Addis Ababa University

Addis Ababa Institute of Technology

School of Electrical and Computer Engineering

STUDY AND ANALYSIS OF SMART METER IN POWER QUALITY MANAGEMENT AND REAL TIME MONITORING

A Thesis Submitted to the School of Electrical and Computer Engineering in the Partial Fulfillment of the Requirements for a MSc. Degree of Microelectronics Engineering

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Approval by Board of Examiners

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Declaration

I, the undersigned, declare that this MSc thesis paper is my original work, has not been presented for fulfillment of a degree in this or any other university, and all sources of materials used for the thesis have been duly acknowledged.

Declared by Signature Date

Place

Submission Approval

This thesis entitled ‘Study and Analysis of Smart Meter in Power Quality Management and Real Time Monitoring’ submitted in partial fulfillment of the requirements for the Masters of Science in Microelectronics Engineering to School of Electrical and Computer Engineering, written by Srash Sendekie, has been submitted for examination with my approval as Addis Ababa University advisor.

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Date of submission: ______________________________

Abstract

Power Quality is an area of serious concern for end users due to the frequency of power quality issues and their financial impact. In this context, real -time power quality monitoring needed so as to detect power quality problems and take control action within right time at right place. Utilities are already installing systems to monitor power quality in the distribution system. The equipment used is mostly power quality monitors which have the capability of measuring all the needed parameters specified by the power quality norms. But the price of these instruments dictates that monitoring of all the points in the distribution network with these instruments is from a techno-economic point of view not feasible, especially for developing country. Therefore, utilizing smart meter devices installed in all points of distribution network to gather more accurate data about power quality. In this thesis real-time power quality monitoring and enhancement role of smart meter is presented.

To this end, this thesis proposes single phase smart electricity meter based on Arduino Uno and GSM module. The proposed meter was simulated using proteus software and the results of simulation tests of power quality monitoring and enhancement capability of a proposed smart meter are analyzed. The performance of the system measurement is verified based on absolute percentage error (APE) and shown the results to be appropriate. Accuracy of measurement for RMS value of voltage and current, frequency variation, power factor, active power, energy consumption, and supply voltage total harmonics distortion was found less 1% error. Necessary data sent to customers via GSM was tested with help of virtual terminal. Furthermore, it was found that power quality enhanced and consumption of electricity becomes much more efficient (12% increment) by using dynamic power factor correction scheme integrated in smart meter and applying capacitors for the correction of power factor. Real-time power factor monitoring was sophisticated and thyristor switch for capacitor connection without mains supply distortion and delay free. Continuous real-time monitoring capability of meter performance tested over one hour with standard PQ data aggregation time interval.

***Key Words*: Smart Meter, Real-Time Monitoring, Power Quality Monitoring, Dynamic Power Factor Correction, Thyristor, GSM module, Arduino.**

Acknowledgement

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Abbreviations

AC	Alternative Current
ADC	Analog to Digital Convertor
AMI	Advanced Metering Infrastructure
AMR	Automatic Meter Reading
APE	Absolute Percentage Error
CT	Current Transformer
DIAC	Diode for Alternating Current
DPFC	Dynamic Power Factor Correction
GSM	Global Service for Mobile Communication
IC	Integrated Circuit
IEC	International Electro Technical Commission
IEEE	International Electrical and Electronics Engineering
IDE	Integrated Developmental Environment
IPQMS	Integrated Power Quality Monitoring System
IoT	Internet of Things
KVAR	Kilovolt-Ampere Reactive
LCD	Liquid Crystal Display
LED	Light Emitting Diode
LoRa	Low Power Long Range Wireless Data

LV	Low voltage
MV	Medium Voltage
PF	Power Factor
PLC	Power Line Carrier
PQ	Power Quality
PQM	Power Quality Monitoring
RMS	Root Mean Square
SCR	Selective Catalytic Reduction
SCADA-DMS	Supervisory Control and Data Acquisition- Distribution Management System
SEMCE-DAC	Data Acquisition System Power Quality Monitoring
SMS	Short Message Service
THD	Total Harmonic Distortion
TRIAC	Triode for Alternative Current
Wi-Fi	Wireless Fidelity
Wi-SUN	Wireless Smart Utility Networks
ZCD	Zero- Crossing Detector

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Chapter 1

1. Introduction

1.1 Background

In recent years, electric meters have developed dramatically from a system capable of measuring only energy consumption to a system capable of performing sophisticated mathematical algorithms such as power quality and time of use calculation; tamper detection etc. [1]. One of the AMR / AMI system's most appealing and realistic add-on features, provided by various manufacturers, is the real-time monitoring of outages and power quality issues. Many smart meters currently available on the market are capable of calculating certain parameters of power efficiency. The state-of-the-art smart meters of today will record power quality events depending on the vendor and form of the meter [2].

