider and customers, by informing them about the data collected at a certain interval. Further description illustrates that AMI integrates two-way communication and electronic meter designed to observe and regulate the grid system Edison Electrical Institute/EEI and AEIC MeterComittees(2011).

In recent time, meter reading grew from one direction into two-way due to high demand for a more humanly interactive metering system. Vitra team (2012) reported that in a year time (2020), an estimated one billion smart meters would be produced globally. The researcher further stated that by the said year US will be closing to 65 million demands quota of smart meters; the expected highest demand by any country out a billion quantities. More so, dated as far back the year 1990, exploration of gathered information collected from an energy metering device for the purpose of billing through a central data base, came to limelight through a technology called Automatic Meter Reader which took over from the then electromechanical meter.

Additionally, first-generation smart meter was developed in 2005, to transmit data back to the energy supplier. During the process, transmitting of data monthly was upgraded to transmitting of data daily and/or hourly. The process has helped the customers to be able to consume and produce concurrently. This demonstrates the significance of smart meter to electromechanical device Effah & Owusu(2014)which is only limited to the measurement of electricity

[15] The picture in Figure 2.19 was adapted from Scotty (2009)and Vadda & Seelam, (2013)

consumption. Apart from that, electromechanical device lacks consistency when it comes to energy measurement and encouragement for criminal activities.

The demand for the supply of electrical energy brings about the existence of electronic meters with additional functions. However, electronic meters work on a principle of digital micro-technology (DMT). The application of this principle has no involvement in the moving disc, which results in wear and tear of the moving parts Isam (2017). The electronic meter performs the automatic meter reading from consumer to both production and control executes by the utility. In that case, the smart energy meter combines the electronic device, intelligent communication technology, and control system in real time.

The active grid is a flexible and highly controlled grid. The flowchart diagram displayed in Figure 2.20[16] illustrates the process involved in the evolution of smart meter (Sun et al., 2015; Zivic et al., 2016a). According to Bhagawati et al.(2017). AMR is a classy system that automatically calculate billing and relays information about the consumption rate to the energy supplier. The researcher further stressed that the system could involve various techniques used as a means of communication such as GPRS, SCADA, RF, and GSM. In view of this, the researcher concluded that GSM is the most adaptive device with large quantity of users and coverage zone for data transmission. This quality enhances the chances of using the system for metering purposes. In addition, energy meters that use GSM prepare data for easy access to both energy consumers and energy suppliers.

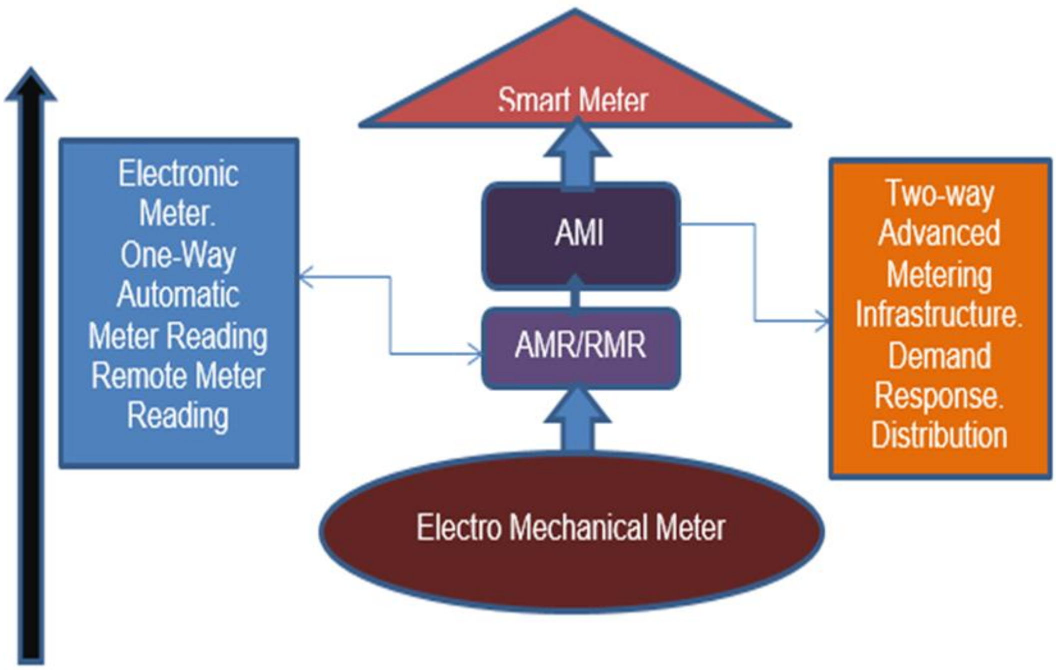

Figure 2.20: Evolution flow chat of energy metering system

[16] The diagram displayed in Figure 2.20 was adapted from Zivic et al (2016a) and Sun et al (2015)

Alternatively, AMI was developed to support the functional process of the smart meter as a two-way communication device that fosters the evolution of a smart meter. The development of AMI was mainly to enhance the data management efficiency of a smart meter. To buttress this illustration, Umang & Mitul (2015) emphasised that AMI was developed to replace the AMR to function as a two-way communication and data processor.

2.9.2 Smart meter architectural structure

Smart meter design was based on the architectural understanding of two structures that determine the fundamental structure of a smart energy metering system.

2.9.2.1 Basic architecture of smart meter

In the diagram demonstrated below, the smart meter is classified into two parts which are hardward and software (refer to Figure 2.21). The hardware part, as diagrammatically shown, is made up of three major units which are acquisition, data processing and data transmission units. These units

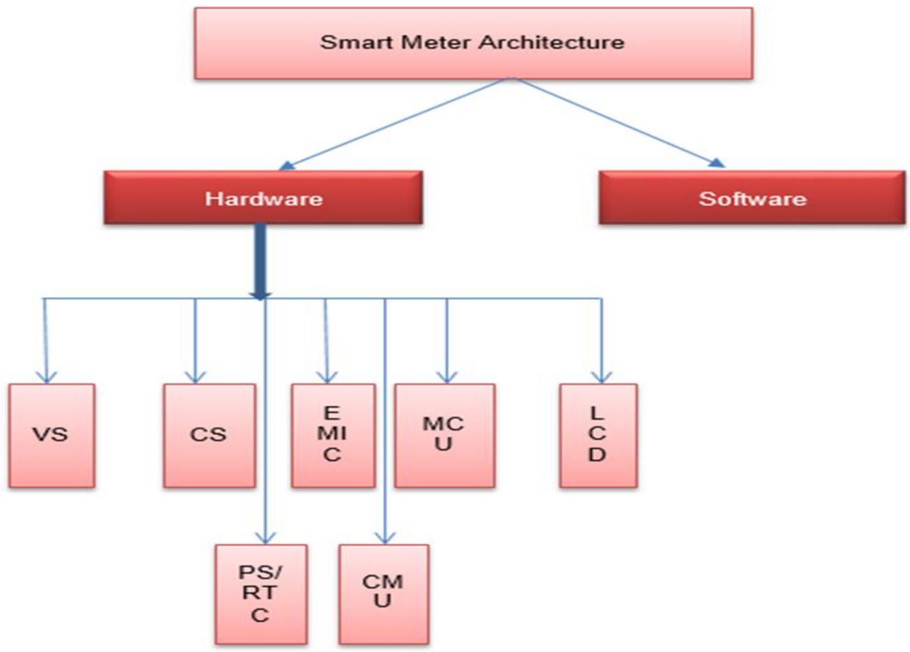

Figure 2.21: Basic architecture of smart meter

represent the combination of components like voltage sensor (VS), current sensor (CS), energy metering integrated circuit (EMIC), micro-controller unit (MCU), liquid crystal display (LCD), power supply/real-time clock (PS/RTC) and communication unit (CMU) (Youssef et al., 2016; Ellerbrock et al., 2012; Chandima, 2014).

2.9.2.2 Data acquisition unit

Data acquisition, as one of the units considered in the architectural development of a smart meter, is referred to as unit where analog data is obtained, processed, and converted into a required digital input for data processing. It is advised that a careful execution of this process is required to generate a reliable result. This unit consists of VS, CS and level shifter circuits (LSC) Youssef (2016). The VS and CS functions as the facilitators of data acquisition before being transmitted to the energy metering IC for signal conditioning, while simultaneously convert analog to digital developments. This type of controller is considered to be “system on chip (SOC)”. SOC constitutes analog front end (AFE) with MCU.

More so, AFE is a section of the smart energy device that is connected to the high voltage lines Youssef (2016). This component regulates the high voltage and high current rates from the mains into smaller values that ADC and MCU can easily absorb or process Ajenikoko & Olaomi, 2014 (2014). In essence, MCU can be referred to as the brain of the device because it dictates and controls all processes initiated within the smart energy meter. However, the data transmission unit is responsible for transferring and receiving generated energy parameter for full notification of the billing and monitoring purposes to both the energy supplier and customers.

2.9.2.3 Data transmission unit

Under data transmission unit, data is transmitted to a centralised server with customers’ identities stored to aid easy determination of unwillingness and criminal activities exercised by the customers such as unpaid usage of electricity, electricity theft, and electricity property vandalism Waghchaure (2016).

2.9.2.4 Communication network system for smart energy meter

Communication network system for smart energy meter are the basic existing networks which can be adapted into energy metering. It can be subdivided into cable and wireless networks as shown in figure 2.22 below.

According to Umang (2015), smart meter should be built to carry out some functionalities like measuring, applying, and communicating energy parameters with the intention to stimulate the efficiency use and supply of energy across to the households and industries. However, this efficiency is possible through a proper selection of communication networks and ports to manage the transmission and reception of energy data (see Figure 2.22).

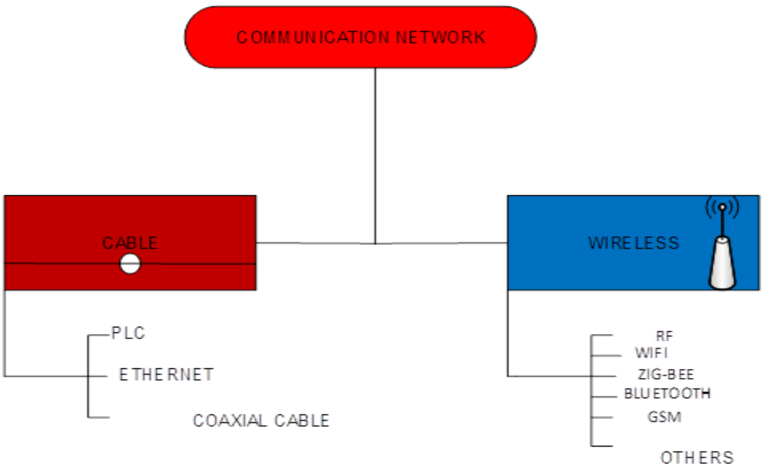

Figure 2.22: Communication network system for smart energy meter

2.9.3 Hardware internal structure of a smart energy meter

Smart energy meter is composed of both the software and hardware structure. This section will force on the internal structure of the hardware the smart energy meter consists of. The section comprises of detail scrutiny of the voltage sensor, current sensor, break down and their application as discussed below:

2.9.3.1 Voltage divider for voltage sensing

Voltage divider is a modest design of voltage sensor due to its less cost in the market. The circuit connection is aimed at scaling down the AC source voltage magnitude to meet the voltage input range of the energy metering integrated circuit for appropriate measurement. The resistor R1 is connected in series with R2 , having the input voltage (Vin) across each. The output resulted voltage (Vout) is tapped from the connections in between the resistors. In this case, the voltage divider could be used for voltage references and be grounded at resistor R2 (Figure 2.23[17])

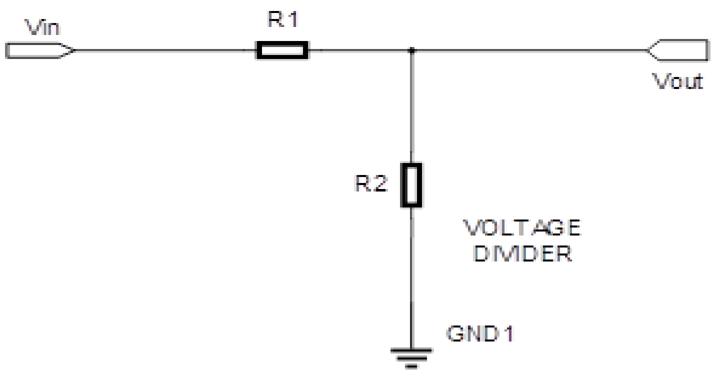

Figure 2.23: Voltage divider

[17] The diagram displayed in Figure 2.23 was adapted from (Sugumaran, 2014; Porcarelli et al., 2013; Shahrara, 2011)

$$Vout = Vin^* \frac{R2}{R1+R2} \quad (2.1)$$

From the above diagram, Vout denotes voltage output and Vin denotes voltage Input.

Note: it is importance during selection that the resistor R1 should be greater than R2.

2.9.3.2 Current sensor unit

Current sensor is one of the units categorised under data acquisition unit. This unit is grouped into four subcategorises, such as:

- Current transformer (see Figure 2.24 below[18]),
- Rogowski (see Figure 2.25 below),
- Hall effect sensor, and
- Shunt resistor.

According to Guimaraes et al.(2015), current sensor is sub-divided into two systems, such systems as aggressive and non-aggressive. In the aggressive system, current sensor is linked in series with the mains, whereas in the non-aggressive system, current sensor is not linked directly with the mains. Examples of the aggressive system are inductor with high inductance values, resistor, one axis hall-effect sensor, and solid current transformer. Also, examples of non-aggressive system are hall effect sensor and split-core current transformer.

2.9.3.2.1 Current transformer

Current transformer is a device that generates or supplies smaller value of current at the secondary source, while the primary source is stepped down for signal measurement. In this case, the input and output winding of the transformer helps in calculating its values. Typically, the current transformer works based on the same principles governing the normal voltage transformer.

[18] The picture displayed in Figure 2.24 was adapted from Chandima (2014)

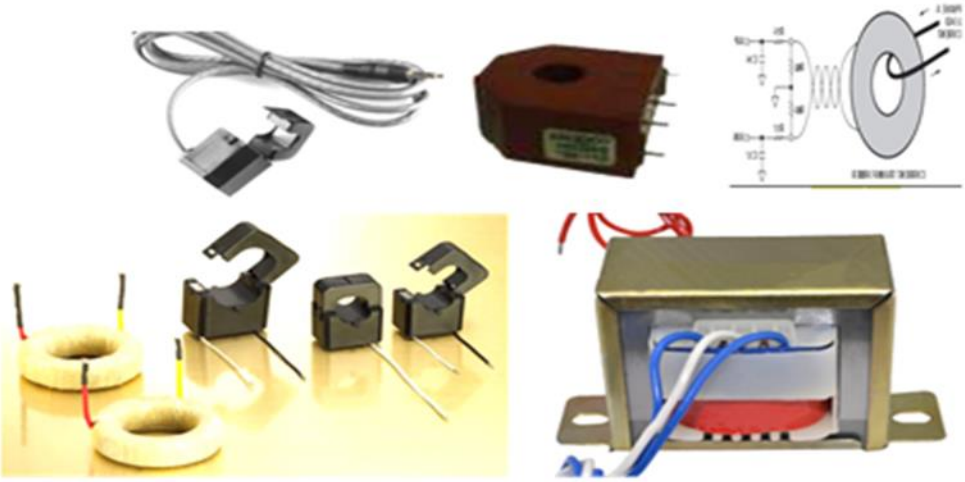

Figure 2.24: Current transformer collection

The process involved in the current transformer demonstrate that primary winding aids the transformation of the AC current that flows across it. Then, a magnetic field is generated and induced on the secondary winding coil. The ratio association between the number of turns in the secondary and primary windings yields the output magnitude. Moreover, a burden resistor is connected to the secondary winding coil based on the recommended rating as specified in its datasheet. Chandima(, 2014) reported that current transformer's performance rating predicts its use. The capacity standards of current transformer used for energy metering purposes are 0.1, 0.2, 0.5 and 1. Other attributes indicate that current transformer has a nonlinear phase lower current and higher power factor. But current transformer sells at higher price more than shunt resistor.

2.9.3.2.2 Rogowski

Rogowski was considered as a perfect design for air core because it has no saturation, hysteresis, and non-linearity due to its dependent on magnetic field measurement Devices (2009).The disadvantage of using this device is its indirect interference with the external magnetic field in comparison with the current transformer.

Figure 2.25: Rogowski

This picture above[19] shows the form of current measuring device that is subsequently used in the power distribution sector as found in arc-welding and sub-station transformer machines William koon (2010).

2.9.3.2.2.1 The basic principle for Rogowski

The principle used in the Rogowski is fundamentally based on the transmitting of current through a conductor to galvanise or induce a magnetic field that causes an electromagnetic force (EMF) around the coiled wire. Therefore, the magnitude of the magnetic field is directly proportional to the amount of current flowing through the conductor, and output voltage is proportional to the differential of the current with respect to the time of the coiled core.

The relationship between the output voltage and the current flowing through the coiled wire is deduced mathematically below:

$$V = K\frac{di}{dt} \qquad (2.2)$$

Where V is the output voltage, I is the measured current, t is the time, and K is the constant.

For us to get the current from the differential signal ($\frac{di}{dt}$), thus, the above formula is cross-multiplied to yield Equation (2.3)

$$V.dt = k.di \qquad (2.3)$$

Make di the subject of the formula by dividing through with k and integrate with respect to dt from Equation (2-3)

[19] The picture displayed in Figure 2.25 was adapted from Chandima (2014)

$$\therefore \quad \int V \frac{dt}{k} = \int di$$

$$\frac{1}{k} \int Vdt = \int di$$

$$i = \frac{1}{k} \int Vdt \qquad (2.4)$$

2.9.3.2.3 Hall effect sensor

Hall effect sensor is a copper conductor with a chip. This type of sensor was used to design a low-cost smart card prepaid energy meter, wherein ACS712-30A was used as the current sensor Lad (2016). The copper conductor is positioned partly with the die. ACS712 is one of the most widely used current sensor in the energy metering system.

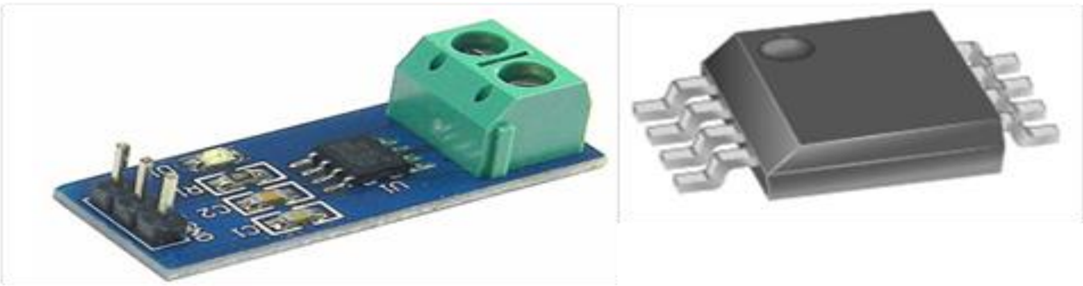

Figure 2.26: Hall effect sensor

Moreover, when current flows through the copper conductor path, a magnetic field is generated and sensed by the hall integrated circuit (IC).

2.9.3.2.4 Shunt resistor

Shunt resistor is a built resistor in series that performs voltage and current measurement tasks within a smart energy meter Kabalci (2016). More so, the design of shunt resistor includes the use of materials with low resistance standard that resist harsh conditions such as temperature changes, age and current. Subsequently, Chandima (2014) advised that resistors within the range of 100μΩ and 500mΩ are suitable for the development of a smart energy meter. The power dissipation is directly proportional to the square of the current. This effect demonstrates a need for a smaller resistor value to reduce the amount of heat losses (refer Figure 2.27[20]). The current fed into the microcontroller or the energy metering IC can be calculated when the resistor used is measured in ohms and the quantity generated is calculated through the application of ohms law. The voltage across the shunt resistor is proportional to the sum of current conveys through it.

[20] The picture displayed in Figure 2.27 was adapted from Chandima (2014)

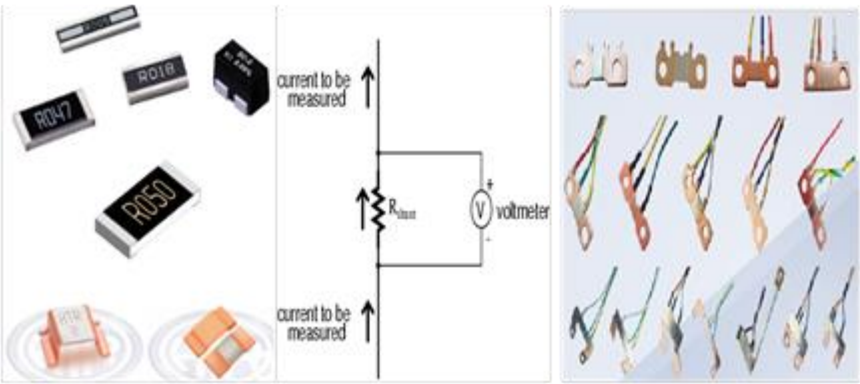

Figure 2.27: Shunt resistor

The discussions in this chapter provides detailed knowledge on the components and procedures adopted in the design and development of a smart energy meter. These components or materials were critically evaluated to suit affordable cost of purchase to enable or encourage further modification development in future.

In the subsequent chapter, analysis of the basic functionalities within the energy metering IC, signal conditioning, noise sampling, oversampling, and basic electrical parameter calculation in a sinusoidal single-phase system will be discussed.

Chapter 3: Functionality of energy metering integrated circuit chip

3.1 Chapter review

This chapter covers the practical functions of the energy metering device that can facilitate accurate acquisition of energy parameters measured. In addition, the chapter discusses basic functionality of all energy metering integrated circuit, with the purpose of differentiating their individual capacity in generating energy parameters. The chapter also discusses the three important operations carried out by metering system, namely: signal conditioning, energy parameters, and ADC. Some other important factors are discussed to substantiate the significant of the operations like signal conditioning and filters, which are applied to generate non-interference signal based on the effect of the anti-aliasing process. Also, reduction of unwanted noise, sampling, and quantization techniques are discussed in this chapter. As part of the discussions in this chapter, two conditions are considered based on the functionality of the energy parameters like apparent power, active power, reactive power, RMS voltage, RMS current, power factor, and quality measurement. The two conditions discussed considered are non-sinusoidal and sinusoidal conditions.

3.2 Introduction

The international electrical regulated bodies called ANSI and IEC approved of digital signal processor (DSP) and energy metering IC as requisite devices for the accurate computation of energy parameters measured. These devices are also used in signal conditioning processes such as apparent power, RMS (current and voltage), active power, reactive power, power quality measurement and line frequency. Technology advancement has raised the design and innovation development of various energy metering IC to sustain evolutional functionality and market value. The three functional operations determined in the operational functionality of the energy meter IC are signal conditioning, ADC, and parameter calculation.

3.2.1 Signal conditioning

In this section, signal generation is discussed. According to Turner (2016), the signal generated through the voltage and the current sensor is not fed directly into the on-chip ADC of any energy metering chip. This is because the on-chip ADC converts the analog voltage and current signals from the sensor into digital signal, which could be considered as its pulse or binary form for data processing, calculation, and communication Turner (2016). In addition, the energy metering chips are powered in volts range of 3.3v, 5v, and 10v, which are made available in the market. The differential voltage ranges of this chip are between $\pm$250mV and $\pm$500mV.

In view of this, an efficient signal conditioning process is required to scale down the voltage and current input waveforms to a measurable and suitable signal levels for the ADC. Therefore, the process followed in converting current waveforms into voltage waveforms is expected to undergo attenuation process and filtered from high unwanted frequency signals. The diagram[21] displayed in Figure 3.1 illustrates the signal conditioning process of voltage and current signal generated from respective sensors, and the attenuation and filtering processes. This process is initiated within the energy metering device used today (Chandima, 2014).

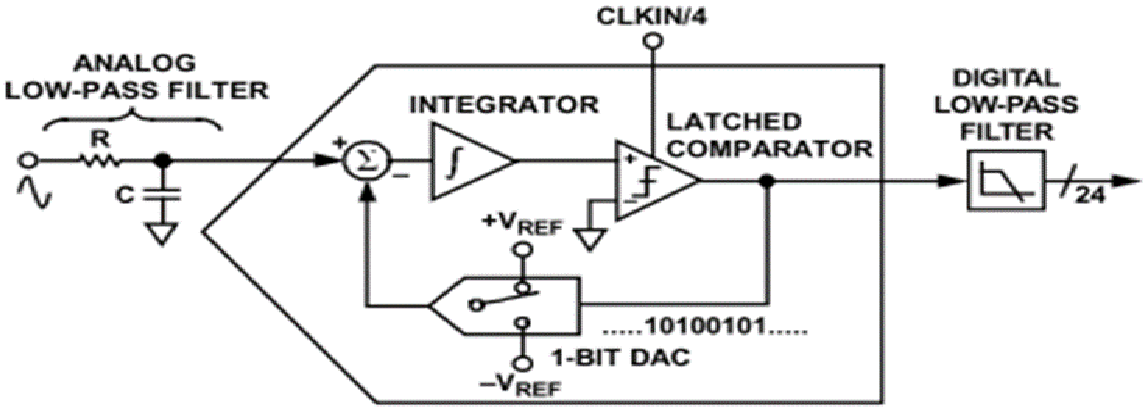

Figure 3.1: Signal conditioning through analog to digital conversion

In every architecture, aliasing occurrence is prone with ADC which is due to inadequate sampling. For ADE7953 IC, the energy metering device has three $\sum - \Delta$ (second-order sigma delta) modulator. Each sigma delta modulator is attached with a low-pass filter in either analog and digital Devices(2009). The sigma-delta modulator is responsible for the conversion of the input signal into binary bits of 1s and 0s as sampled by the clock. The ADE7953 has a sampling rate of 895 kHz. Aliasing occurs when the frequency component is bigger than half the sampling rate of the chosen frequency band. This effect requires the introduction or adoption of oversampling to attain high resolution. However, oversampling and noise are the two simple systems used inside $\sum - \Delta$ modulation converter.

3.2.2 Oversampling

Oversampling, generally, occurs when the input signal is sampled at a higher frequency several times in comparison with the intent bandwidth illustrated in Figure 3.2[22]. This process enhances noise distribution over a wider bandwidth area due to sampling. Though, oversampling is not consistently enough to enhance the signal to noise ratio (SNR) in the intent bandwidth. It is necessary to retain the oversampling ratio to attain higher frequencies, in order to reshape the quantization noise. This aspect of the discussion is diagrammatically

[21] The diagram in Figure 3.1 was adapted from Devices (2013)
[22] The diagram in Figure 3.2 was adapted from Data (2002) and Devices (2013)

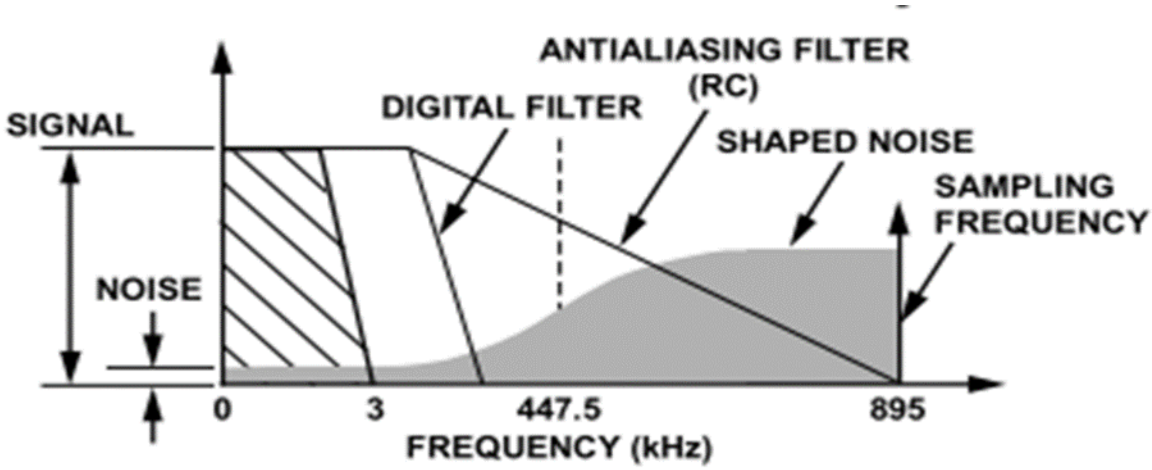

Figure 3.2: Noise decline via oversampling

Illustrated in the diagram above.

3.2.3 Noise shaping

Another way of attaining a high resolution is by reshaping the noise as illustrated in the Figure 3.3[23]. The integrator inside the $\sum - \Delta$ modulator reshapes the noise and generates a feedback through high pass filter for quantization noise. The integrator raises the noise to a higher frequency that could be regulated through digital low-pass-filter.

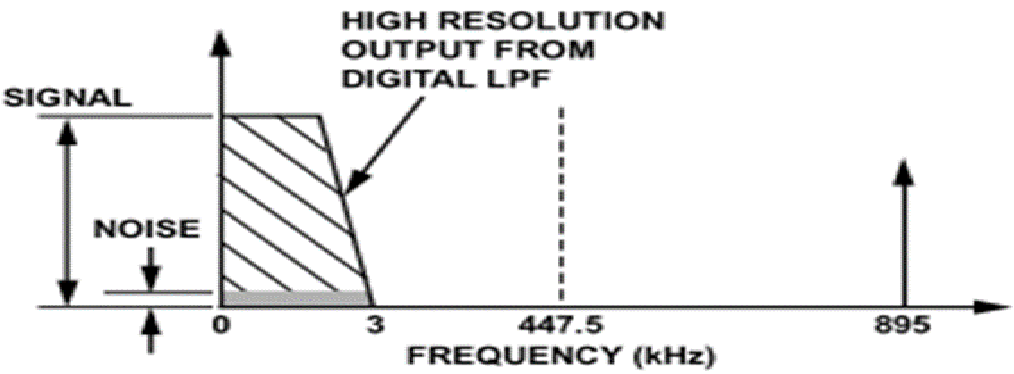

Figure 3.3: Noise shaping inside analog modulator

3.2.4 Antialiasing filter

Aliasing can be removed in all the energy measurement chips by introducing anti-aliasing filters to the input signal which is achieved through an RC low pass filter. The graphical illustration presented in Figure 3.4 below demonstrates that when the frequency component is bigger than

[23] The diagram displayed in Figure 3.3 was adapted from Devices (2013)

half of the sampling rate of the chosen frequency band it is called Nyquist frequency, which initiated the occurrence of aliasing.

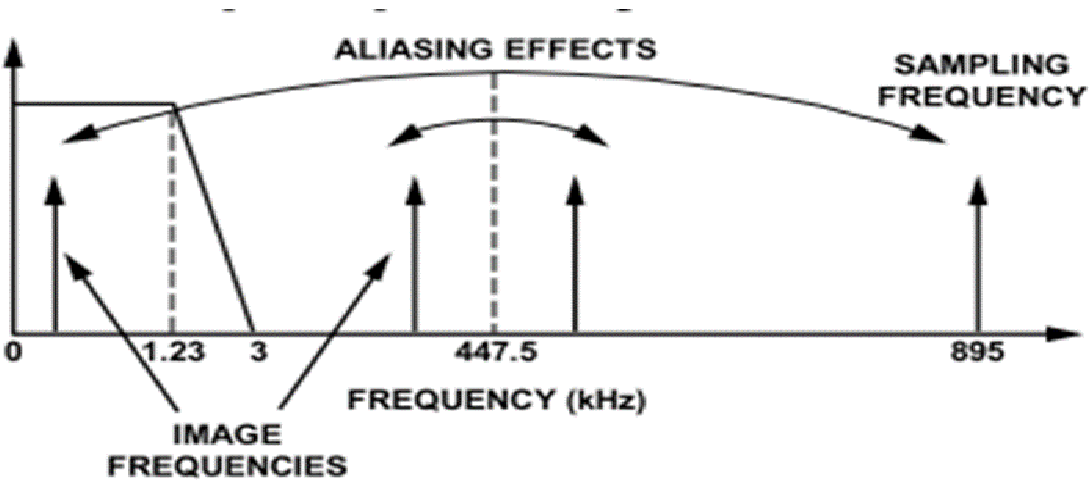

Figure 3.4: Antialiasing filter Devices (2009)

The illustration below in Equation (3.1) reflected the implementation of the RC low pass filter in ADE5166 energy measurement.

$$\frac{Vout}{Vin} = \frac{1}{1+j\omega RC} \qquad (3.1)$$

$$\left|\frac{Vout}{Vin}\right| = \frac{1}{\sqrt{1+(\omega RC)^2}}$$

3.2.5 Electrical parameter calculation in a sinusoidal single-phase system

Energy meters manufactured by different manufacturers are structurally designed differently with the ability to execute accurately as discovered previous reports Garcia (2017). This quality offers a broad calculation formula for energy and power estimation. In addition, there are some energy chips with the capacity to determine other electrical parameters. This segment concisely elucidates the mathematical techniques and equation used in most energy metering device existing in the market.

3.2.6 Root mean square (RMS) calculation

RMS is the measured value of an AC signal. Precisely, the rms of an AC signal equals the quantity in value of the required dc to produce an equivalent amount of power in the load. RMS, is expressed mathematically as Equation (3.2) below:

$$F_{RMS} = \sqrt{\frac{1}{T\int_0^T f^{2}(t)dt}} \qquad (3.2)$$

Where;

F_{RMS} denotes the RMS value of the function f(t), and

T is the periodic time.

The equation given below represent the RMS value of a time sampling signal.

$$F_{rms} = \sqrt{\frac{1}{N}\sum_{n=1}^{N} f_{\{n\}}^2} \quad (3.3)$$

Where; F_{rms} denotes the RMS value of the sampling signal, N denotes for the number of samples, and n denotes the n^{th} sample point of the signal. To calculate the RMS current of the sampling signal, the following methods were used in most energy measurement chips by considering ADE7953 energy metering IC chip. It uses the following methods to calculate the RMS current.

We can write the instantaneous current as shown in the Equation (3.4) below;

$$I(t) = \sqrt{2}.I_{RMS}^2.\sin(\omega t) \quad (3.4)$$

Hence;

$$I^2(t) = 2I_{RMS}^2.\sin^2(\omega t) \quad (3.5)$$

Where,

$I(t)$ denotes as the instantaneous current,

I_{RMS} refers to the RMS current,

ω denotes the angular frequency, and

t denotes to be the time used.

Therefore, in Equation (3.5), square both sides and substituting the value of 1- $\cos^2(\omega t)$ for $\sin^2(\omega t)$ as explained in a trigonometry formula that states;

Recall:

$$\sin^2(A) + \cos^2(A) = 1, \cos(2A) = \cos^2(A) - \sin^2(A) \quad (3.6)$$

The equation above is re-written as Equation (3.7) by making $\sin^2(A)$ the subject of the formula, and it becomes:

$$\sin^2(A) = \cos^2(A) - \cos(2A) \quad (3.7)$$

Since,

$$\cos^2(A) = 1- \sin^2(A) \quad (3.8)$$

$$\sin^2(A) = 1- \sin^2(A) - \cos(2A)$$

$$2\sin^2(A) = 1- \cos2(A)$$

Therefore,

$$\sin^2(A) = \frac{1 - \cos2(A)}{2} \quad (3.9)$$

∴ from Equation (3.5) above we have:

$$I^2(t) = 2I_{RMS}^2.\sin^2(\omega t)$$

Hence;

$$I^2(t) = 2I_{RMS}^2.\frac{1- \cos2(\omega t)}{2} \quad (3.10)$$

$$I^2(t) = I_{RMS}^2(1- \cos2(\omega t))$$

$$I^2(t) = I_{RMS}^2 - I_{RMS}^2.\cos2(\omega t) \quad (3.11)$$

To obtain the RMS current, the input signal from the current channel linked with ADC is squared as illustrated in Equation (3.11), while the square root of the average value is calculated. The averaging process is done by adding a low pass filter. The signal passes through the low pass filter, and then a high frequency component value is obtained, which is attenuated and the DC term I_{RMS}^2 is generated (see Figure 3.5[24]).

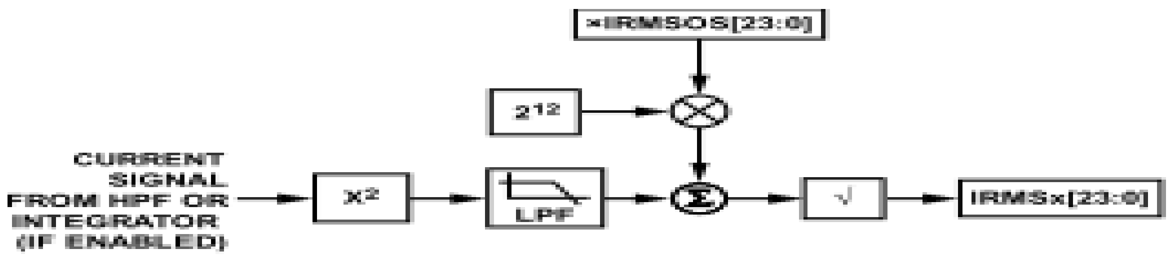

Figure 3.5: Current RMS

3.2.7 Root mean square (RMS) voltage

The calculation of the RMS voltage is like that of RMS current. However, some energy measurement chips use the mean absolute value calculation to derive the RMS voltage. The mean absolute value is accurate when the signal has only the fundamental component. When

[24] The diagram displayed in the Figure 3.5 was adapted from Devices (2013)

the signal has harmonic components, the calculation is somewhat inaccurate. Therefore, the mean absolute value calculation can be described as follow (see Equation 3.12) below;

$$V_{MAV} = \frac{1}{T}\int_0^T \left|\sqrt{2}.V_{RMS.}\sin(\omega t)\right| dt \qquad (3.12)$$

V_{MAV} denotes the mean absolute voltage,

$\frac{1}{T}$ denotes the periodic time, and

V_{RMS} denotes the periodic time.

$$= \frac{1}{T}\left[\int_0^{T/2} \sqrt{2}.V_{RMS.}\sin(\omega t)\, dt - \int_{T/2}^{T} \sqrt{2}.V_{RMS.}\sin(\omega t)\, dt\right] \qquad (3.13)$$

When we consider a change in the derivative with respect to $\omega = 2\pi f$; where $f = \frac{1}{T}$, $\omega = \frac{2\pi}{T}$, $\pi = \frac{\omega T}{2}$, $\pi = \omega(\frac{T}{2})$

$\theta = \omega t$

Find the derivative of θ with respect to t in the equation below

$$\frac{d\theta}{dt} = \omega(\frac{dt}{dt})$$

$$\therefore dt = \frac{d\theta}{\omega} \qquad (3.14)$$

Furthermore, put $\frac{d\theta}{\omega}$ for dt, θ for ωt, $\frac{\omega}{2\pi}$ for $\frac{1}{T}$ in Equation (3.13) above. Therefore,

$$V_{MAV} = \frac{\omega}{2\pi}\left[\int_0^{\pi} \sqrt{2}.\, V_{RMS.}\sin(\theta)\frac{d\theta}{\omega} - \int_{\pi}^{2\pi} \sqrt{2}.\, V_{RMS.}\sin(\theta)\frac{d\theta}{\omega} \right] \qquad (3.15)$$

$$V_{MAV} = \frac{\omega}{2\pi}.\frac{\sqrt{2}.\, V_{RMS.}}{\omega}\left[\int_0^{\pi}\sin(\theta)d\theta - \int_{\pi}^{2\pi}\sin(\theta)d\theta\right]$$

Hence, $V_{MAV} = \frac{\sqrt{2}.\, V_{RMS.}}{2\pi}\left[[-\cos\theta]_0^{\pi} - [-\cos\theta]_{\pi}^{2\pi}\right]$;

$$V_{MAV} = \frac{\sqrt{2}.\, V_{RMS.}}{2\pi}[-(-1-1) + (1+1)]$$

Finally,

$$V_{MAV} = \frac{\sqrt{2}.\, V_{RMS.}}{2\pi}$$

$$V_{MAV} = \frac{\sqrt{2}.}{2\pi}.\, V_{RMS} \qquad (3.16)$$

V_{MAV} is directly proportional to V_{RMS}. Equation (3.16) is applicable when the fundamental components are available. And the equation is then used for the calculation of RMS voltage. The diagram displayed in Figure 0.6[25] illustrates the process involved in attaining the output signal through accurate computation of the RMS voltage.

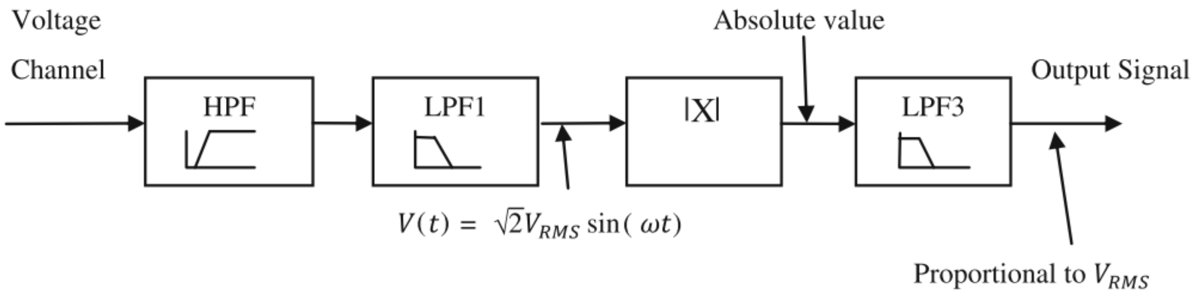

Figure 0.6: RMS voltage

3.2.8 Active power and energy calculations

Active power and energy calculations are being carried out within this section. The definition of the active power for every consumption is quite looked and mathematically solved.

3.2.8.1 Active power calculation

The electrical power is defined as the rate at which energy flows from the source to the load for consumption. The product of the instantaneous current and voltage, as written in Equation (3.17) and Equation (3.18) over a waveform, is called an instantaneous power signal. The power signal is equal to the rate at which energy flows within a periodic time (see Figure 0.6 above).

The unit of power is watt or joule/seconds. Therefore, mathematically we have:

$$V(t) = \sqrt{2}\,.V_{RMS}.\sin(\omega t) \qquad (3.17)$$

$$I(t) = \sqrt{2}\,.I_{RMS}.\sin(\omega t - \emptyset) \qquad (3.18)$$

$\emptyset$ denotes the phase angle between the voltage and the current.

V(t) and I(t) denote the instantaneous voltages and current respectively.

Hence, instantaneous power P(t)

$$P(t) = V(t).I(t) \qquad (3.19)$$

Substituting Equation (3.17) and Equation (3.18) for V(t) and I(t) respectively.