A smart meter is an electronic system that records information such as electrical energy consumption, voltage rates, power factor, and current. This shares user information for better understanding of consumer behavior, and energy suppliers for network control and customer billing. Smart meters usually record near real-time energy and monitor short intervals on a regular basis during the day, allowing two-way communication between meter and central network. Such an advanced metering system (AMI) is distinct from automatic meter reading (AMR) as it enables two-way contact between the meter and the supplier. Communication systems can be wireless from the meter to the network, or through fixed wired connections like the power line carrier (PLC). Commonly used wireless networking solutions include cellular phones, Wi-Fi (free of charge), wireless ad hoc networks over Wi-Fi, wireless mesh networks, low-power long-range wireless (LoRa), ZigBee (low power, low wireless data) and Wi-SUN (Smart Utility Networks) [3]. As an important smart grid system, smart meters are microprocessor applications and network communication technologies as the core of energy measurement, data storage and processing, real-time monitoring, automatic control, knowledge sharing and other functions [4].

Power Quality is an issue of serious concern for end users due to the frequency and financial effect of problems with power quality. The study estimated that between 30 and 40 percent of all business downtime is linked to problems with power quality. Poor power quality costs in some industries, such as manufacturing, can exceed 4 per cent of annual turnover. Low power quality has a significant effect on the deterioration of reliability and protection of overcurrent and under frequency relay operation, electromagnetic filed generation and corona in transmission lines, distributed generation, and frequency / voltage control [5]. Customer-owned equipment produces a significant number of perturbations in the power quality. To this reason, more and more utilities have placed in place rewards and penalties to their customers with ignoring violations in network power quality. On the contrary, consumers complain about the utility being the source of the issue of power quality [6]. Real-time monitoring of power quality helps to take immediate control action after power quality problems identified. Since the time the order was given the returned information is correct.

Variability in the power factor is one symptom of power quality. Utilities have installed a static capacitor bank on a secondary distribution line to improve the poor PF of a low voltage network. This is an ineffective, ineffective and unsustainable custom, because;

- It is very difficult and costly to fix and maintain mounted capacitor banks
- These static capacitor banks are constantly online and harm the distribution network by drawing large-line current at a time when domestic consumers are in low energy demand.
- Not efficient with very fast fluctuating load for these.

Installing a dynamic power factor correction system at the customer service entry point recommended as an economical way to avoid problems caused by a poor power factor. Dynamic (delay-free) power factor correction systems, among others, are fast reactive power compensation for dynamic loads with sudden and rapid demands of VARs and reactive power compensation without transients when switching to applications with high-sensitivity loads. This method benefits from the stability of the system voltage, avoids voltage drops, improves the efficiency of the customer's electrical system, reduces harmonic distortion, maximizes the power factor and significantly reduces flicker [7].

Many distribution system operators are already installing power quality monitoring systems in the distribution system. The equipment used is mainly power quality monitors in accordance with the IEC 61000-4-30 standard, which have the capability to measure all the required parameters specified by the power quality standards. The price of these instruments, however, dictates that the monitoring of all points in the distribution network with these instruments is not feasible from a techno-economic point of view. As a result, ways to use other smart electronic devices installed in smart distribution grids to gather some more data on power quality. Smart electricity meter as power quality monitoring device is the modern trend in modern power industry due to digitalization era and evolution of two-way advanced communication technology [8].

Integrating power quality functionalities in smart meters is a cost-effective solution, as the existing smart meters hardware, such as analog signal conditioning, power supply and communication interface, would be used instead of installing a power quality monitoring instrument at that location [9]. The Integrated Power Quality Monitoring System (IPQMS), which collects, stores and processes power quality data in the distribution network, is presented as a response to the demands of power quality in future smart distribution grids [10].

Therefore, innovative approach which integrating dynamic power factor correction in smart energy meter and installed at entrance of customer needed to monitor and improve power quality problem in real-time is vital in low voltage network.

1.2 Statement of the Problem

Even though the integration of power quality monitoring (i.e. RMS voltage, RMS current, frequency, power factor, active power, reactive power, harmonics distortion, and total harmonics distortion) in smart electricity meters has been presented as an efficient, low-cost, and real-time monitoring device, the lack of integration of power quality control/enhancement in smart meters is the major bottleneck issue for smart meter to achieve full demand in real-time power quality management. Power factor variability is one symptom of power quality. This variability is due to fast load fluctuation which requires a dynamic power factor correction method instead of installing a fixed capacitor bank on the secondary distribution line to improve poor low voltage network PF, which means that immediate load PF measurement and enhancement must be in real-time.

Hence, an innovative approach that incorporates dynamic power factor correction into a smart meter with robust communication technology built at the customer's entrance to monitor and control power quality problem in real-time system is important for low voltage network.

1.3 Objective of the Thesis

1.3.1 General objective

The aim is to study and analyze of smart meter in power quality monitoring and enhancement in real-time monitoring.

1.3.2 Specific objective

a. To study existing power quality monitoring practice
b. To study smart electric meter role on power quality management
c. To develop Arduino and GSM based smart energy meter integrated with dynamic power factor correction.
d. To simulate the proposed system by using proteus 8.6 platform and Arduino software.

1.4 Scope and Limitation of the Thesis

1.4.1 Scope

The scope of the thesis is limited to study on smart meter role in power quality management and the development of integrated dynamic power factor correction in single-phase smart meter based on Arduino and GSM module.