[25] The diagram displayed in Figure 0.6 was adapted from Devices (2013)

$P(t) = \left[\sqrt{2}\,.V_{RMS}\,.\sin(\omega t)\right].\left[\sqrt{2}\,.I_{RMS}.\sin(\omega t - \emptyset)\right]$

By opening the bracket, we have

$$P(t)=2V_{RMS}.I_{RMS}.\sin(\omega t)\,.\sin(\omega t - \emptyset) \qquad (3.20)$$

Recall, the trigonometry products of identities states:

$$\sin(A).\sin(B) = \frac{\cos(A + B) - \cos(A - B)}{2} \qquad (3.21)$$

if A=ωt and B = (ωt - ∅), then Equation (3.21) becomes

$$\sin(\omega t)\,.\,\sin(\omega t - \emptyset) = \frac{\cos\big(\omega t + (\omega t - \emptyset)\big) - \cos(\omega t - (\omega t - \emptyset))}{2}$$

Therefore, substitute $\frac{\cos\big(\omega t + (\omega t - \emptyset)\big) - \cos\,(\omega t - (\omega t - \emptyset))}{2}$ for $\sin(\omega t)\,.\,\sin(\omega t - \emptyset)$ in the Equation (3.20) above.

$$P(t) = 2V_{RMS}.I_{RMS}.\sin(\omega t)\,.\sin(\omega t - \emptyset)$$

$$P(t) = 2V_{RMS}.I_{RMS}.\frac{\cos\big(\omega t + (\omega t - \emptyset)\big) - \cos(\omega t - (\omega t - \emptyset))}{2}$$

$$P(t) = V_{RMS}.I_{RMS}.\cos(2\omega t - \emptyset) - V_{RMS}.I_{RMS}.\cos(\emptyset) \qquad (3.22)$$

The average power over an integral number of line cycle (n) is given as

$$P = \frac{1}{T}\int_0^{nT} p(t)dt \qquad (3.23)$$

Where,

P denotes the average power, and T denotes the line cycle period. For one cycle line, the average power can be obtained as written below:

$$P = \frac{1}{T}\int_0^{T} p(t)dt \qquad (3.24)$$

Then, substituting the value of $V_{RMS}.I_{RMS}.\cos(2\omega t - \emptyset) - V_{RMS}.I_{RMS}.\cos(\emptyset)$ in Equation (3.22) for p(t) in Equation (3.24).

$$P = \frac{1}{T}\int_0^{T} [V_{RMS}.I_{RMS}.\cos(2\omega t - \emptyset) - V_{RMS}.I_{RMS}.\cos(\emptyset)]\,dt \qquad (3.25)$$

If the derivative and the limits are represented in the form of θ, then we have $\frac{1}{T} = \frac{\omega}{2\pi}$ and $\omega t = \theta$, while $dt = \frac{d\theta}{\omega}$. Furthermore, substitute $\frac{\omega}{2\pi}$ for $\frac{1}{T}$, ωt for θ, $\frac{d\theta}{\omega}$ for dt in Equation (3.25) above

$$P = \frac{\omega}{2\pi}\int_0^{2\pi} [V_{RMS}.I_{RMS}.\cos(2\theta - \emptyset) - V_{RMS}.I_{RMS}.\cos(\emptyset)]\frac{d\theta}{\omega} \qquad (3.26)$$

$$P = \frac{\omega}{2\pi} \cdot \frac{V_{RMS}.I_{RMS}}{\omega} \int_0^{2\pi} [\cos(2\theta - \emptyset) - \cos(\emptyset)]\, d\theta$$

$$P = \frac{V_{RMS}.I_{RMS}}{2\pi} \int_0^{2\pi} [\cos(2\theta - \emptyset) - \cos(\emptyset)]\, d\theta$$

$$P = \frac{V_{RMS}.I_{RMS}}{2\pi} \int_0^{2\pi} \cos(2\theta - \emptyset) d\theta - \int_0^{2\pi} \cos(\emptyset)\, d\theta$$

$$P = V_{RMS}.I_{RMS}\cos(\emptyset) \qquad (3.27)$$

The active power (P) in the Equation (3.27) is equal to the DC component of the instantaneous power signal P(t). The power signal of the DC instantaneous component helps to extract the active power.

3.2.9 Active energy calculation

In the process of computing the active energy, rate of energy flow called power is considerable subject of the formula. The equation formulated is expressed mathematically as:

$$P(t) = \frac{dE}{dt} \qquad (3.28)$$

Where, P denotes the power, and E denotes the energy. The active power within the time domain is equal to:

$$\int dE = \int_0^t P(t)dt$$

$$E = \int_0^t P(t)dt \qquad (3.29)$$

T denotes the time period considered. In most energy measurement chips; the discrete accumulation time is used for the active energy calculation.

$$E_D = \sum_{n=0}^{N} p(nt)\,.t \qquad (3.30)$$

E_D denotes the obtained discrete time accumulated, t denotes sampled period for a discrete time, n denotes the n^{th} sample point, and N is the number of sampled points. When the discrete time sample period tends to zero, the energy calculated will become:

$$\int_0^{t_1} P(t)dt = \lim_{t \to 0} \sum_{n=0}^{N} p(nt)\,.t \qquad (3.31)$$

Equation (3.31) illustrates that active energy is measured high, whenever discrete time sample is very small. Thus, to eliminate active energy measurement error, the sample period value should be very small.

3.2.10 Reactive power and energy calculation

The section examines the how reactive power and energy calculation for every input voltage and current signals can be demonstrated within any particular energy meter.

3.2.10.1 Reactive power calculation

Reactive power occurs when the voltage and current waveform signals multiplied phase is shifted by 90^0. The generated waveform is called the instantaneous reactive power signal. Other essential mathematical illustration is formulated to elucidate the attainment of instantaneous current and voltage if an AC source connected to a load is lagging with a power factor. The attained equation is given below as:

$$RP(t) = V(t).I^{'}(t) \quad (3.32)$$

Recall.

Since,

$$I^{'}(t) = \sqrt{2}.\ I_{RMS}\ [\omega t - \emptyset + \frac{\pi}{2}] \quad (3.33)$$

$$V(t) = \sqrt{2}\ .I_{RMS}.\sin(\omega t - \emptyset + \frac{\pi}{2})] \quad (3.34)$$

Hence, substitute $\sqrt{2}.\ I_{RMS}\ [\omega t - \emptyset + \frac{\pi}{2}]$ for $I^{'}(t)$ and $\sqrt{2}\ .I_{RMS}.\sin(\omega t - \emptyset + \frac{\pi}{2})]$ for $V(t)$ in Equation (3.32) above.

Then, we have

$$RP(t) = \left[\sqrt{2}.V_{RMS}.\sin(\omega t)\right].\ [\sqrt{2}\ .I_{RMS}.\sin(\omega t - \emptyset + \frac{\pi}{2})];$$

$$RP(t) = [\sqrt{2}.\sqrt{2}.V_{RMS}.I_{RMS}.\sin(\omega t)\sin(\omega t - \emptyset + \frac{\pi}{2})]$$

$$RP(t) = [2.V_{RMS}.I_{RMS}.\sin(\omega t).\sin(\omega t - \emptyset + \frac{\pi}{2})] \quad (3.35)$$

3.2.10.2 Reactive energy calculation

The energy is defined in the equation (3.36) below:

$$E_R = \int_0^{t_1} q(t)dt \quad (3.36)$$

Where E_R denotes the reactive energy, q(t) denotes the instantaneous reactive power, and t_1 denotes the considered time period. However, reactive energy measured uses discrete time accumulation for reactive energy calculation. The formula employed in computing the reactive energy is written below:

$$E_R = \lim_{t \to 0} \sum_{n=0}^{N} q(nt).t \quad (3.37)$$

Where t denotes the discrete time sample period, n denotes the n^{th} sample point, and N is the number of sample points. Since the sample period cannot be kept at zero, a system with low reactive energy measurement errors is expected to be produced (by energy chip manufacturer) to keep the value small.

3.2.11 Apparent power calculation

Apparent power is referred to as the maximum power capable enough to be accessible to a load through the product of V_{RMS} and I_{RMS}. Therefore, apparent power is defined as the product of V_{RMS} and I_{RMS}. This type of power is independent of the phase angle between them. The apparent power signal is calculated in the AC signal.

$V(t) = \sqrt{2}.\, V_{RMS}.\sin(\omega t)$

$I(t) = \sqrt{2}.\, I_{RMS}.\sin(\omega t + \theta)$

Therefore,

$$P(t) = V(t).\, I(t) \quad (3.38)$$

$$P(t) = \sqrt{2}.\, V_{RMS}.\, \sin(\omega t)\, .\, \sqrt{2}.\, I_{RMS}.\sin(\omega t + \theta)$$

$$P(t) = 2.V_{RMS}.I_{RMS}.\, \sin(\omega t)\, .\sin(\omega t + \theta) \quad (3.39)$$

Recall from Equation (3.21) that:

$$\sin(A)\, .\, \sin(B) = \frac{\cos(A+B)-\cos(A-B)}{2} \quad (3.40)$$

Therefore, let $\sin(A) = \sin(\omega t)$, $\cos(A + B) = \cos\,(\omega t + (\omega t + \theta))$;

$\sin(B) = \sin(\omega t + \theta)$, $\cos(A - B) = \cos\,(\omega t - (\omega t - \theta))$

From the above equation (3-40),

$$\sin(\omega t)\, .\, \sin(\omega t + \theta) = \frac{\cos(\omega t + (\omega t + \theta)) - \cos(\omega t - (\omega t - \theta))}{2} \quad (3.41)$$

$$\sin(\omega t)\, .\, \sin(\omega t + \theta) = \frac{\cos(2\omega t + \theta) - \cos(-\theta)}{2}$$

Note that, $\cos(-\theta) = \cos(\theta)$

$$\sin(\omega t)\, .\, \sin(\omega t + \theta) = \frac{\cos(2\omega t + \theta) - \cos(\theta)}{2} \quad (3.42)$$

Substitute $\frac{\cos(2\omega t + \theta) - \cos(\theta)}{2}$ from Equation (3.42) for $\sin(\omega t)\, .\sin(\omega t + \theta)$ in Equation (3.39) and obtain the equation below

$$P(t) = 2.V_{RMS}.I_{RMS}.\frac{\cos(2\omega t + \theta) - \cos(\theta)}{2} \quad (3.43)$$

Simplification of Equation (3.43) produces Equation (3.44) below:

$P(t) = V_{RMS}.I_{RMS}.[\cos(2\omega t + \theta) - \cos(\theta)]$

$$P(t) = V_{RMS}.I_{RMS}\cos(2\omega t + \theta) - V_{RMS}.I_{RMS}.\cos(\theta) \quad (3.44)$$

3.2.11.1 Apparent energy calculation

Apparent energy calculation is a simplification of important parameters like apparent energy, E_A; instantaneous apparent power, s(t); and time period of consideration, t_1 in the equation below.

$$E_{A=\int_0^{t_1} s(t)dt} \quad (3.45)$$

3.2.11.2 Power quality measurements

In this section, it is necessary to discuss the quality of power generated and its maintenance procedures without any interference or shortcoming. In addition, IEC categorised power quality as a source of noise disturbance. Power quality is defined as the process of keeping the sinusoidal waveform of the bus power distribution of voltage and current constant, in terms of their rated magnitude and frequency, in the process of transporting it from one location to another Sengupta (2011). Similarly, a research report from Dugan (2004) claimed that power quality could be defined based on various frames of reference.

This power quality is used for definite voltage quality, current quality, the reliability of service, and power supply quality Nkusi Emmanuel Musoni (2018). Power quality is described by the utility as the statistical validation that the system used in 99.98% consistent and efficient in accordance with the graphical illustrations in Figure 3.7[26] Toledo (2013). Regulated agencies also take a clue from this term by following up with the definition in the same direction. Similarly, manufacturers defined power quality as a feature of the power supplied that empowered the equipment to work appropriately well Bara (2016). Power quality is the end user issues and the consumer-driven point of reference that become vital in the efficient report of power supply and consumption rate between the customers and utility.

[26] The graphical diagrams displayed in Figure 3.7 and Figure 3.8 were adapted from Toledo (2013)

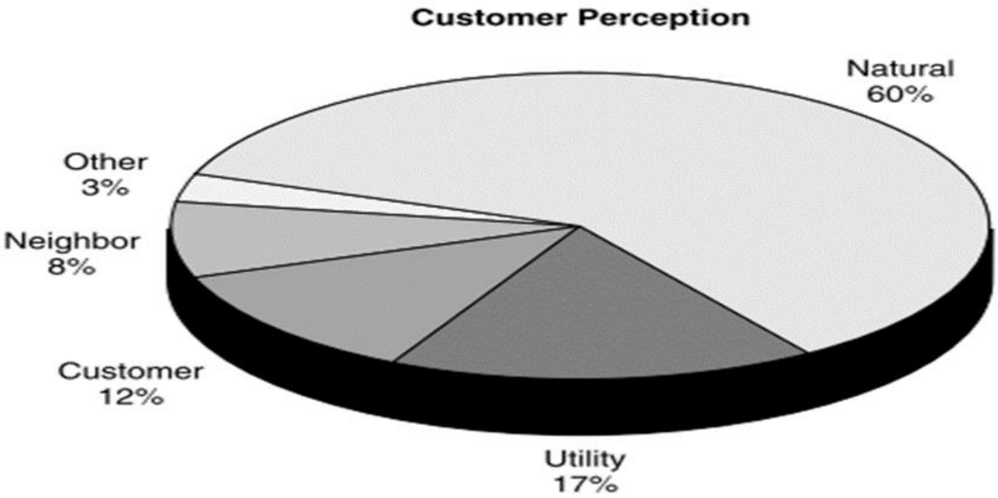

Figure 3.7: Customer's perception

Additional finding discloses that power quality is the power drawback discovered in the current, voltage, or frequency abnormality that result in customer equipment failure Toledo (2013). Many times, there have been paramount complaints from the end users to the utility whenever there is incessant power outages and equipment breakdown Nkusi Emmanuel Musoni (2018). Although, from the utility viewpoint, the process could develop a problem from the feeding process to the customer Bara (2016). Capacitor switching is identified as one of the commons factors causing these problems for the utility system and giving rise to transient overvoltage which degrade the performance efficiency of any manufactured equipment Dugan (2004).

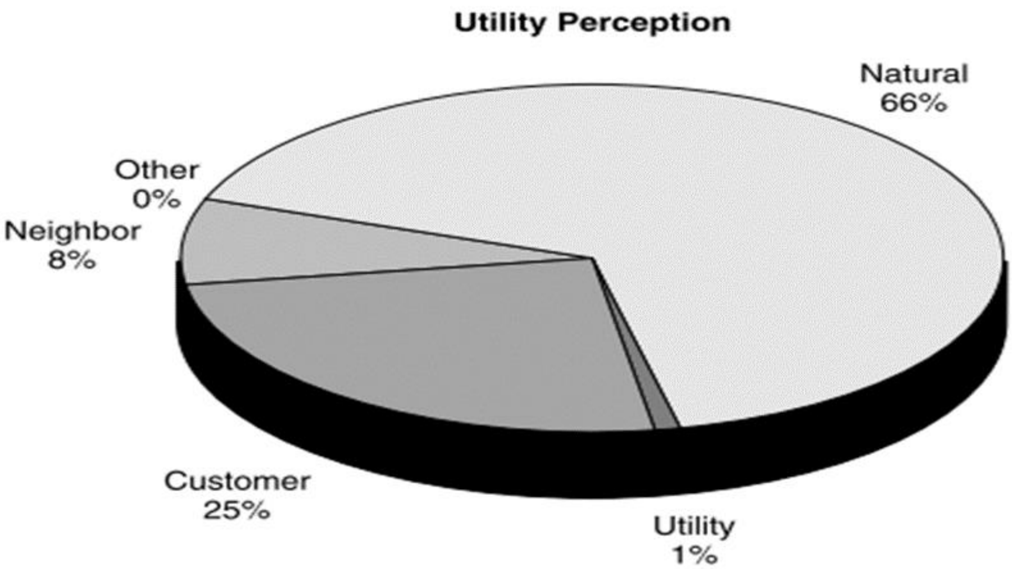

Figure 3.8: Utility's perception

Furthermore, an electronic component can experience degradation over a period of time due to constant encounter with transient voltages Nkusi Emmanuel Musoni (2018). This effect makes the component to fail because of its relatively low magnitude event. In that case, to relate specific cause of failure, it's extremely problematic many times. This urges the software control designers to develop microcontroller-based equipment with the purpose of comprehending how power systems operate. A device can perform poorly due to inefficient software.

Actually, poor quality is generally hampered by power line disruption, such in the aspect of instance impulses, notches, voltage sag, swell voltage, current unbalances, momentary interruption, harmonic deformations, and reactive power. Sengupta (2011) further enumerated stages in which power qualities can be divided into, such stages as:

- Sources,
- Effects,
- Fundamentals concepts,
- Modeling and analysis,
- Instrumentation, and
- Solutions.

From the highlighted stages, sources are described as vicinities in which undesirable variation in the events of electrical parameters occurs. Power engineers encounter difficulty when determining the source of power quality because of the ever-increasing complex network. Other contributing factors identified are the efficiency of the utility and consumer equipment due to diverse disturbances caused by bad quality conflicts. Fundamental concept assists in the recognition of the parameters and the intensities of variation; most especially, the rated magnitude which is the bases for power quality deprivation (Dugan et al., 2004). In modeling and analysis domains, the mathematical based approach is considered a means of averting the presence of disturbance, occurrence, source, and its effect. Instruments are used to monitor and measure the constant parameter and the electrical power quality. Nevertheless, the complete distribution of pure power for consumption is considered improbable. Then, the major solution is to determine how disturbance effect of power quality can be totally decreased.

3.2.12 Classification of power system disturbance

Electrical disturbance of various kinds gives rise to power quality degradation. Power quality is said to depend on the amplitude and frequency of electrical parameters (Sengupta, 2011). The orders of degradation caused in a power system are identified as transients, interruption/under voltage/over voltage and voltage/current unbalance. Further discussions on these orders are provided in the subsequent subsections.

3.2.12.1 *Transients*

Transients, one of the orders of degradation caused in a system, is perceived to be triggered by the system itself or other systems involved (Dugan et al., 2004). Transient is classified into two categories, which are AC and DC transient. The AC transient is further fragmented into single and multiple cycles.

3.2.12.2 Interruption / under voltage / over voltage

These are the very common types of disturbances. It occurs during power interruption as the voltage level of a bus goes down to zero (Sengupta, 2011). The interruption maybe for short, medium, or long period of a time. The fall and rise of voltage levels of a particular bus give rise to either over-voltages or under-voltages (Dugan et al., 2004). Nevertheless, under-voltages and over-voltages are permitted for certain percentage limits. If these limits are exceeded, therefore they are disturbance. Disturbance increases the amount of reactive power drawn or delivered by the system Sengupta (2011).

3.2.12.3 Voltage / current unbalance

Voltage and current unbalances are discovered during instability in systemic operations like generating, transmitting, and loading Toledo (2013). Negative sequence components discovered during unbalance hampers the performances and stabilities of voltages in the system(Sengupta, 2011).

Chapter 4: Design of low-cost smart energy meter using GSM

4.1 Chapter review

This chapter considers introduction on the need for the choice between DSP and energy metering IC. More discussion is carried out on smart energy meter operational block diagram to depict the major blocks that constitute energy meter. More so, a clear discussion on the common energy metering IC and the development boards is discussed, to buttress the actualization of the smart energy meter operational block diagram. Significantly, further discussion is extended towards forms of microcontroller, interfacing LCD with microcontroller, and interfacing relay with current sensor. Notwithstanding, the daunting challenges encountered in the design are discussed

4.2 Introduction

Operational block diagram of the developing smart energy meter is composed of standard energy measuring chip, microcontroller, LCD and GSM module as the basic in smart energy meter design. The design and development of the new smart energy meter involved the use of component like Arduino Uno board ATmega328P. This component operates as the microcontroller unit to stabilise the energy meter, due to its diversity use and multifunctional qualities. Other advantages of considering this Arduino Uno board ATmega328P are fundamentally based on its ability as an integrated single based microcontroller that serves as open-source platform. It has 14 digital input and output pins that accommodate pulse width modulation (PWM) which comprises of 6 pins, six analog inputs a 16MHz crystal oscillator and a USB connection, a power jack and ICSP header, and a reset button.

Furthermore, this microcontroller board can be programmed to measure the active, reactive, energy, power current and voltage RMS; all in single-phase system. Use of datasheet guides through a test circuit with a suitable schematic diagram approach. This study boosts the advantage of date readings as well as control the distribution of SMS and calls in monitoring the household energy consumption rates and engaged energy billing. This operation is aided with microcontroller unit Arduino Uno board ATmega328P, to attain proper communication of data and calibration. However, this operation is catalysed by the introduction of the SPI bus, which enables the microcontroller to receive information from the energy chip and relay it to the consumers through LCD. Therefore, the consumers can access and monitored their energy consumption by communicating the energy parameter GSM to the consumer. The device has a reset button linked with the microcontroller to enable a constant check of the information relay to the consumers from the utility on a monitoring screen. The information relayed include a time stamp processed by in-built real time clock located in the controlling unit, which relay up-to-date signal to keep records with every data.

Furthermore, the energy parameters are transmitted via the SIM900 module as it communicates with the GSM and sent to the end-user's phone as display. The power supply is inevitably modelled to power all the components in the system. The system is design for local and residential applications. In addition, the system can be upgraded for industrial use in the future research. The below smart energy block diagram shows the proposed smart energy metering device.

4.3 Smart meter operational block diagram

The smart energy operational block diagram in Figure 4.1.demonstrates the set of components involved in making a low cost smart energy meter that is multifunctional, robust, highly efficient, and thus lessened consumers' stress in purchasing energy credit unit from vendors and utilities. From the utility viewpoint, the device will reduce production cost, billing cost and maintenance cost of procuring one.

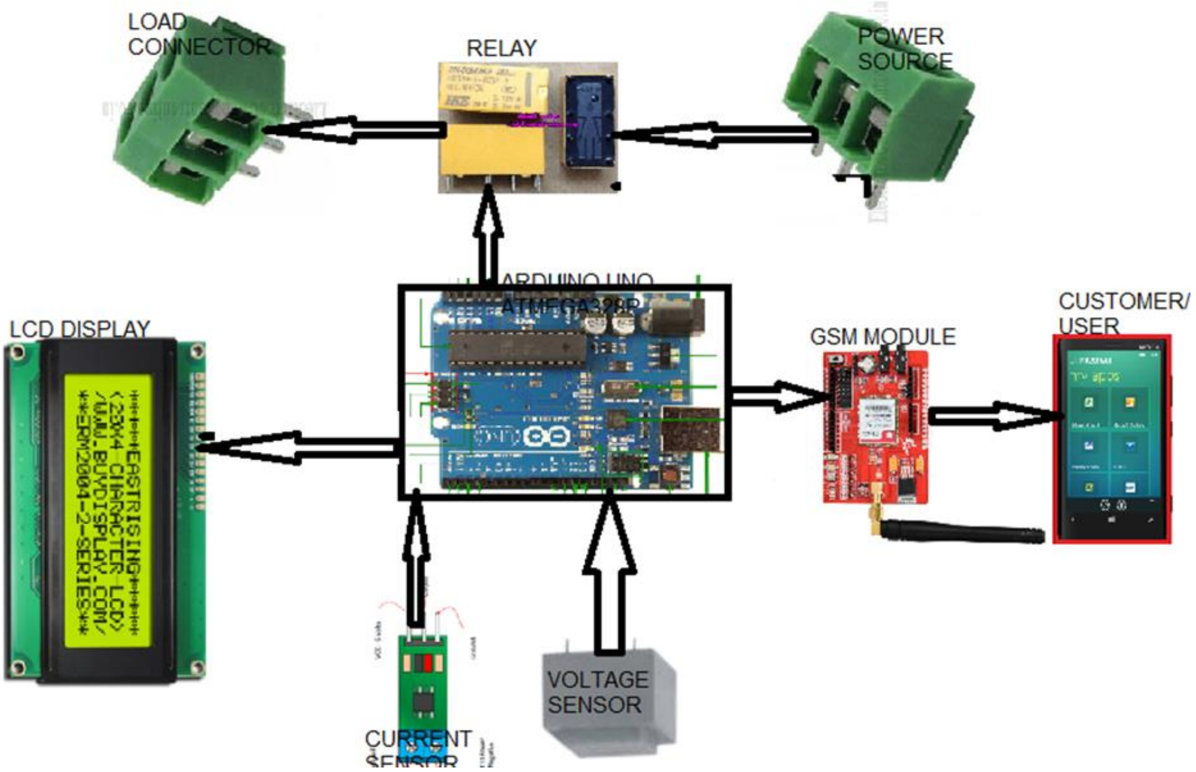

Figure 4.1: Smart meter operating block diagram

4.4 Common energy metering IC

This section analysis the available common energy metering IC used at executing energy metering design with respect to their strengths, functionalities, features

4.4.1 Energy meter IC

There exist various energy metering IC available in the market. Among these are ATM90EXX, MCP39xx, ADE77xx, ADE79xx, 71M6541x, and STPM3x.

4.4.4.1 ATM90EXX energy meter IC

ATM90EXX is a high-performance energy metering device for single-phase two-wire, single-phase three-wire, or anti-tampering energy meters (see Figure 4.2 below[27]). This energy meter IC is also used in power instruments to measure voltage, current, etc.

- Fully compliant with IEC standard IEC62052-11 and IEC62053-21.
- Applicable to class 1 or class 2 single-phase watt-hour meter.
- The active energy accuracy of 0.1% and 0.2% for reactive energy over a dynamic range of 5000:1.
- Temperature coefficient is 15ppm/^{0}C (typical) for on-chip reference voltage.

Electrical parameters measurement:

- Less than 0.5% fiducial error for Vrms, Irms mean active/apparent power, frequency, power factor, and phase angle.
- Standard 4-wire/simplified 3-wire SPI interface.

It has dedicated ADC and different gains for L and N line current sampling circuits. Current sampled over shunt resistor or current transformer (CT). Voltage sampled over resistor- divider network or potential transformer (PT).

Programmable L line and/or N line metering modes:

- Anti-tampering mode (larger power)
- L line mode (fixed L line)
- L+ N mode (applicable for single-phase 3-wire system)
- Flexible mode (configure through register)

Voltage channel (when the gain is '1') → 120 (Vrms~600mVrms)

L line current channel (when the gain is '24') → 5 (Vrms~25mVrms)

N line current channel (when the gain is '1') → 120 (Vrms~600mVrms)

Parameters:

Measurement error → 0.1%

[27] The picture displayed in Figure 4.2 and Figure 4.3 were adapted from Microchip Technology Inc (2014)

Dynamic range → 5000:1

Gain selection → Up to 24x

ADC resolution bits → 16

Channels → 3

Phase → single-phase

Device type → energy meter IC

Interface → SPI/pulse output

Operating voltage (V) → 3.0 - 3.6

Temperature Range (^{0}C) → -40 to 85

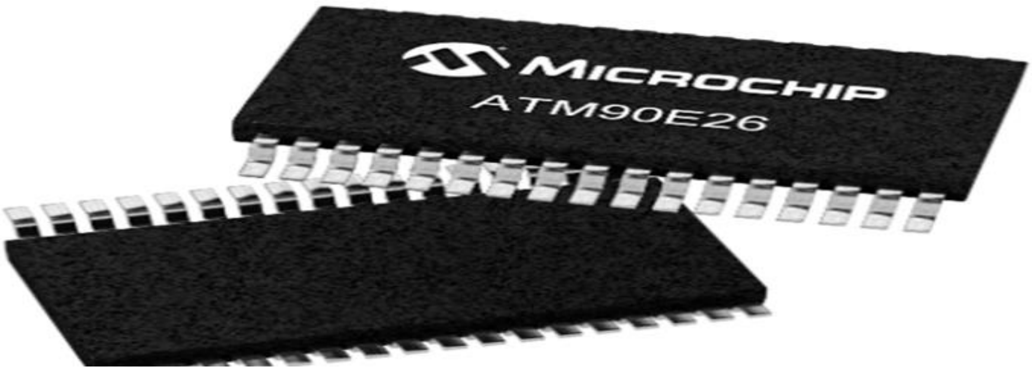

Figure 4.2: ATM90Exx energy meter IC

4.4.4.2 MCP39XX energy meter IC

MCP39xx is an energy measurement IC that supports the IEC 62053 international energy metering specification (see Figure 4.3 below). The output of the device includes a frequency proportional to the average active (real) power at the inputs, with a simultaneous serial SPI interface to access the ADC channels and multiplier output data. The MCP39xx incorporates two 16-bit delta-sigma ADCs with a programmable gain up to 16. The output waveform data is available at up to 14 kHz with 16-bit ADC output, including a 20-bit multiplier output data. The integrated on-chip voltage reference has an ultra-low temperature drift of 15 ppm/^{0}C.

Features:

1. Supplies active (real) power measurement for single-phase and residential energy metering.
2. Supports IEC 62053 international energy metering specification and legacy IEC 1036/61036/687 specifications.

- Two multi-bits, DAC, second order, and 16-bit.
- Delta-sigma analog-to-digital converters (ADCs).
- Ultra-low drift on-chip reference → 15 ppm/^{0}C (Type) and Low IDD of 4 mA (Type).
- Active power pulse output.
- SPI™ interface for access to raw ADC and multiplier data AEC-Q100 Grade 1.

Parameters:

Measurement error → 0.1%

Dynamic range → 1000:1

Gain selection → 1:16

ADC resolution bits → 16

Channels → 2

Phase → Single-Phase

Device → Energy Meter IC

Interface → SPI/Pulse Output

Operating voltage (V) → 2.7 - 3.6

Temperature range (°C) → -40 to 125

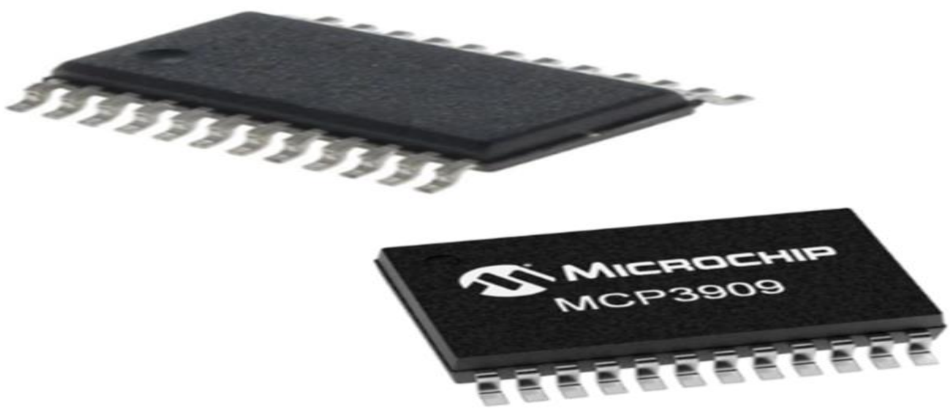

Figure 4.3: MCP39xx energy meter IC

4.4.4.3 ADE77xx energy meter IC

ADE77xx is an energy device designed and developed by Analog Device Company to perform a high accuracy energy metering task (see Figure 4.4 below[28]). The design of this device

[28] The picture displayed in Figure 4.4 was adapted from Mouser Electronic (2019)

incorporates an on-chip clock oscillator that serves as clock source with up to 50Hz-60Hz. Moreover, the device is characterised with less error of about 0.1% over a dynamic range of 500:1. This quality makes the device unique among other similar devices.

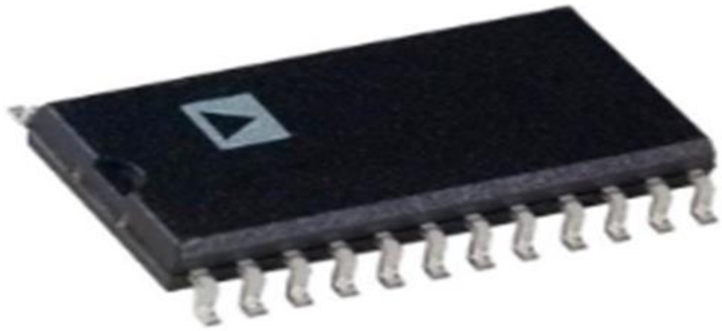

Figure 4.4: ADE77xx energy metering IC

Other qualities include its ability to operate at a positive real power; explicitly at two basic output frequency namely F1 and F2. The device has viability of detecting any malicious connection through its logic detector and on-chip power supply monitoring scheme generated by a single 5v DC supply. The chip is cost effective in building a smart energy meter.

4.4.4.4 ADE79xx energy metering IC

ADE79xx IC is a single-phase, multifunction metering IC that provides a second current input for neutral current measurement (see Figure 4.5[29]). It has high accuracy in electrical energy measurement particularly design for single-phase applications, Other features includes line voltage and current, which enable the device to calculate active power, reactive, apparent power, and instantaneous Vrms and Irms. Also, the device is manufactured by Analog Device Company.

Figure 4.5: ADE79xx energy meter IC

Basically, the device includes three sigma-delta ADC with a high-accuracy energy measurement core. The third input channel simultaneously measures the neutral current, tamper detection, and neutral-current billing. The additional channel incorporates a complete

[29] The picture displayed in Figure 4.5 was adapted from Devices (2013)

signal path that allows a full range of measurements. Each input channel supports independent and flexible gain stages, which make the device suitable for use with a variety of current sensors like current transformers (CT's) and low-value shunt resistors.

4.4.4.5 71M6541x energy meter IC

71M6541x energy meter IC is a system-on-chip device used as energy metering IC. The device is named Teridian considered as the 4th generation, with components such as single-phase MPU core, low- power RTC, digital temperature compensation, flash memory, and LCD driver (see Figure 4.6[30]). More so, it has single converter technology with a 22bit delta-sigma ADC, four analog inputs, precise voltage reference, digital temperature recompense and a 32bit computation engine (CE) that supports a wide range of metering applications with very few external components.

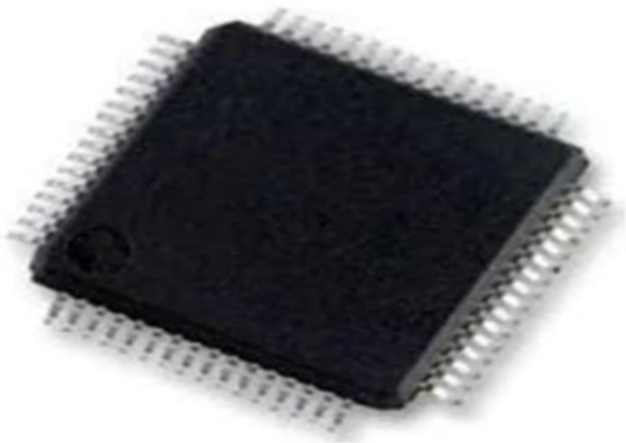

Figure 4.6: 71M6541x energy meter SOC IC

Further attributes include its ropes optional interfaces, and series of isolated sensors that offers BOM cost reduction, immunity to magnetic tamper, and improved reliability. Furthermore, it has 64-pin LQFPs with 32/64-kbyte flash memory options. The device has 0.1% accuracy rate over 2000:1 dynamic range with a programmable 32-bit metrology engine that adapts to meeting the changing utility requirements.

4.4.4.6 STPM3x energy meter IC

This is another form of smart energy meter IC like analog front end (AFE) (see Figure 4.7 below[31]). The design operational responsibilities include the measuring of active, reactive, and apparent energy parameters in power line system, through the application of shunt sensor and current transformer. This is because the device has features that can attain accurate measurement of DC and AC energy, when extremely low measurement is being considered.

[30] The picture displayed in Figure 4.6 was adapted from Corp (2016)
[31] The picture displayed in Figure 4.7 was adapted from STMicroelectronics (2018)

Also, it can perfectly compute a successful measurement rate of instantaneous Vrms and Irms, frequency (ripple-free active energy pulsed output) and selectable RC or crystal oscillator less than 0.1% error over 5000:1 range, precision voltage reference of 1.23v and 30ppm0/c max.

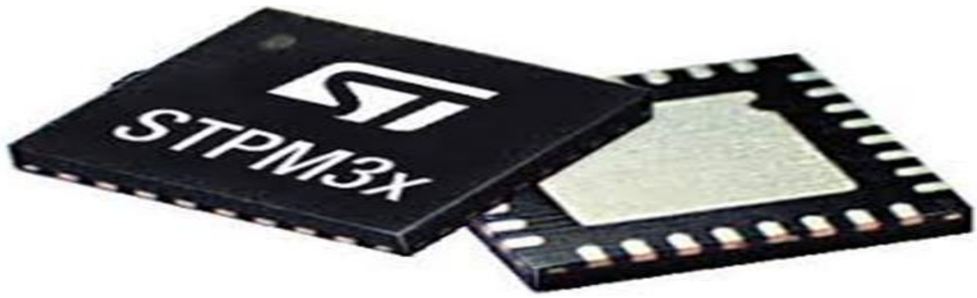

Figure 4.7: STPM3x energy meter IC

Features of high accuracy is applicable in class 0.2 meters, 4 kHz bandwidth, and very fast single point calibration. In addition, the uniqueness of considering this device is its ability to support and adapt with various sensors such as Rogowski coil, shunt resistor, and current transformer. More so, it can host three to five wires interfaced SPI and UART; and it is used as split, single– and poly–phase energy meters, up to class 0.2 accuracy, smart plugs, and appliance with smart power monitoring systems.

4.5 Common development boards

The most important section of any design are the Hardware section and the software section. The software section is prone to constant changes and modifications. Nevertheless, the hardware section of every design requires diligent attention so that a design without malfunction can be put into proper consideration. This necessitated the use of the relatively efficient and cost-effective components to avoid bogus circuit designs. The information below highlights the common boards which could be considered at a low-price smart energy meter design which are durable in design.

4.5.1 ATM90E25 development board

ATM90E26 is a single-phase energy metering development board used in demonstrating the process and testing involved in the development of AT90 E26 (single-phase energy metering AFE chip) (see Figure 4.8[32]). It has the capacity to sample current, voltage, input active/reactive energy, and output active/reactive energy, as well as measures parameters such as voltage current and power.

[32] The pictures in Figure 4.8 and Figure 4.9 were adapted from Microchip Technology Inc. (2014) and Silicon Labs. (2019)

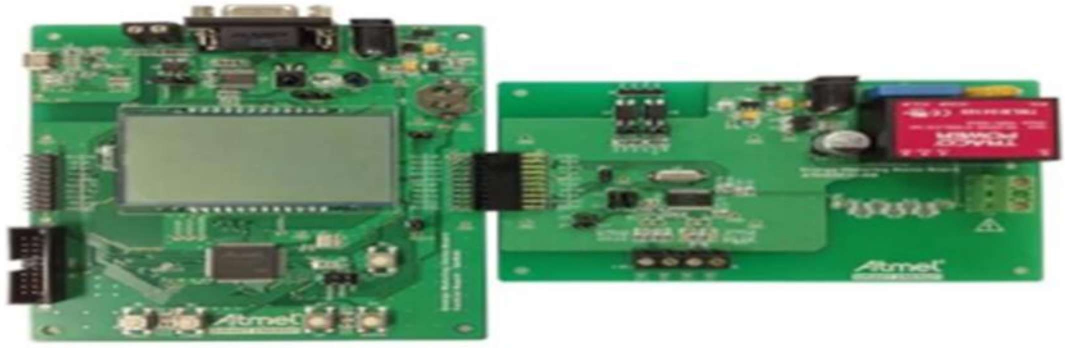

Figure 4.8: ATM90E25 development board

4.5.2 C8051 development board

This development board integrates innovative energy–smart USB peripheral interface charger that detects circuit and 8KV ESD protection (see Figure 4.9 below). It has upgraded high speed communication interfaces into small packages and make them ideal for space–constrained USB applications. The C8051 core is highly efficient with analog precision, such as categories as. The family has:

- USB I/0 controls and dongles.
- Medical equipment.
- Fast speed communication bridge.
- Consumer electronics.

Features in 8051 development board are highlighted as:

- It features 8-bit C8051 core with 50 MHz maximum operating frequency.
- It has 22 multi-function, 5V talent I/) pins.
- Slave and 12C slave have the development board.
- 16-bit timers.
- USB charger detect circuit (USB – BCS 1.2).

Figure 4.9: C8051 development board

4.5.3 MSP-430 development board

MSP-430 is an ultra-low power microcontroller (see Figure 4.10 below[33]). It was designed by the Texas Instruments called mixed-signal microcontroller. The board has a very low idle mode that is less than 1uA. It has 16-bit CPU and 25MHz that can be regulated to low power consumption. This device has a variety of configurations including the internal oscillator, watchdog, and timer including PWM, SPI, i2, USART, 10/12/14/16/24-bits ADC's and reset circuit. There are exceptional peripherals on the device board such as comparators, signal conditioning, LCD Driver, 12-bit DAC, DMA, USB, and hardware multiplier. The EEPROM and high-volume mask ROM in-system

[33] The picture displayed in Figure 4.10 was adapted from SLAU747B (2017)

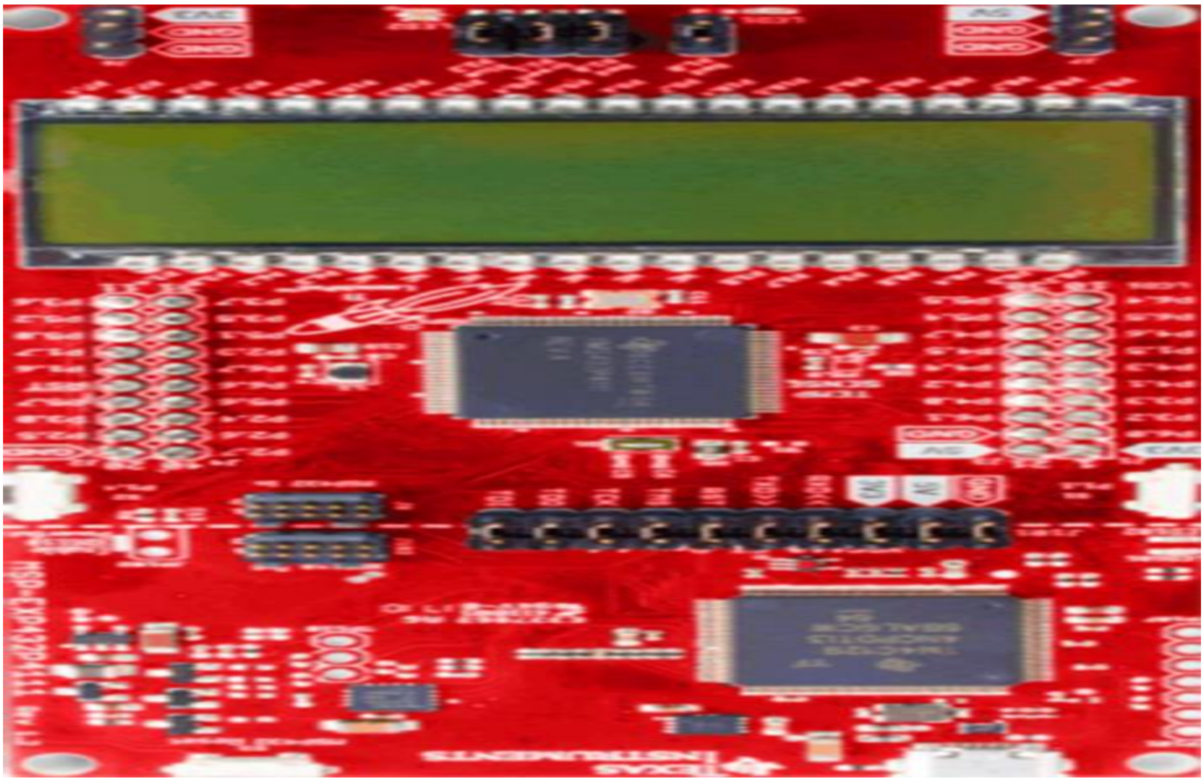

Figure 4.10: MSP-430 microcontroller development board

programmed through JTAG or UART or USB. It can work perfectly in 12V AC/DC power supply with an on-board rectifier for the conversion of AC to DC.

4.5.4 ARM-32bit development board

ARM-32bit is a single chip 16/32bit microcontrollers with different size of flash such as 512KB, 256KB, and 128KB (see Figure 4.11 below[34]). The device has a 4- channel 10-bit ADC. The device has on-board RS232 ports with Philips flash burner for the hex code downloading through the RS232 port and on-board 2line x 16-character LCD Display. The board works on either 12V AC/DC with optional USB socket for the purpose of power supply.

Table 4.1 below displays a tabularised list of various potential smart energy metering used energy metering IC and development boards with their corresponding costs. There are some key parts that fundamentally constituent hardware and software for every smart meter (Ajenikoko & Olaomi, 2014). The emphasis of the project development is based on the choice of the hardware components used in cost alleviation relative to functionality and efficiency of the device (Bacurau et al., 2014). We shall be taking inventory of these keywords such as low-cost, robustness, multi-functioning, and energy efficient.

[34] The picture displayed in Figure 4.10 was adapted from Microchip (2019)

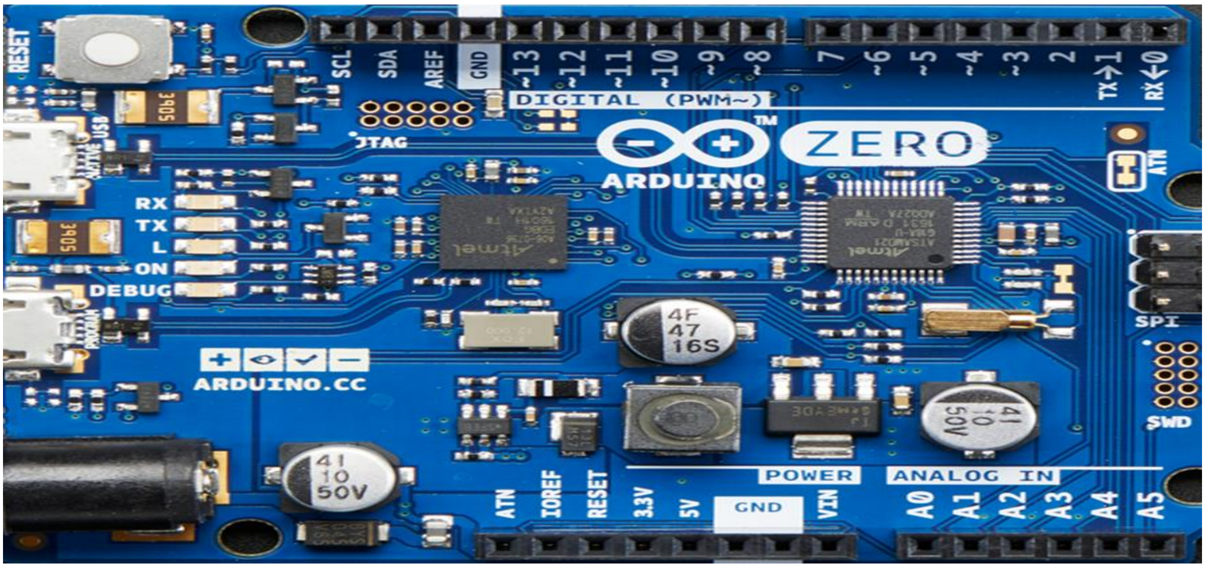

Figure 4.11: ARM-32bit development board

Table 4.1: Common energy metering IC and development board mostly used

Names	Prices
ATM90Exx energy meter IC	R6383.31
MCP39xx meter IC	R25.6
ADE77xx energy metering IC	R144.25
ADE7953 IC energy meter IC	R21.05
71M6541x metering SOC IC	R171.46
STPM3x energy meter IC	R25.26
ATM90E25 energy meter development board	R1543.2
C8051 development board	R401.80
MSP-430 microcontroller development board	R347.83
ARM-32bit development board	R159.36
Atmega328P Arduino Board	R126.09

4.5.5 Smart Energy Meter Robustness

According to Business Dictionary (2019), low-cost means to buy, procure at a relatively minimum cost. It could also mean a strategy set out to moderately meet the demand of the consumer at a lower cost. Although cost of values is greatly imperative to the process of achieving a prototype that could be affordable. In that case, this study adopts this cost approach with respect to hardware components cost analysis, by comparing the costs of the hardware components used for available manufactured products in the market. This approach offers the possibility of selecting the most suitable one, with the right specifications and cost affordability to suit the required objectives.

As reported by Taguchi (2019), robustness in a design means making an active response to contradict any source of variation in a particular system. This variation, in most times, is classified as noise which would make the product unfit for acceptability. The smart energy meter design as in Figure 5.10 below can withstand any harsh wealth. It has the capability to operates consistently for decades and still produce accurate measurements. It has a stable protective measure set a limit at 2000W, if surpassed spark off the PNP transistor to open the relay. In that case, energy consumption is easily truncated, which assists the consumers to reduce his or her consumable loads. This effect displays overload on the display unit. Hence, building structure is prevented from any sudden fire attack. The ability of a device to carry out different tasks independently is called multi-functioning device (MFD). Ultimately, the device must be energy efficient and adequate to raise product market value.

4.6 Methodology actualization, choice, and breakdown

The method used in this study is the implementation of serial communication principle in conjunction with the embedded system. It has components such as energy metering IC, microcontroller, and GSM modem. The GSM\ modem is used in communicating between modem and the system through the interfaced microcontroller unit. The components used in the design is invariably itemised in detail in the subsections.

4.6.1 Voltage and current sensor unit

Generally, voltage and current sensors are widely available in the market today but identifying suitable ones to sense electrical physical parameter such as RMS current and voltage, apparent, active, and reactive power is important. Therefore, for energy consumption to be calculated in real time, voltage and current sensing are significantly required. Literally, this means that selection of components is highly valued by following the manufacturing specification standard. In addition, common voltage sensors identified are voltage divider and potential transformer (refer to subsection 2.9.3.1), while common current sensors identified are current transformer, Rogowski, shunt resistor, and Hall Effect sensor (refer to subsection 2.9.3.2 above).

Voltage divider covers limited space covered on the printed circuit board (PCB). It boosts linearity performance while it is being compared with a potential transformer. The dissimilarity between them is that voltage divider is not isolated, while potential averts any needless electrocution if one touches unprotected cable. Therefore, this requires spontaneous need for voltage isolation when installed in a smart metering that has potential transformer.

Clearly, data acquisition processing is one of the basic operations that constitute a smart meter. This necessitate the importance of considering the use of a potential voltage for voltage signal acquisition, wherein ACS712-30A current sensor relates to the analog part to initiate signal in pulse-form required for current measuring to meet energy metering IC specification. Although, high cost of voltage sensors plays important role in achieving the objectives of this study. Consequently, potential transformer will be considered because it is simple, affordable, and accessible. Also, the LEM product has a high resolution which dictates the performances of the smart meter.

4.6.2 Smart energy Meter standard

Generally, most of the electricity smart energy meter designed are hinged around standards specific for their implementation. These standards are adopted in the area of achieving inter-operability within communications modules and smart meters. ANSI C12.2014 protocols are defined for transportation of data bi-directionally. Furthermore, South African government introduced national smart metering standards NRS049:2008 were released for the enactment of Advanced Metering infrastructure (AMI) systems in the country. The standard corroborated the need for meter to store in total registered energy consumption data every thirty minutes intervals. In addition, the acquiring billing system engages the total cost and the half hourly data policy. Finally, all the standards are duly incorporated within our smart energy metering design.

4.6.3 Current sensing unit

From the datasheet containing ADE7953 IC, the two integrated circuit channels, current channel A and B were sub-divided into input phases (Analog Devices, 2013). Each phase has a neutral current line (Analog Devices, 2013). The variables discussed in the datasheet are IAN, IAP, IBN, and IBP, whereas inputs channels are driven by the Pin 5, Pin 6, Pin 9, and Pin 10 of the ADE7953 IC respectively, with full differential values ranging from ±500mV. In this application, two current sensors considered are ACS712-30A current sensor and the hall effect sensor (LEM product; LV–25p).

4.6.4 Microcontroller unit

A microcontroller is a self-sufficient system that has peripheral memory and a processor that constitutes an embedded system. This system is built on a single integrated circuit, which is a combination of components of processor core, programmable input/output peripherals, and memory. The program memory could be in form of NOR flash or OTP. As part of the components embedded in the system, read only memory (ROM) and reading access memory (RAM) are encompassed in the chip.

Operational description of microcontrollers demonstrates that the device is used as an embedded application to control the activities going on in the system as its main brain. This statement validates the importance of reducing the size and cost associated with the design of a system that uses single microprocessors, memory, and input/output devices. Microcontrollers make it cheaper to run, control, and process a system digitally. These tasks are executed by mixed-signal microcontrollers, which integrate analog components required to control non-digital electronic systems. However, another name for the microcontroller is the embedded controller. This microcontroller based on several embedded features, which are bits, flash, RAM, size, number of input/output lines, packaging types, supplied voltage and speed.

4.6.5 Manufacturers

The microcontrollers listed in the Table 4.2 are automatically controlled devices that include power tools, toys, office machines, appliances, remote controls, and metering. Others are remote controls, automobile engine control systems, office machines, implantable medicals devices, appliances, and other embedded systems. The table below have lists of microcontroller manufacturers we have today, as seen in table 4.2.

Table 4.2: A tabularised list of manufactured microcontrollers with notable brand names

Manufacturer owned microcontrollers with notable brand names	
Materials	
Cypress	MSP430
Microchip	Texas
NXP	PIC
Renesas Electronics	ARM
STMicroelectronics	AVR

ATMEL Corporation	8051
Innovasic	

4.7 Forms of microcontroller in use till date

The table 4.3 itemised the forms of microcontroller unit in used till date as seen below. This table x-ray the notable microcontroller chips available in the market. It discusses and compare the following features as the microcontroller to ascertain which one is best suitable for use in designing energy metering.

Table 4.3: Forms of microcontrollers used

	8051	**PIC**	**AVR**	**ARM**
Bus width	8-bit standard	8/16/32-bit	8/32 bit	32/64 bit
Communication protocols	UART, USART SPI, 1^{2}C	PIC, UART, USART LIN, CAN-Ethernet, SPI,1^{2}S	UART, SPI,1^{2}C Special purpose AVR Support CAN USB Ethernet	UART, USART, LIN,1^{2}C, SPI, CAN, USB, Ethernet,1^{2}S, DSP, SAI (serial audio interface)
Speed	12-clock instruction cycle	4-clock Instruction Cycle	1-clock instruction cycle	1-clock instruction cycle
Memory	ROM, SRAM, Flash	SRAM Flash	Flash, SRAM, EEPROM	Flash, SDRAM, EEPROM
ISA	CLSC	Some feature of RISC	RISC	RISC
Memory	Van Neuman	Harvard	Modified	Modified Harvard architecture
Power Consumption	Average	Low	Low	Low
Families	8051 Variant	PIC 16,17,18,24,32	Tiny, Atmega, Xmega, Special purpose AVR	ARMV4,5,6,7 and series
Community	Vast	Very Good	Very Good	Vast

Table 4.3 continues below.

	8051	PIC	AVR	ARM
Manufacturer	NXP, Atmel, Silicon, Labs, Dallas, Cyprus, Infineon	Microchip	Atmel	Apple, Nvidia, Qualcomm, Samsung Electronics and TI
Cost	Very Low	Average	Average	Low
Another Feature	Known for its standard	Cheap	Cheap and effective	High- speed operation vast
Popular Mic	AT89C51, P89V51	PIC18fxx,16,32	ATmega8,16,32, Arduino	LPC2148, ARM cortex-Mo-M7

4.7.1 Liquid crystal display (LCD)

LCD is a widely used technology in desktop, cellular phones, laptop computers, digital clocks and televisions and host of other electronic systems. LCD was first discovered in 1880 by a botanist called “Friedrich Reinitzer” Wu (2019). It is more advantageous in comparison with cathode ray tubes, in which they are much lighter, thinner and use minimal power to operate. Moreover, the device has electrical liquid crystals, which based on the liquid crystal technology Wu (2019)

However, by applying voltage to the LCD, it changes from transparent material to opaque material. This property is the main operating principle of the LCD. Hence, it is applicable for displaying account balance and power usage, and it acts as an interface between the user and power energy meter.

4.7.2 Global system for mobile communication (GSM) modem

GSM modem is a form of modem with SIM card insertion and facilitates electronics subscription between the subscriber and supplier or dealer. This device operates in similar ways to the mobile phone; they both communicate in similar ways because they require the internet connectivity to be able to send and receive information. It comprises a dedicated modem device with a USB, serial, or Bluetooth connection.

Communication with the GSM can be carried-out using successions of machine instructions to activate structures on an intelligent modem known as AT command set. The AT command set is widely known as the Hayes standard AT command set. This functions as set of instructions for configuring and controlling modems. The commands are short sequences of ASCII characters. All command strings (that is, sequences of characters) must be supplementary by the letters AT; an abbreviation for attention that accounts for the set name.

4.7.3 Relay

A relay is an electrical activated switch. Many relays use electromagnet to control a switching mechanism mechanically Rahman et al (2015). Although, there are some other operating principles that were used. Relays are used to initiate a low-poor signal control process in a circuit, that is, with complete electrical isolation between control and controlled circuits or where several circuits must be controlled by one signal K.Bowya, I.S.Pradeeba Levina (, 2017). This process is enhanced through a high power that controls electric motor or other loads called contactor.

In addition, calibrated relays with multiple operating coils help to protect electrical circuits from overload or faults; clearly, in modern electrical power or system, which are executed through digital instruments referred to as protective relays (Li et al., 2015; Patel et al., 2013; Sengupta, 2011).

4.7.4 Voltage sensing circuit

The voltage sensor measures voltage including the phase angle of the voltage across the load (Preethi & Harish, 2017;Rashid, 2014; Weranga et al., 2012). It is a device that accurately execute linearly in some precise voltage range. The voltage sensor module was developed to connect the main source of power on the input side and extends to the energy meter IC on the output side.

4.7.5 Current sensing circuit

Current sensor is designed to track the flow rate of current relays (Li et al., 2015; Patel et al., 2013; Sengupta, 2011). This task involves measuring and recording of the actual current usage alongside the current phase angle, and thereby communicating this to the microcontroller. This device operates linearly to measure the accurate power usage, not beyond a maximum current rate of 10 amperes.

In similar way to the voltage sensor connection, the current sensor connects directly to the load on the input side and extends to the energy meter IC on the output side (Preethi & Harish, 2017;Rashid, 2014; Weranga et al., 2012). The input to the entity is the value of the voltage drop across a shunt resistor and the output to the meter IC is the voltage that is proportional to the input voltage. The ratio of the input and the output voltage depends on the type of transformer used in the circuit.

4.8 Energy meter components

4.8.1 RC filter

RC filter, is a filter capacitor, used in smoothing the waveform in power supply Muzafar Imad Ali Ahmed (2013). This literally means that the filter smooths the DC signal produced by the bridge rectifier. When a capacitor is placed parallel across the load as shown in Figure 4.3 above. The device charging capacity indicates a rapid charge rate in the positive half of the cycle, but charge rate decline in the negative half of the cycle due to capacitor discharge from the load, and a desired ripple effect is created Integrated (2006).

Evidently, when the value of a resistor is higher at the load, then the discharge becomes slower or smoother the line. Otherwise, if a resistor with lower value is selected, the discharge becomes faster and more ripplr is created in the waveform. General knowledge confirms that large resistance values for capaictor and resistor facilitate creation of a small ripple voltage filtered.

4.8.2 Current sensing design

The design of a current sensor involves the feasibility study of the basic fundamentals, sensitivity attributes, configuration pin settings, pictorial view of its functional block diagram, and output of ACS712-30A Integrated (2006). Current sensor was designed to sense the flow of current in the various applications like over-current protection circuits, battery chargers, switching mode power supplies, digital wattmeter, programmable current sources, etc.

In this design of a current sensor, ACS712-30A is a sensor component considered suitable to sense current flow in the household, industries, automobile, and other commercial purposes Mnati (2017).

4.8.2.1 ACS712-30A pin configurations

The picture displayed in Figure 4.12[35] illustrates the pin configurations around ACS712-30A. The pins are numbered from 1 to 8. Pin numbers with IP+ and IP– represent current sampled terminals fused internally. Pin 5 and 6 denote GND (terminal ground) and filter (terminal external capacitor) respectively. Pin 6 set the bandwidth for the ACS712-30A Integrated (2006). Additionally, Pin 7 and 8 denote VI_{out} (analog output signal) and V_{CC} (terminal for power supply) respectively.

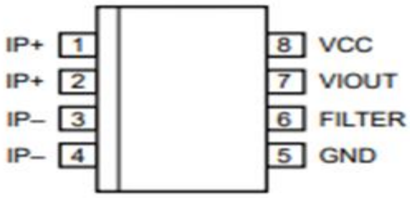

Figure 4.12: ACS712-30A pin configurations

4.8.2.2 Functional block diagram

The diagram presented in Figure 4.13 demonstrates the circuit flow of electrical mechanisms that constitute ACS712-30A functional block. In other word, this diagram reveals the process transitions amongst stages as occurred in the ACS712-30A showed in the Figure 4.12 above.

[35] The diagrams displayed in Figure 4.12 and Figure 4.13 were adapted from Integrated (2006)

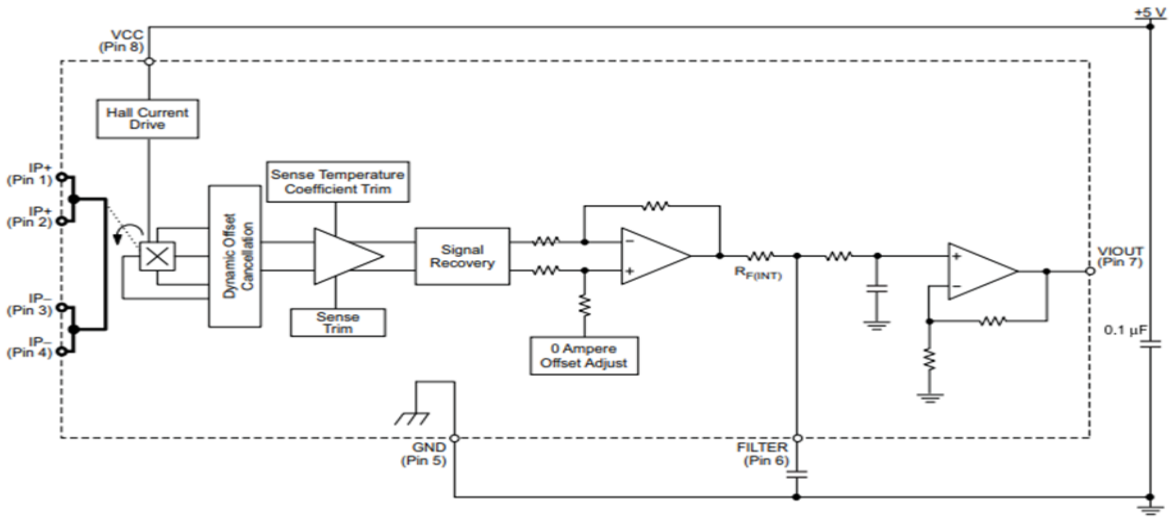

Figure 4.13: ACS712-30A functional block diagram

4.8.3 Sensitivity and output of ACS712-30A

According to Integrated (2006), as indicated in the ACS712-30A datasheet, a current upsurge in ACS712-30A yields a positive slope when flux occurs from one side to another of the copper conduction path. Then, at zero current, the VI_{out} (output voltage) is half of the V_{CC} (supply voltage) as shown in Figure 4.13 above. Moreover, ACS712-30A provides a radiometric output in Pin 7 as indicated in the function block diagram. This indicates zero current output, with the device indifference proportionate to supply voltage. Nevertheless, the microcontroller ADC consumes V_{CC} at 5.0V as a reference to A/D conversion; since it is the equal level of voltage that powers ACS712-30A sensor chip. In the process, analog output of ACS712-30A digitised through the ADC chip yielding zero current through the current sensor when supply voltage is at 5.0V.

The nominal sensitivity and transfer characteristics of the ACS712-30A current sensor is powered with a 5.0V supply. The output of the sensor module goes to ADC channel (Pin 1 → IP+) of the Arduino Uno ATmega328P microcontroller. This microcontroller uses the supply voltage between 2.7V and 5.5V; although, 2.56V was used as a reference voltage for A/D conversion. The digitised sensor output is processed through software to convert it to the actual current value.

4.8.4 Voltage sensor

The circuit diagram in Figure 4.14[36] illustrates the process stages in voltage sensor that execute supply of voltage signals within the built device. As demonstrated in the diagram, the potential transformer is connected in parallel with the two lines from the source–this serves as the input. In addition, the output from the potential transformer is connected in series with diode

[36] The diagram in Figure 4.14 was adapted from Labcenter Electronics (2013)

1N4148. They are both connected in series in other to deliver a constant DC voltage across the diode (Diodes, 2008).

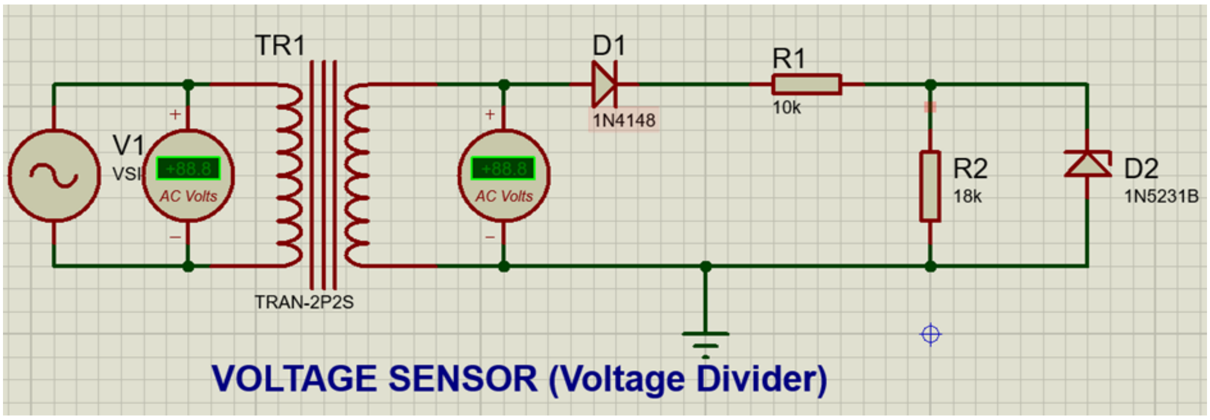

Figure 4.14: Interfaced voltage sensor

Hence, the output voltage across the diodes remains constant despite deviations in load current connected in series. It enhances a change in the DC power supply voltage that feeds them. The diode, then, converts the AC signal into DC pulse. The DC pulse is further step-down via voltage divider R1 and R2, with another Zener diode of 1N5231B (Rectron Semiconductor, 2019) connected in parallel before being fed into the microcontroller.

4.9 Criteria for Arduino Uno ATmega328P R3 selection

This section highlights the criteria that validate the selection of the Arduino Uno ATmega328P microcontroller displayed in Figure 4.16 below[37]. This microcontroller remains focus because of its importance in achieving the objectives of this study and the unique ability to control all the operations in the entire system. The criteria for selecting the microcontroller are given below:

1. It must meet the computational requirements of the task efficiently,
2. It must be cost effective, and
3. It must be acceptable, available, and compatible with general software development tools such as compiler assemblers and debuggers.

For the measures, Arduino Uno ATmega328P microcontroller is considered suitable for the development of the smart meter (Mohammed, 2016).

[37] The picture displayed in Figure 4.15 and Figure 4.16 were adapted from Arduino Zero (2016) and Barbosa (2014)

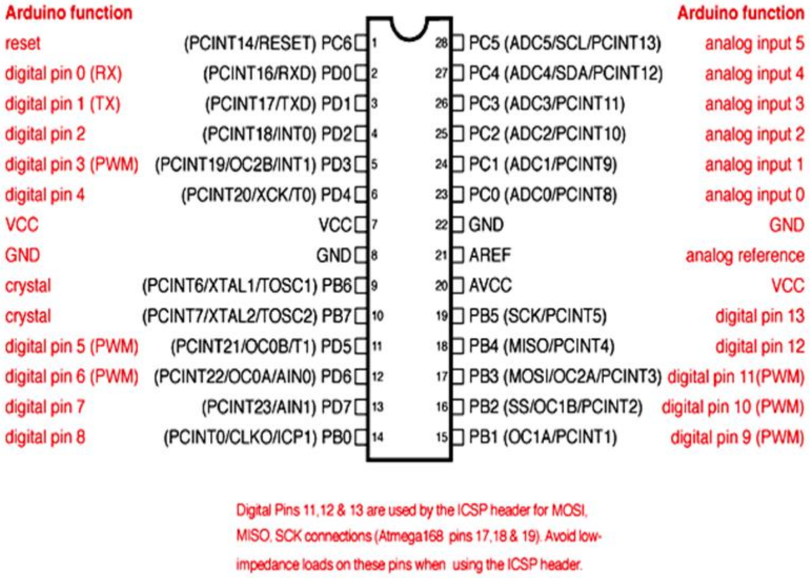

Figure 4.15: Arduino Uno ATmega328P–PU pin configuration

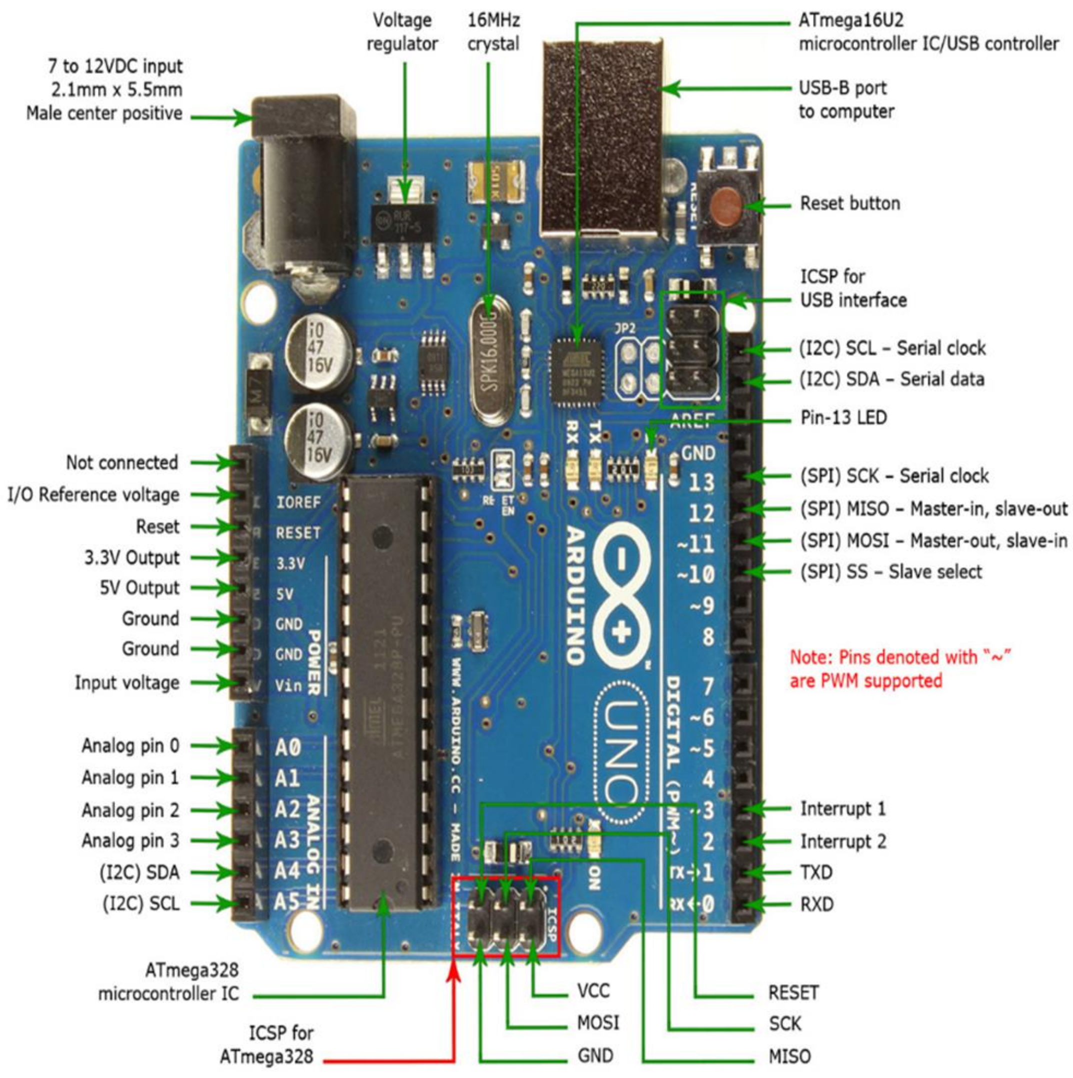

Figure 4.16: Block diagram of Arduino Uno ATmega328P R3

The unique features of the selected microcontroller are outlined below as diagrammatically demonstrated in Figure 4.15 above.

- Pin count – Arduino Uno ATmega328P has 28 pins: two for power, Pin 7 → +5V and Pin 8 → GND; two for the oscillator, Pin 9 and 10; a reset → Pin 1, three for providing the necessary power and a reference voltage to its internal ADC, and 23 I/O pins.
- About I/O pins – Arduino Uno ATmega328P is capable of handling analog inputs. Port A can be used as either digital I/O lines or each individual pin can be used as a single input channel to the internal ADC, and a pair of pins AREF, AVCC & GND together can make an ADC channel.
- Digital I/O pins – Arduino Uno ATmega328P has 23 pins: 2 ports and 8 pins each for Port B, Port D and 7 pins for Port C.
- Timers – Arduino Uno ATmega328P has 3 inbuilt timers/counters; two 8 bit → timer 0 and timer 2; and one 16 bit → timer 1.
- ADC – Arduino Uno ATmega328P has one successive approximation type ADC, wherein 8 single channels are selectable. Their external reference can be connected to the AREF pin.

Arduino Uno ATmega328PU pin configuration comprises three data transfer modules embedded. The transfer modules are outlined as follows:

- Master/slave SPI serial interface (Pin 16, Pin 17, Pin 18, and Pin 19), and they are suitable for programming in the microcontroller.
- Programmable serial USART → Pin 2 and Pin 3, and they are suitable for programming in the microcontroller.
- It has a two-wire serial interface → Pin 27 and Pin 28, and it can be used to correct peripheral devices like sensors and LCD.

Peripheral features:

- Two 8-bit timer/counters with separate pre-scaler, one compare mode.
- One 16-bit timer/counter with separate pre-scaler, compare mode, and capture mode.
- Real-time counter with separate oscillator.
- Three PWM channels.
- 8-channel ADC → 8 channels 10-bit accuracy.
- 6-channel ADC → PDIP package 6 channels 10-bit accuracy.
- Byte-oriented two-wire serial interface.
- Programmable watchdog timer with separate on-chip oscillator.
- On-chip analog comparator.
- Flash memory → 32KB (0.5KB of the flash memory is used for boot loader)

- SRAM → 2KB, and EEPROM → 1KB.
- Frequency (clock speed) → 16Mhz.

Microcontroller special features:

- Power-on reset, and power barrel jack.
- USB connection.
- ICSP header.

Operating voltages:

- 7V → 12V (Arduino Uno ATmega328P).
- 6V → 20V (Arduino Uno ATmega328P).

Speed grades:

- 0Hz → 16MHz (Arduino Uno ATmega328P).
- DC Current on I/O Pins: 40mA.
- DC Current on 3.3V Pin: 50mA.

4.10 The Reason for choosing Atmega328P

The reasons while Arduino Uno ATmega328P was used for this project are highlighted in "4.9 the criteria that validate the selection of the Arduino Uno ATmega328P microcontroller above". This microcontroller beccame focal point due to its significance in achieving the objectives of this study and the unique ability to control all the operations in the entire system. The criteria for selecting the microcontroller are given below:

1. It has met the computational requirements of the task efficiently.
2. It's cost effectiveness.
3. It's generally acceptable, available, and compatible with general software development tools such as compiler assemblers and debuggers.

4.11 Interfacing the LCD with the microcontroller

LCD was previously discussed in subsection 4.7.1 above a widely used technology to display information in some electronic systems. LCD is simply an electronic device used to display information in numbers and text format as demonstrated in Figure 4.17[38]. There are two main types of LCD display, which are numeric and alphanumeric text displays. The numeric display is applied in devices such as wristwatches, calculators, etc. The LCD screen is an electronic

[38] The diagram displayed in Figure 4.17 was adapted from Labcenter Electronics (2013)

display module generally accepted in global use. Furthermore, the LCD display modules are preferred over seven segments and other multi-segments LEDs. This is because LCDs are economical, easily programmable, no limitation in displaying process such in special & even custom characters display–unlike the segment display, animations display is quite real, and users friendly.

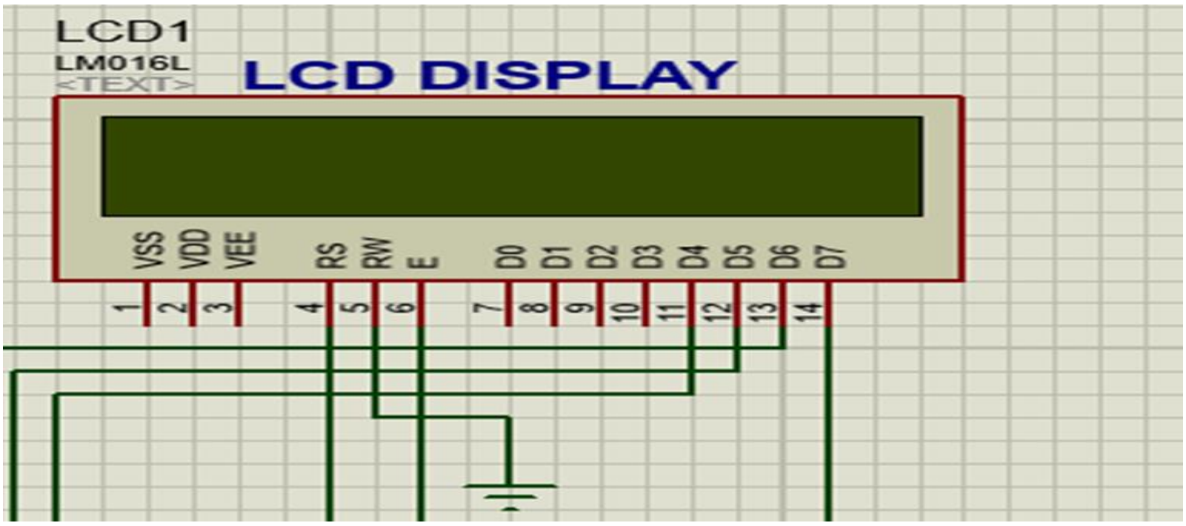

Figure 4.17: LCD interfaced with microcontroller Source ;(Author)

Additionally, a 16 x 4 LCD displays 16 characters per line and 2 such lines are the most widely used in various design. In LCD, each character is displayed in 5 x 7 pixel matrix. More so, the LCD has two registers, namely command and data registers. The command register stores the command instructions such as initialization of the LCD, clearing of its screen, setting the cursor position, controlling display, etc. Inevitably, the data register stores the data to be displayed on the LCD Campus (2015). The data is the ASCII value of the character displayed on the LCD. Table 4.4 below

Table 4.4: Function of LCD pins

Pin functions		
No.	**Symbol**	**Function**
1	Vss	GND, 0V
2	VDD	+5V
3	VEE	For LCD drive
4	RS	Function select
5	R/W	Read/write
6	E	Enable signal
7 - 9	D0 - D2	Data bus line
10	D3	Data bus
11	D4	-
12	D5	-
13	D6	-
14	D7	-
15	Led+	-
16	Led-	LED power supply

presents functions of LCD pins. In addition, LCD has 6 lines that are connected directly to the Atmega8 pins (see Figure 4.17). Nevertheless, it is significant to include a low-value resistor on the lines to protect against static discharges. The unused pins are left floating. The R/W pin is grounded as indicated in the diagram above (Figure 4.17).

4.12 Interfacing relay with current sensor

The diagram presented in Figure 4.18 demonstrates the circuit design of an interfacing relay with a current sensor. The circuit has a transistor driven relay, connected on the collector side. The voltage impressed on this relay is a rated full coil voltage at the peak period. Although, in OFF time, the voltage is completely zero to avoid any hazard during use. The PNP transistor is connected to control the switching of the relay. This process facilitates the selection of BC 327 PNP transistor because of its capacity to handle current, voltage, and power supply.

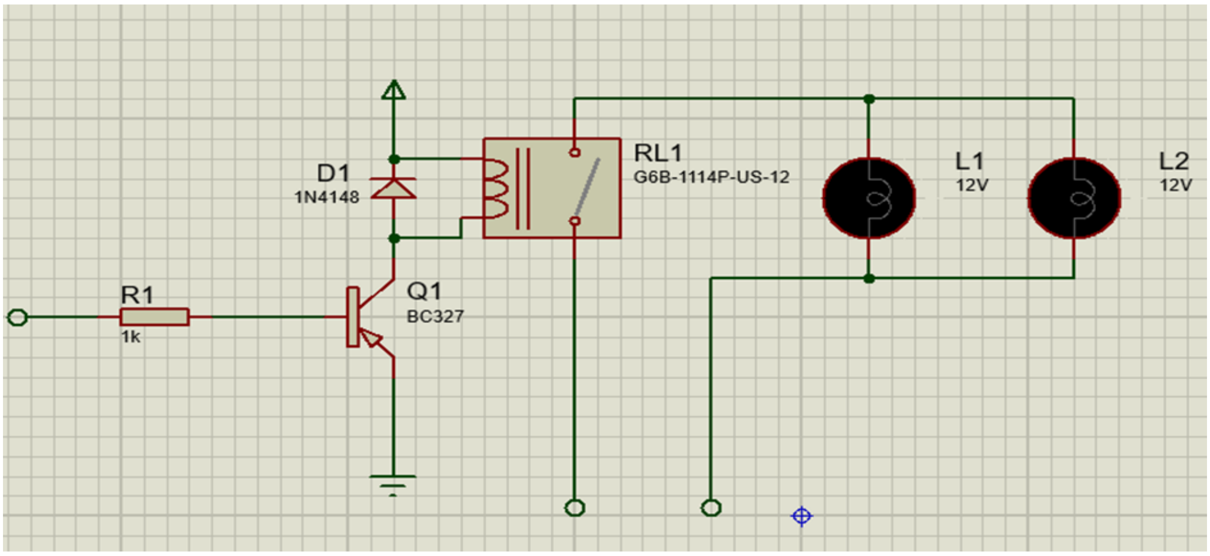

Figure 4.18: Relay interfaced with a current sensor Source ;(Author)

Also, the transistor is driven into saturation (turned ON) when Logic 1 signal is written on the port pin. Thus, turning ON the relay. The relay is turned OFF by writing Logic 0 on the Port 13 of the Arduino Uno board. In addition, a diode 1N4148 is connected across the relay coil. This is done to protect the transistor from damage due to the 'back EMF' generated within the relay's inductive coil. Thus, the transistor is turned OFF.

Furthermore, energy is stored in the inductor as dissipated through the diode, and internal resistance of the relay coil when the transistor is switched OFF. This diode 1N4148 is called free-wheeling diode. The resistor R1 is used in series base resistor to set the base current. This process is computed mathematically below:

$$I_{Csat} = (V_{CC} - V_{CE})/R_{Relay} \qquad (4.1)$$

$$= 12 - 0.2/400 = 0.0295A$$

$I_{Bsat} = I_{Csat}/10 = 0.0295/10 = 2.95mA$ (4.2)

$R_1 = (Vin - V_{BE})/I_{Bsat}$

$= (4.6 – 0.7)/(2.95 \times 10^{-3}) = 1322.03 = 1\Omega$ (4.3)

According to the E12 of code resistor I chose 1.5KΩ.

4.11.1 Functional block detailing of the energy Meter

The complete design of the smart energy control meter, as shown in Figure 4.19 below, contains a sectional diagram presented in the Figure 4.18 above which is referred to as load section. It relates to two 220V lamp bulb used as one of the main loads. The current sensor adaptively indoctrinated the hall field effect principle.

The voltage sensing circuit comprises of a step-down transformer and a voltage divider. The voltage divider contains excepted voltage rate or magnitude for a required microcontroller as indicated in datasheet(Atmel Corporation, 2009; Integrated et al., 2006). The current sensor signal is detected using ACS712-30A, in which both the current and voltage signal parameter are calculated based on the programmed microcontroller and displayed on LCD. Additionally, the above generated parameters are transceiver through GSM device.

Voltage sensing → the voltage fed into the transformer is step-down as connected in Figure 4.14. From the diagram, the input voltage which is also called primary voltage, is given as $220V_{rms}$ and secondary voltage is about 9.5V. Hence, the step-down transformer ratio is 220V/9.5V. Although, the step-down ratio varies based on the manufacturer’s interest, and the required specification for the microcontroller. The diode interlock with the transformer rectifies the output voltage and ensures that only the positive half goes through. Nevertheless, this process is quite essential for the required microcontroller configuration. The microcontroller, Arduino Uno ATmega328P, accepts non-negative voltages (Atmel Corporation, 2009).

With in-depth insight, it is understood that Arduino Uno ATmega328P should be configured and programmed to accept 5V as reference voltage, as found in the program configured pins in Figure 4.16 above. Literally, this means that maximum input that can be measured on the ADC pin is 5V. Therefore, it follows that the peak value of the voltage specified to the MCU must be 5V.

Hence the calculations followed thus:

The transformer rated voltages used 220/9.5V.

The peak voltage of the secondary = $9.5 \times \sqrt{2}$ (4.4)

$= 13.44V$

Note: $\sqrt{2}$ = 1.4142 (4.5)

A diode will have a voltage drop of about 0.6 → 0.7. If 0.7 is selected, then, peak voltage after diode = 13.44 – 0.7 (4.6)

= 12.74V.

Recall that the maximum voltage to the MCU must not surpass 9.5V.

Therefore, we must divide the voltage by means of a resistor in series within the ratio of (12.74 – 5): 5 (4.7)

The ratio yields 7.735: 5. If we have an upper value of resistor to be 10KΩ. The lower value x becomes

x = (10 x 5)/7.735

= 50/7.735

= 6.464KΩ (in theory). (4.8)

From Equation (4.8), we are going to make use of 6.464V. This value was adjusted in the design process. The Zener diode shields the MCU against high voltages, in order to prevent it from been damaged via excess voltage. Similar explanation goes for the current sensing. The very hall effect sensor output increases by 66mV for every amp increment in one measured amount, but this involves little calculation. With the voltage sensing, the hall sensor does not generate zero-voltage output. Since there is no current flowing in the device output of 5.1V, then when current begins to flow, voltage increases linearly by 66mV/A. The objective achieved here is that measured current should not exceed a value that causes the voltage to be more than 5V. We only measure current or voltage from 5.1V → 5V. At 5V, a current equal to

= (6.464-5.1) V/66mV/A. (4.9)

= 1.364/0,066A

= 20.67A per current or (4.10)

= 20.67A /$\sqrt{2}$ RMS

= 14.61A RMS (4.11)

4.13 Design challenges

In this study, there are some design challenges identified, which are perceived to be problematic to the design of the smart energy meter. The primary challenge with the current design of the smart energy meter is the issue of loss of information or values due to power cut off and resumes processing all over without any relay of previously values. In that case, two ways to prevent loss of values are identified as:

1. Ensuring alternative power supply–use a simple battery or a rechargeable device.
2. Ensuring constant save of the current values before power is cut off.

If the second option is considered, then the power interruption must be checked through MCU initiation. So, if power is out; it saves current values and restores them when power is restored. At this point, there is an adequate backup charge to do data saving. An appropriately sized capacitor should be able to achieve this.

4.14 Complete smart energy meter design

The pictorial view found in figure 4.19 is the complete design circuit of the smart energy meter as developed via kicad. The circuit is further sub-divided based into Voltage sensor, Current Sensor, LCD display connection, Input and Output data from Arduino, high voltage power control section and finally the relay control energy. All consist the smart energy with respect to components used in Table 5.5

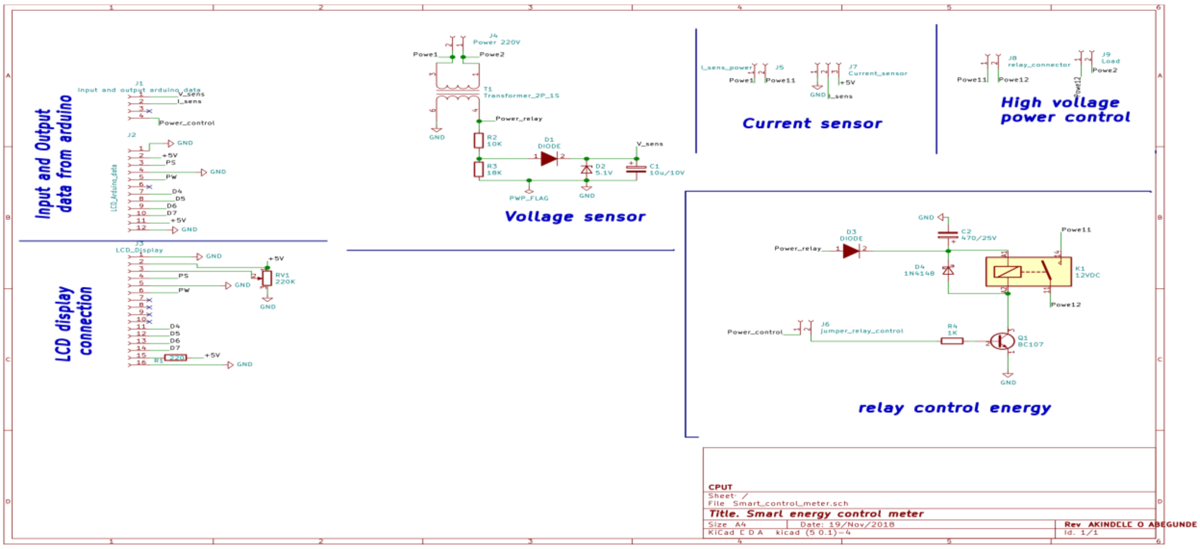

Figure 4.19: Complete design Source ;(Author)

4.15 3D visualizer for the smart energy meter from KICAD (5.0.1)

The 3D visualizer for the smart energy meter from KICAD (5.0.1) gives the visual picture of the designed energy meter in its 3D form.

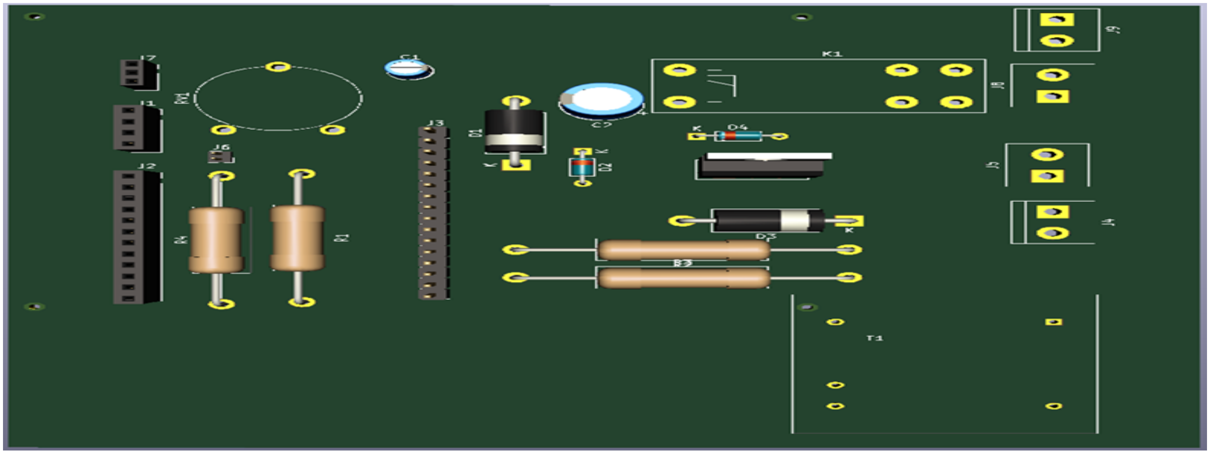

Figure 4.20: Simulation 3D visualizer diagram Source ;(Author)

4.16 PCB layout of the smart energy meter

The picturial view seen below particularly states the PCB layout of the smart energy meter with its dimension. The board is dimensioned in 109,093mm by 105,025mm. The deep green tracks indicates the supply track and the neutral track. This PCB layout speaks more about the functionality of the Board.

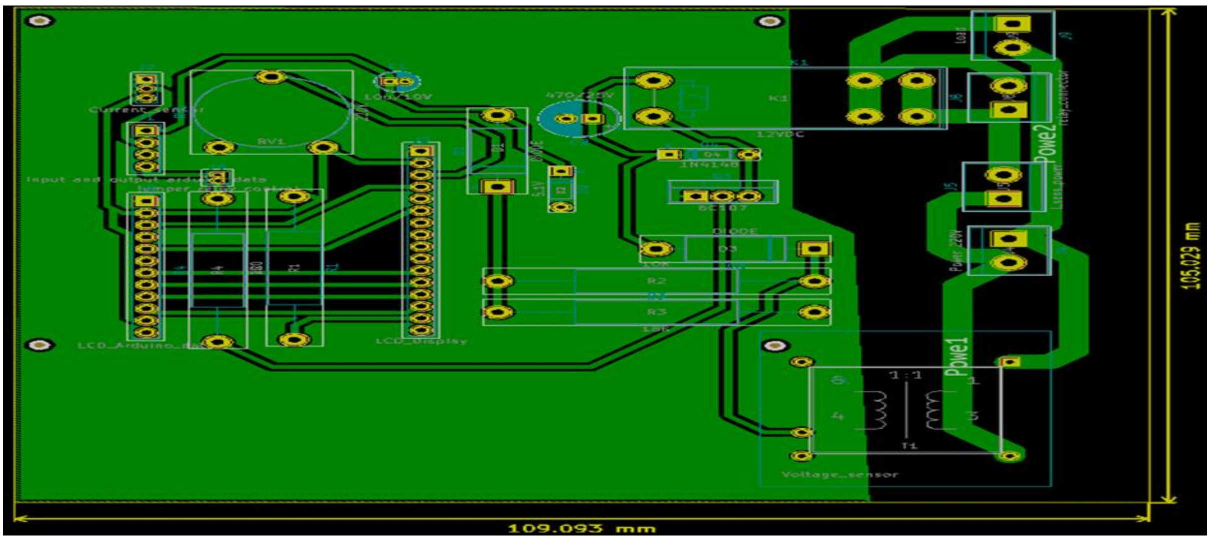

Figure 4.21: PCB layout Source ;(Author)

Chapter 5: Implementation and Design Testing.

5.1 Chapter review

This chapter discusses the implementation and testing of the design. The discussion extends discussion to the combination of components used in the evaluation and testing processes. Further understanding on how some of the major components were interfaced with the microcontroller unit–the brain of the system. The chapter presents the completed smart energy meter illustrative view, including the result derived from the process initiated through the exchange of information as displayed by the serial Arduino serial monitor on monitoring screens. Final part of this chapter covers the analysis of the smart metering preliminary market result in South Africa, based on its performance rate and cost evaluation.

5.2 Design implementation and testing

This section discusses the ultimate design of the smart energy meter by adequately combining and interpreting the experimental results. The design actualisation was a bit difficult to attain at the early stage of the implementation process. More so, necessary equipment and components were worked through, while the software for the smart energy meter was worked upon through Arduino Uno R3 IDE (integrated development environment). This step enhances easy understanding of the procedures involved in the experiment.

One major challenge encountered is improvise power supply for the two energy boards, that is, Arduino board and GSM SIM900. The energy boards range from 220VDC → 5VDC, 5VDC → 12VDC, and 9VDC → 12VDC. Afterwards, the LCD used was tested to determine its degree of suitability. This was performed by considering the pin-out configuration of the LCD from 0 → 15 pin, with the use of jumper wires. Based on the use Arduino IDE, each pin port of the LCD was assigned for the Arduino Uno board. The LCD pins–RS for Pin 10, EN for Pin 11, D4 for Pin 2, D5 for Pin 3, D6 for Pin 4, and D7 for Pin 5 of the Arduino Uno R3 board, which is finally considered for use. And analog Pin A0 and A1 were recognised as the voltage sensor and current sensor pins accordingly. Hence, the display unit was initialized and activated to read data.

5.3 Combination of components and testing

In this section, necessary components were assembled and tested to ascertain the reliability of the device. Figure 5.1 displays the segmental hardware parts of the smart energy meter. In the picture, the board in the right top corner, accommodates the power section, current sensor section, voltage divider section, relay section, LCD section, and Arduino section. The component was placed on the PCB board with dimension of 109.093mm x 105.029mm. The component directly below the PCB board is Keyes GSM shield SIM900 (EB00591) as found

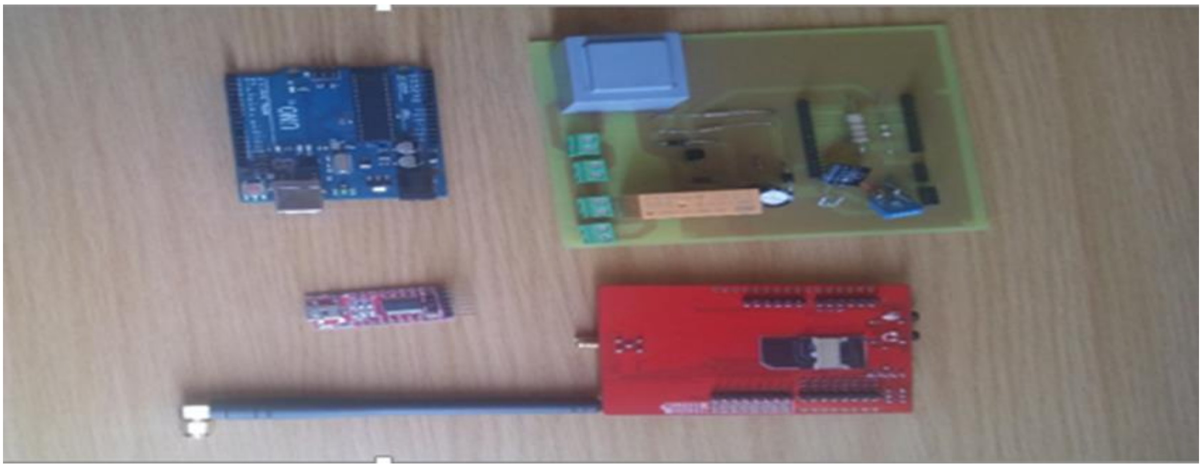

Figure 5.1: Combination of components Source ;(Author)

on ManTech, which is highly compatible with Arduino expansion board. The smallest board, by the left bottom corner of Arduino shield, is future technology devices international (FDTI) programmer used for the initialisation of the GSM SIM900 shield. While the other board, by the left top corner, is the microcontroller unit called Arduino Uno R3h.

5.4 Main board of the smart energy meter

The development of the smart energy meter is mainly based on a PCB board, which conducts tracks as a single layer board. On this board, twenty-one components are accommodated as shown in Figure 5.2, such components were previously mentioned in the section 5.3. On the PCB board, there are four green terminals N/C PCB 2W 2.54 STR that are close together. The far right one is used as the load output terminal, while the second from the far right is used as

Figure 5.2: PCB board of the smart energy meter Source ;(Author)

the relay input terminal, and the second from the far left is used as current sensor terminal, while the far left one is used as the power input terminal from the source. The transformer helps to step down this power supply from 220VAC to 9.5V on the secondary pin of the transformer. The voltage was divided through voltage divider where in R_1 is 10k and R_2 is 18k hence we:

$V_{out} = V_{in} (R_2/ (R_1 + R_2))$

$= 9.5(18k/ (10k + 18K))$

$= 6.1V$

The value of V_{out} obtained is added or connected to a 5.1V Zener diode to prevent the voltage from exceeding 5V supply to the microcontroller, which accommodates voltage rates between 5V→12V, with the power supply for the GSM shield ranging from 9V→12V. Therefore, if the un-filtered supply is feed into the circuit, it can lead to unwanted noise in the system. Due to this effect, a filter with 470uf and 25V rates was used in the circuit.

5.5 LCD interface with MCU simulation

The communication of output data from the interpretation of the codes written to the MCU is displayed on the LCD in every two second (see Figure 5.3). The Port B is selected as the port on the microcontroller where the LCD was connected. Also, a 220 KΩ potentiometer was used for the regulation of the LCD's brightness/contrast just as programmed in the appendix below.

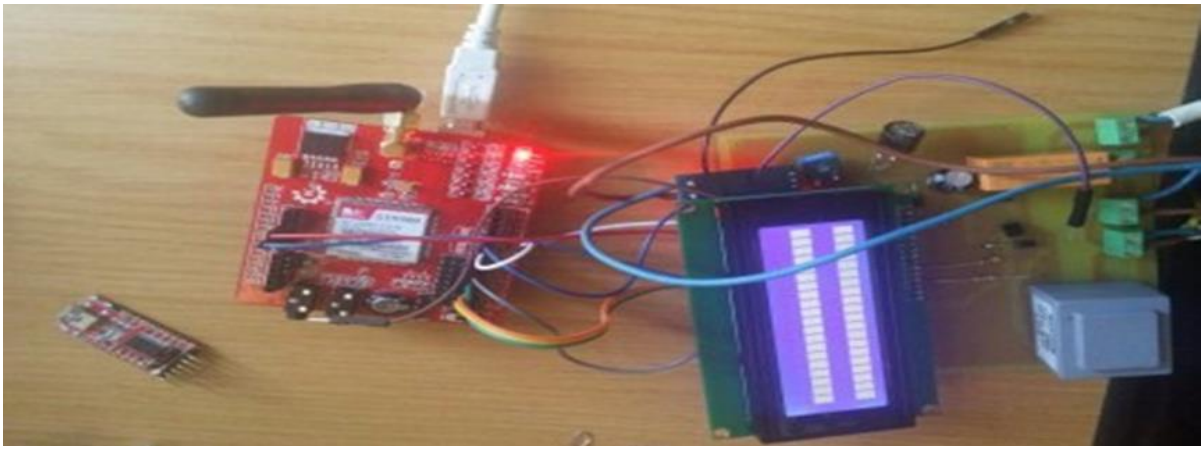

Figure 5.3: 1LCD initialization display Source ;(Author)

5.6 Design power supply

A built power supply device with 9V and 2A rates was considered to power both the GSM Shield SIM900, and Arduino Uno R3 board which consumes voltage rates between of 9V→12V can charge a mobile phone. The power supply top view is displayed in Figure 5.4, while the bottom view is displayed in Figure 5.5.

Figure 5.4: Power supply top view Source ;(Author)

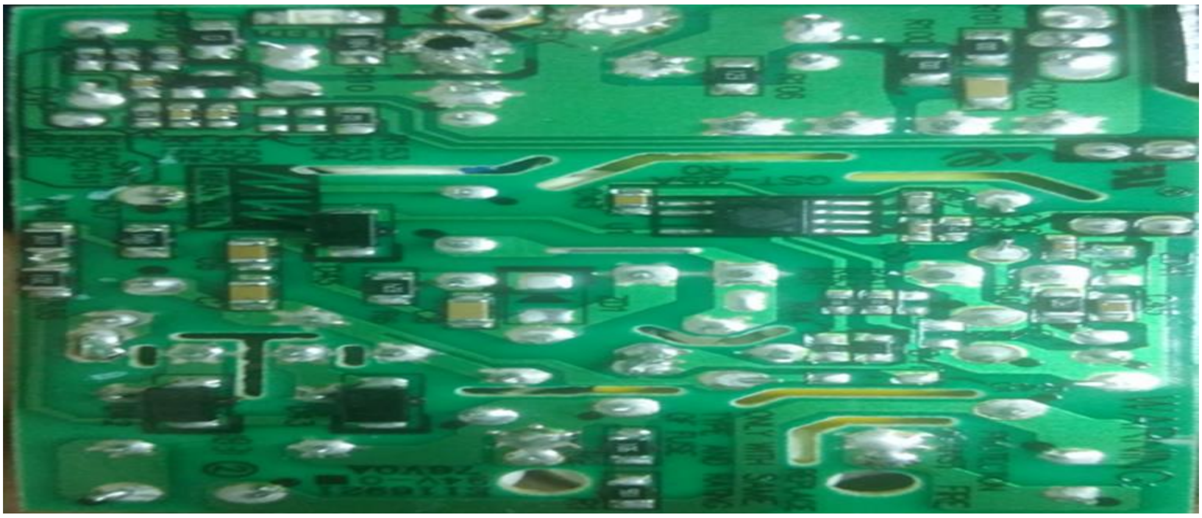

Figure 5.5: Power supply bottom view Source ;(Author)

5.7 Interfacing LCD with microcontroller unit

The circuit shown in the Figure 5.6 was connected and plug-on the PCB during the assemblage of the smart energy meter. After thorough inspection, the LCD was transferred on the board with the microcontroller unit. The LCD is connected to display interpretation of the code written on Arduino IDE.

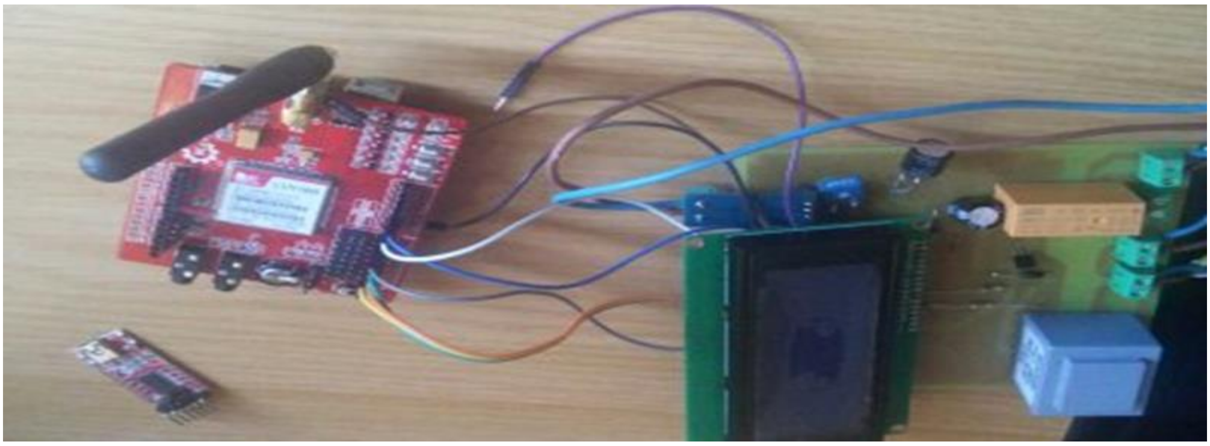

Figure 5.6: The interfaced LCD with microcontroller unit Source ;(Author)

5.8 Interfacing GSM SIM900 with the microcontroller unit

The illustrative picture displayed in Figure 5.7 demonstrates the circuit connection of the GSM module SIM900 shield plugged into the microcontroller board. This component is tested and observed on the GPRS SIM900 library. The observation was basically performed by ensuring that the TRX pin for the GSM is connected to the RX for both microcontroller and GND. The serial monitor screen enhances the possibility of employing the smart energy meter monitor by the utility.

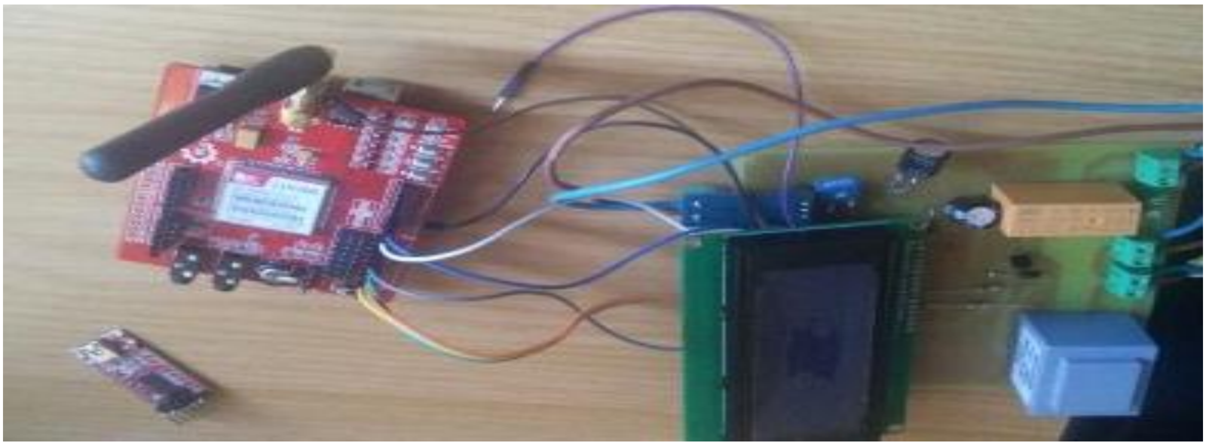

Figure 5.7: Displayed interfacing GSM SIM900 with the microcontroller unit Source ;(Author)

5.9 System testing

The circuit displayed in Figure 5.8 was accommodates the alignment of the voltage transformer, the CT, relay port, and power supply on the same role. Relay is connected to cut off supply when it exceeds the rated power output, so as avoid any unnecessary or unwanted damages to the device. Complete code was written and loaded in the MCU to control the operation.

Figure 5.8: System testing Source ;(Author)

5.10 Smart energy meter illustrative view

The display unit in Figure 5.9 demonstrates the final assemblage and testing of the new smart meter, with 197 mm x 114 mm x 62 mm dimension that displays unit accurately and working adequately in good condition. Figure 5.10 shows the new smart energy meter.

Figure 5.9: Displayed power and cost reading Source ;(Author)

Figure 5.10: Smart energy meter front view Source ;(Author)

The picture in the Figure 5.11 shows the bottom view of the new smart energy, with two main output ports which are in red and black banana plugs. These plugs represent the terminal blocks that link loads with the new device.

Figure 5.11: Smart energy output bottom view Source ;(Author)

Figure 5.12: Smart energy meter sides view Source ;(Author)

Figure 5.13: Smart energy meter side view Source ;(Author)

More so, Figure 5.12 shows the side view of the new smart energy meter with two input ports identified as red and black banana plugs. Alternatively, Figure 5.13 shows the smart energy meter side view with GSM module antenna and USB port.

5.11 Results from the smart energy meter

The low-cost energy meter was designed, developed, and assembled in Cape Peninsula University of Technology, Bellville Campus Laboratory. The meter was designed with some technical specifications that are identified as accuracy (class 1.0); rated voltage; single-phase (230V → 250V); frequency (50Hz/30A); display (LCD display), information record, and energy parameters such as power, current, voltage, power, energy, and cost of billing. More so, the tested results with high precision values are tabularized in Table 5.1, Table 5.2, and Table 5.3, which are based on the response of the meter when they are subjected to loading.

Table 5.1: Result of smart energy meter when not loaded

Time	Number	Voltage (V)	Current (AMP)	Power (KW)	Energy (KWH)	Total P(KW)	Total E(R)
17:13:56	910	202:97	0:21	42.62	0.01	R0.04	R0.04
17:13:56	910	224:51	0:21	47.14	0.01	R0.08	R0.04
17:13:56	910	225:23	0:21	47.30	0.01	R0.12	R0.04
17:13:56	910	224:99	0:21	47.23	0.01	R0.16	R0.04
17:13:56	943	224:99	0:21	47.23	0.01	R0.20	R0.04
17:13:56	977	225:23	0:18	40.54	0.01	R0.24	R0.04
17:13:56	977	225:23	0:24	54.06	0.01	R0.28	R0.05
17:14:10	385	225:23	0:21	47.30	0.01	R0.33	R0.04
17:14:10	385	225:23	0:21	47.30	0.01	R0.37	R0.04
17:14:10	419	225:23	0:21	47.30	0.01	R0.41	R0.04

The results presented in Table 5.1 indicate that no appliances connected to the meter or they temporarily not in use. The interpretation of the result is displayed on the LCD for the energy parameters considered, which remain the same at a constant voltage between 230V→250V. In addition, the costs remain the same and meter stores the record on the Arduino serial monitor in every 30 seconds. Consumers are advised to send/text ‘consumption’ as SMS on their mobile phone to enable meter reading update. In addition, further experiments were carried out when loaded with a fan.

Table 5.2: Result of smart energy meter when loaded with fan

Time	Number	Voltage (V)	Current (AMP)	Power (KW)	Energy (KW)	Total E(KW)	Total E(R)
17:08:34	492	206:08	0:26	53.56	0.01	R0.05	R0.05
17:08:35	492	224:51	0:24	52.88	0.01	R0.09	R0.05
17:08:35	526	224:75	0:24	52.90	0.01	R0.14	R0.05
17:08:35	526	224:75	0:24	52.90	0.01	R0.19	R0.05
17:08:35	560	224:99	0:24	54.00	0.01	R0.23	R0.05
17:08:35	560	224:75	0:21	47.20	0.01	R0.27	R0.04
17:09:01	981	224:75	0:21	47.20	0.01	R0.31	R0.04
17:09:01	981	224:99	0:21	47.25	0.01	R0.36	R0.04
17:09:02	015	224:99	0:21	47.25	0.01	R0.40	R0.04
17:09:02	015	224:99	0:21	47.25	0.01	R0.44	R0.04

Table 5.3: Result of smart energy meter when loaded with fan and air blower

Time	Number	Voltage (V)	Current (AMP)	Power (KW)	Energy (KW)	Total P(KW)	Total E(R)
17:08:34	492	224:51	5.41	1.22	0.34	R1.11	R1.06
17:08:35	492	224.28	5.41	1.21	0.34	R2.17	R1.06
17:08:35	526	224.28	5.41	1.21	0.34	R3.23	R1.06
17:08:35	526	224.28	5.47	1.23	0.34	R4.30	R1.07
17:08:35	560	224.28	5.44	1.20	0.34	R5.37	R1.07
17:08:35	560	224.28	5.41	1.21	0.34	R6.43	R1.06
17:08:35	981	224.04	5.44	1.22	0.34	R7.58	R1.07
17:08:35	981	224.04	5.44	1.22	0.34	R8.57	R1.07
17:08:35	015	224.04	5.39	1.21	0.34	R9.62	R1.06
17:08:35	015	224.04	5.39	1.21	0.34	R10.68	R1.06

The result generated for the energy parameter are as listed in Table 5.2. Although, the results obtained from the inclusion of a hair blower in increasing the meter load is presented in

Table 5.3 The cost value E(R) was quite minimal due to the programmed in function presented in the Appendix A. Hence, the energy meter captures little or no report for the energy displayed except if analysed for more days. The smart energy meter is quite durable and accurate. This device is highly well-matched with the commercially obtainable energy meter in the market.

5.12 Compared Cost of Available Commercial Products in South Africa

As technology keeps increasing, the need for improvement in mode of metering maintains rapid growth daily. From Table 5.4 below itemised some of the new technology adopted in South Africa as preliminary market result of smart meter in South Africa. Therefore, we can compare cost of these available commercial metering devices with the invented one of ours as tabulated below with respect to its' cost.

Table 5.4 Compared cost of Available commercial products in South Africa

	Cost	Available Smart Energy Meter in South Africa	Cost
Designed Low Cost Smart Energy Meter	R 2,197	SMA Energy Meter @#	R6000
		CAK Smart Metering @#	R2000
		DMED 130 Meter @#	R2,458
		Recharger (OHL-1228) @#	R976
		Linky rollout *#	R2,605
		Recharger Din Rail @#	R1000
		Ontec Systems/Itron SA *#	R1440
		Landis + Gry *@#	
		Conlog*@#	R899
		Palace Group @#	

5.13 Preliminary market result of smart meter in South Africa

Competitors/location/products/unique attributes/prices

In view of the growing technology in south Africa and the need for the electronic energy metering to be faced-out, but the below table 5.4 analyse all the notable smart metering available in south Africa with their prospective manufacturer, location, and respective price value where applicable.

Table 5.4: Analysis of smart metering manufacturer with prospective products in South Africa

Company name	Location	Remarks/unique/product(s)/feature(s)	Price (R)
Actom@#	Johannesburg	Distributes SM products from China partner (hexing)	
Citiq Prepaid@#	HB, CPT, KZN	STS meter vending, extensive range of meters/reporting	
CityPower#	JHB	Host various vending sites and energy management	
Conlog*@#	KZN	Locally manufacture prepaid meters and vending solutions	R899
Enermatics*@#	Pretoria	Locally manufacture with SABS class 1 grade/vending	
Electrowatch@	Gauteng: HO	Distributor of Landis & Gyr meters	
Eusystems@	JHB, HO	Distributes smart meters locally and continentally	
I buy #	CPT	Sells prepaid electricity	
Eprepaid*#	JHB, CPT	Prepaid metering and vending solutions	1285
Empire Hexing *@#	JHB	A vast range of metering and vending solutions	549
IdealPrepaid @#	JHB	Distribute/install and vends electricity	
I pay #	CPT	BizSwitch switching platform for online prepaid transactions	
Ontec Systems/Itron SA *#	CPT	International with the local officials to develop and sell SM	1440

Table 5.5 continues below.

Company name	Location	Remarks/Unique/ Product(s)/Feature(s)	Price (R)
Jknvenergy @#	JHB	Prepaid meters distributor and vending solutions	
Landis + Gry *@#	Worldwide, JHB	Swiss-based with local metering solutions to meter testers	

LiveWire(livec.co.za)#	Cape Town	Provides online/ smart phone energy management solutions	
MeterMate @#	Johannesburg	Supplies wide range of prepaid and smart meters	
MobiPower @#	Johannesburg	Supplies various smart meters/vending solutions	
Mr Prepaid @#	Pretoria	Make and sells various range of prepaid and smart meters	
Net Vendor #	KZN	Token Electricity vending/Management solutions	
Palace Group @#	Sandton	Licenced to develop smart metering systems	
Pecutilities @#	Pretoria	Smart Phone energy management solutions/vending	
Power24.co.za #	Johannesburg	Electricity token sales	
Powertech SI (ptsi.co.za) @	Pretoria	SM distributor and energy management	
Power-time #	Cape Town	Recharge on-the-go, on any device	
Power Meter Technics * @#	Midrand	Internationally based with local offices	
PrepaidElectric @#	Pretoria	Stocks various prepaid meters token vending	
Prepaid Meters4U @#	Pretoria	Sells prepaid meters/vending	Install 700
Prepaid Meters@#	SA/Worldwide	Prepaid sub-meters, vending (STS & AMI)	
ProteaMetering*@#	Pretoria	Develops, sells prepaid meters token vending	
Recharger Din Rail @#	Johannesburg	Split wireless Single Phase	999

Table 5.5 continues below.

Company Name	Location	Remarks/unique/product(s)/feature(s)	Price(R)
Recharger @#	Sandton	Sells, install prepaid meters/vending device/ manage them	

Siemens SA *@	Johannesburg	Internationally based with local office	
SOS-Prepaid @#	Pretoria	Electricity vending	
Submetering/AMSO *@#	Cape Town	AMR, Electrical load profile recording/Energy verifying	
Tellumat*	Cape Town	SM contract R&D and manufacturing	
The Meter man @	Johannesburg	Supplies various meters as well as do installations	
Tupa @#	Johannesburg	Sells prepaid electricity meters	
T-Systems #	Midrand	German-based with local offices that provide SM solutions	Install 850
XpressPrepaid @	Pretoria	Retails and install smart meters	

5.14 Performance and cost evaluations

In this section, the performance and cost evaluations of the components used in the development of the smart energy meter right from the process of simulation. Table 5.5 presents lists of all variables considered in the design and development of smart energy meter. As listed in the table 5.5 below, it is observed that the cost of producing a unit is expensive due to the procedures and methods of executing the design. This illustration demonstrates that the project is cost effective. It is evident that for a mass production on a commercial scale the cost will reduce than the cost of producing a unit since components are purchased in bulk. Reem Heakal; Will Kenton (2019) said that good or service can be produced on a larger scale, yet with input costs can be accomplished via “Economies of scale”. Therefore, as a company grows and production of units increases, the likelihoods are that reduction in the costs of units is sure. Furthermore, “economies of scale” can be described as the cost benefits acquired by companies when production becomes effective. It is utmost importance for every company to increase its production which enhance lowering of costs. Radder & Louw (1999) said mass production and mass customization determines the way manufacturers products behaviour. A system that engages mass production, operates within a standard which generally accept and forecast the implementation of prices reduction through economies of scale. And the price difference between mass produced and customized goods helps to lower the prices of units in order to achieve ‘low-cost’ in its generality. Therefore, the table 5.5 below shows the list of all components used and the corresponding unit cost.

Table 5.5: Cost evaluation of component used for design implementation

S/N	Component name	Manufacturer	Pieces	Ratings	Cost (R)
1	USB TTL Serial/RS232 Converter	EIE	1		R86.26
2	Term N/C PCB 2W 2.54 GRN	DEGSON	4		R15
3	ENCL ABS N/R BK 197 x 114 x 62	Plaster Converter	1		R114.02
4	Socket Banana 4mm 6A w/h Red	EIE	2		R18.95
5	Socket Banana 4mm 6A w/h Black	EIE	2		R19.50
6	Plug Banana 4mm Stack Rub BLK	ELE	2		R35.15
7	Plug Banana 4mm Stack Rub Red	EIE	2		R34.60
8	PSU W/M I-90/264 o=09V @2A2	HG POWER	1		R276
9	TRF P =220 S = 9.5V 1.5A PCB	EIE	3		R135

Table 5.5 continues below.

S/N	Component name	Manufacturer	Pieces	Ratings	Cost (R)
10	Zener DO-35 500mW 5.1V 1N5231B	Fairchild	12		R3.01
11	Terminal Block PCB 10mm 2W SIL	DEGSON	2		R9.8
12	Current Detector Board	EIE	1		R78
13	CAP ELEC RAD 1000uf 6V3	RUBYCON/ HITANO	4		R26.08
14	PS TO92 EBC 50V 0.8A 60M 160	SOT TECH	2		R1
15	PS TO92 EBC 50V 0.8A 60M 160 SMD	NXP	2		R0.60
16	Header SIL STR 40W 2.54	GTX	1		R3.15
17	Jumper Wires	ARD117E (40 15cm)	1		R95
18	GSM Shield SIM900	KEYES	1		R961
19	ARDUINO UNO R3	CPUT	2		R0.51
20	LCD1602 module(16x2)	HD44780 Adafruit	2		R180.81
TOTAL					**R2,197.048**

Chapter 6: Conclusion and Future Research

6.1 Conclusion

This smart energy meter has been tested within our limit of loads as stated in our c language program written in Arduino IDE. A limit was set at 2000W, if exceeded triggers the PNP transistor to open the relay. In that case, energy consumption is easily curtailed, which assists the consumers to reduce his or her consumable loads. This effect displays overload on the display unit.

The completion of the project was primarily based on some significant factors such as low-cost energy efficient, robust, multi-functional smart energy meter for general use. This is a newly metering device developed based on the technical way of measuring energy consumption rate and billing from households to industries as managed by the utility. Additionally, the device is developed to permit the monitoring of energy consumption rate and billing from any part of the world based on the application of the GSM wireless communication concept with great accuracy.

The objectives of this study are met regarding the outcomes derived from the test and components selection carried out on the smart energy meter. During the experimental test, error due to parallax was evaluated to avoid malfunctioning of the device in the future. The code used was modified to prevent recurrent errors when compiled. The PCB was fabricated at the power laboratory of CPUT and crafted out of the LPKF Protomat S63 machine. NPN transistor was connected to a 12V relay switch to regulate and make energy consumption effective for households and commercial uses. The relay switches off to shed load at a rate where the actual limit set for energy consumption is exceeded, and thereby displays the overload on the display unit for visual monitoring.

The GSM module interfaced with Arduino Uno IDE software was test run to ascertain the performance level of the shield with an inbuilt installation of the GPRS SIM 900 library in order to aid the distribution of SMS. The AT command was adjusted to yield a feedback response on the serial monitor of the Arduino IDE. The process was supported with the installation of FDTI programmer to initialise AT command to drive the effective performance of the GSM. The GSM is built with a real time clock (RTC) to harmonise with Arduino board. In case of any errors, the device is developed with reset button to return the system to its original or initial state.

6.2 Implementation Limitation

The designed smart metering device implementation accomplishment could have been hindered due to some summarized limitations encountered as highlighted in this key two aspect: Choice of components and Software, Technical and Time.

6.2.1 Choice of components and Software.

This research work went through the processes of hardware component choice and software identification for the design accomplishment. We had difficulty understanding the choice of components which complement and enhance the aim of the project. The two-letter word "*Low-cost"* mainly restrained us greatly from launching out for devices such as DSP that has great features such as: high data rate, huge processing speed, Huge self-storage data capacity due to high cost price. We visualised buying an already available products, tearing each down, analysing components with respect to their respective cost thereby, enabling prototypes that is sustainable and affordable. This concept can be investigated as a futuristic project.

Finally, all through the implementation process, we encountered challenges while interfacing the LCD with the microcontroller. The Keyes GSM module likewise could not transceiver bidirectionally but broke through after constant checking.

6.2.2 Technical and Time

The technicality of design coupled with time are of great requirement for the actualization of the modelling and smart energy meter design. Lot of precision detailing are required to meet the smart meters acceptable types of standardization. Cautions was taken during the PCB design and while fabricating at the power laboratory of CPUT as crafted out with LPKF Protomat S63 machine that took time.

6.2.3 Design Model Novelty

This research has its uniqueness which makes it stands out as it is highlighted below:

- It set limit at 2000W, by triggering the PNP transistor to open the relay if exceeded.
- It has the capability to communicate bidirectionally.
- Every consumer can easily access their consumer rates on their mobile phone through SMS.
- The prototype is highly durable and quite portable.
- As technology advancement increases, the microcontroller is upgradable.

6.3 Future research work

The completion of this research is achieved regarding the objectives outlined in the inception. However, a future research can be performed where DSP is considered as the main executable machine, with respect to its cost-effectiveness, to initiate thorough evaluation of the GSM module through appropriate installation of AT command. This recommendation will simply stimulate and speed-up performance of the smart energy meter during the peak and off-peak billing processes in South Africa and beyond. Also, the issue of tampering acts and remote configurations for smart energy meter can further be researched upon.

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Appendix A

```
/*
@Author : Akindele O Abegunde
Description: Smart Energy Meter
Last Edited: 26-March-2019
Implementation: Low cost multi-functional, robust smart energy meter.
*/
#include "SoftwareSerial.h"
#include "LiquidCrystal.h" // Importing LCD Library;
#include "sim900.h"
/*
 * RS: Pin 10
 * EN: Pin 11
 * D4: Pin 2
 * D5: Pin 3
```

```
 * D6: Pin 4
 * D7: Pin 5
 */
Liquid Crystal lcd(10, 11, 2, 3, 4, 5); //lcd display pin


char mobileNumber; // Will hold the incoming character from the GSM shield
SoftwareSerial SIM900(6, 7);
const int voltageSensor = A0; // voltage pin
const int currentSensor = A1; // current pin
//float getVPP;
int mVperAmp = 66; // use 100 for 20A Module and 66 for 30A Module
double sumWH = 0.000;
float WH = 0;//energy consumption in watt hour
double sumRand = 0.00;//Total energy consumption in Rand
float Rand = 0;//energy consumption in Rand
double Voltage = 0.0;//AC supply peak voltage
double vrms = 0;//AC supply rms voltage
double current = 0;//load peak current
double irms = 0;//load rms current
double power = 0;//

void setup()
{

 Serial.begin(19200);
 SIM900.begin(19200);
 pinMode(13,OUTPUT);
 delay(800);
 Serial.print("SIM900 ready...");

 // At command to set SIM900 to SMS mode

 SIM900.print("AT+CMGF=1\r"); // turn on caller ID notification , to get missed call number
 delay(100);
  // set module to send SMS data to serial out upon receipt
SIM900.print("AT+CNMI=2,2,0,0,0\r");

 lcd.begin(16,4); // Display Columms, Rows and Size
 lcd.clear();

 delay(800);

}

// Used to send Total Energy Consumption Billing to Customer
boolean sendBilling()
{
  delay(20000); // delay time to send SMS (20s)
  Serial.print("SIM900 ready...");

  SIM900.print("AT+CMGF=1\r");
  delay(100);


  //SIM900.println("AT+CMGF=1");      // Setting the GSM Module in Text mode
  delay(2000);
```

```
  SIM900.println("AT+CMGS=\"+27xxxxxxxxxxxx\"");
// Sending Energy Consumption to Customer's Mobile Number
  delay(100);
    SIM900.print("Welcome to smart energy meter");
    SIM900.print('\n');
    SIM900.print('\n');// break the text
    SIM900.print("Dear Customer, Your Energy Consumption is :");
    SIM900.print(sumWH);
    SIM900.print(" and Total Billing is R ");
    SIM900.print(sumRand);

  delay(100);
  SIM900.println((char)26); // ASCII code of CTRL+Z
  delay(100);

  SIM900.println();
  delay(5000); //time module to send SMS
}

boolean energyCalculations()
{
  // getting voltage from Input PIN
Voltage = analogRead(voltageSensor);

 vrms = (Voltage / 2.0) * 0.707 * 677.1; //find total voltage
 vrms=vrms/1000;
  if (vrms < 150.1)
   {
     vrms=0.0;
  }
 Serial.print("VOLTAGE : ");
 Serial.print(vrms);
 Serial.println("Volt");
// getting current from Input PIN
 current = getVPP(1);

irms = (current / 2.0) * 0.707 * 1000 / mVperAmp;

if (irms < 0.1)
  {
    irms=0.0;
  }

 Serial.print("CURRENT :");
Serial.print(irms);
 Serial.println("Amps");
power=(vrms * irms );

 Serial.print("POWER :");
Serial.print(power);
Serial.println("W");
// energy consume in hour

WH = (power / 3600);
Serial.print("ENERGY CONSUMED :");
Serial.print(WH);
Serial.println("Watt-Hour");

sumWH = sumWH + WH;
Serial.print("TOTAL ENERGY CONSUMED :");
```

```
 Serial.print(sumWH);

 Serial.println("Watt-Hour");



 Rand = getReading();

 Serial.print("ENERGY CONSUMED IN Rand :");

 Serial.print(Rand);

  Serial.println("R ");


 sumRand = sumRand + Rand ;

 Serial.print("TOTAL ENERGY CONSUMED IN Rand :");

  Serial.println("R ");

  Serial.print(sumRand);

 Serial.println(""); // print the next sets of parameter after a blank line

}


void loop()

{

energyCalculations();

gsm();



if(SIM900.available() > 0)

  {

  Serial.println("Inside SIM900 avaialble");

  Serial.write(SIM900.read());

  delay(200);

 }

}


boolean gsm()

{

  //Serial.println("AT+CMGF=1");

  if(SIM900.available() > 0)

  {

    //Serial.println("SIM900 is available");


    delay(10);

    mobileNumber = SIM900.read();

    //Serial.print("AT+CMGS=\"+27xxxxxxxxxxxx\"");

    if(mobileNumber == 'C')


      {

      delay(10);

     Serial.print(mobileNumber);

       mobileNumber = SIM900.read();

       if(mobileNumber == 'O')

       {

         delay(10);

         Serial.print(mobileNumber);

         mobileNumber = SIM900.read();

         if(mobileNumber == 'N')

           {

             delay(10);

             Serial.print(mobileNumber);

             mobileNumber = SIM900.read();

             if(mobileNumber == 'S')

               {

                   delay(10);
```

```
Serial.print(mobileNumber);
mobileNumber = SIM900.read();
if(mobileNumber == 'U')
{
  delay(10);
  Serial.print(mobileNumber);
  mobileNumber = SIM900.read();
  if(mobileNumber == 'M')
  {
   delay(10);
   Serial.print(mobileNumber);
   mobileNumber = SIM900.read();
   if(mobileNumber == 'P')
   {
    delay(10);
    Serial.print(mobileNumber);
    mobileNumber = SIM900.read();
    if(mobileNumber == 'T')
    {
     delay(10);
     Serial.print(mobileNumber);
     mobileNumber = SIM900.read();
     if(mobileNumber == 'I')
     {
      delay(10);
      Serial.print(mobileNumber);
      mobileNumber = SIM900.read();
      if(mobileNumber == 'O')
      {
       delay(10);
       Serial.print(mobileNumber);
       mobileNumber = SIM900.read();
       if(mobileNumber == 'N')

       {
        delay(10);
        Serial.print(mobileNumber);
        Serial.print("... Request Received\n");

//Serial.println("+27xxxxxxxxxx!");
        Serial.println("Sending Billing to Customer");
        //delay(90000);
        sendBilling();
        //the asking billing it's "CONSUMPTION"
       }
      }
     }
    }
   }
  }
 }



 }
 }
 }


 }
 sendBilling();
}
```

```
lcd.setCursor(16,1); // set the cursor outside the display count
lcd.print(" "); // print empty character
delay(500);


/*conditions for power control*/



//power=2;
 if (power<=2000)
 {
  digitalWrite (13,HIGH);

 lcd.setCursor(0,0); // set the cursor at 1st col and 1st row
  lcd.print("Volt =");
 lcd.print(vrms);
 lcd.print("v ");
  lcd.setCursor(0,1);
  lcd.print("Cur =");
 lcd.print(irms);
 lcd.print("A");
 lcd.setCursor(20,0); // set the cursor at 1st col and 2nd row
  lcd.print("Pow =");
 lcd.print(power);
 lcd.print("W");
 delay(4000);
 lcd.clear(); // clear the screen
 lcd.setCursor(0,0); // set the cursor at 1st col and 1st row
 lcd.print("Energy= ");
 lcd.print(WH);
 lcd.print("WH");
 lcd.setCursor(0,1); // set the cursor at 1st col and 2nd row
 lcd.print("Cost=R");
  lcd.print(Rand);
 delay(4000);
 lcd.clear(); // clear the screen
 lcd.setCursor(0,0); // set the cursor at 1st col and 1st row
 lcd.print("Total Pow=");
 lcd.print(sumWH);
 lcd.print("WH");
 lcd.setCursor(0,1); // set the cursor at 1st col and 2nd row
 lcd.print("Total cost=R");
 lcd.print(sumRand);
 delay(4000);
 }



    if (power>2000)
 {
  lcd.clear();
  digitalWrite (13,LOW);
  //delay(10000);
   lcd.setCursor(6,1);
  Serial.print("Overload");
   lcd.print("Overload");
   delay (10000);


 }
```

```
}
// current sensor and voltage sensor

float getVPP(int pinValue)
{
  pinValue = 0; // means it is Voltage Input ,
  pinValue = 1; //means it is Current Input
  float result;

  int readValue;             // value read from the sensor
  int maxValue = 0;          // store max value here
  int minValue = 1024;          // store min value here

   uint32_t start_time = millis();
   while((millis() - start_time) < 1000) //sample for 1
Sec
   {
        if(pinValue == 0)
       {
          // reading Voltage Input PIN
          readValue = analogRead(voltageSensor);
       }
       else if(pinValue == 1)
       {
          // reading Current Input PIN
            readValue = analogRead(currentSensor);
       }

       // see if you have a new maxValue
       if (readValue > maxValue)
       {
           /*record the maximum sensor value*/
           maxValue = readValue;
       }
       if (readValue < minValue)
        {
           /*record the maximum sensor value*/
          minValue = readValue;
        }
   }

  // Subtract min from max
  result = ((maxValue - minValue) * 5.0) / 1024.0;

  return result;
}

 //Energy cost

float getReading()
{

float solution;

if(sumWH <= 50)
 solution = (WH * 3.15);
if(( sumWH > 50 ) && ( sumWH <= 100 ))
 solution = ( WH * 3.60 );
if(( sumWH > 100 ) && (sumWH <= 250))
 solution = (WH * 4.25);
```

```
if(sumWH > 250)
 solution = (WH * 5.20);

return solution;

}
```