1.4.2 Limitation

The limitation of this thesis is lack of laboratory materials to show the hardware and to analyze the system practically.

1.5 Literature Review

In this literature review a numbers of researches have been done on the integrating power quality real time monitoring in smart meter are described below.

Testing mechanism may ensure better performance of smart meter proposed by [17]. The paper addressed a test method that could be used to determine the electrical parameters. This testing mechanism, however, could not guarantee analysis of power quality for low voltage networks. Another work was carried out by Sanduleac et al. [18] to resolve such a problem, where a method is proposed to reduce the computational power of the smart meter and thereby improve its performance. Using ARM processor, the author has carried out the smart meter's hardware design and studied patterns in harmonics currents. The method carries out mathematical analysis, too.

Power quality parameters monitor implemented using Ethernet based smart energy meter. Energy consumption data is sent to server by smart energy meter and stored there. Graphical programming of LabVIEW is utilized to fetch data from server and then various power quality parameters are calculated using virtual instrumentation created. Additionally, at household level, smart energy meter identifies appliance as inductive, capacitive and resistive and, automated method is developed to schedules loads such that the reactive power is cycled within loads. This diminishes needs for higher dependency of reactive power from utility which improves the power factor and also defeat the usage of high cost power factor correction circuits for household

[19]. The study could not have considered power factor correction technique, which implemented with proposed smart meter.

Wireless sensor and actuator network are introduced to track the energy consumption of appliances at home. The network configuration consists of energy measurement nodes and central server, the central server shows the reading from the measurement nodes via user interface in real time and enables the user to turn individual devices remotely on or off. This device provides a convenient way to manage home energy consumption. This is done by ensuring that the customer’s needs and requirements are met [20]. The method, however, could not guarantee power quality monitoring at consumer’s premises.

An innovative approach for monitoring home electric power quality indicators is presented. it is proved that it is possible to track and record electric power quality irregularities, such as long interruptions, voltage dips / swells and frequency oscillations using a smart-meter and a personal computer. An application developed in Java, a user can view electrical parameters in real-time, search for irregularities in the quality of electrical power and analyze the load diagram from previous days. Experimental results concerning the performance of the application are also discussed [21]. However, Java is slow and has a poor performance, memory-consuming and significantly slower than native languages such as C or C++. Moreover, the study could not have considered load control remotely, and power factor correction in real-time.

New framework has been created that will help industrial and residential consumers identify inefficient use of energy and thereby reduce the use of electricity. The device calculates all the power parameters such as instant voltages, instantaneous currents and power factor up to 0.9 and thus distributes quality power to end users. Power factor enhancement is carried out in real time Using pic microcontroller, capacitor bank and relay as capacitor switch [22]. However, pic microcontroller is not user friendly for non-expert user and using ZigBee technology as communication method is another drawback because it has applicable for short distance range, low data rate. And also relay has many drawbacks when use it with smart component.

A novel low cost IoT-based smart meter is presented to calculate and analyze PQ parameters. This IoT-based smart meter is designed using a versatile microcontroller that processes voltage and current signals using IEEE standard 1459-2010. It also consists of a wireless communication feature to communicate with the IoT cloud platform and to store the measured PQ parameters, where these parameters are processed and analyzed. PQ issues not only damages the device but also wastes the energy, and hence this analysis would help in saving energy. The proposed IoT-based smart meter enables utilities to understand the power consumption patterns of individual consumers and help them to predict the next demand of electricity more precisely [23]. The study, however, have not analyzed power quality enhancement in real-time. Another drawback of method implementation was lack of security on privacy.

The possibilities, opportunities and challenges associated with exploiting the advanced metering system already built or rolled out across New Zealand to track PQ in the LV network explored. Work outlined in paper has been done as part of green grid programme. It is noticed that many of New Zealand's over one million smart meters are capable of measuring and recording steady-state voltage, voltage sags / swells, and simple level harmonics to a basic level [24]. The study, however, it could not have proposed best framework after the features and capabilities of different models of smart meters presented in order to make accessible for different class of customers.

In terms of accuracy, Power Quality (PQ) and Smart Grid Synchro-SCADA Monitoring and control in Emerging Networks for Smart Meters was investigated with available instrumentation values in the meter being comparable with the metered electricity. The light PQ assessment method can be implemented in SM, when the meter has a modular (flexible) design. The approach allows a possibility for addressing evolving markets, may help identifying harmonic patterns, voltage variations correlated with prosumer profiles in weak networks. The new approach paves the way to relate the delivered energy to its "quality" in that time interval. The Unbundled Smart Meter allows synchronous data acquisition by taking advantage of new chip sets for the meters, using synchronous re-grouping of measured data at SCADA-DMS level. This helps deploying active network control e.g. preserving voltage quality at the end–user level. Thus, supporting new regulation initiatives [25]. The study, however, could not considered power quality enhancement with help of smart energy meter in real time at end users.

Summary of Literature

To summarize the above literatures and intended area of study, most of the researches done so far are focusing on performance of smart meter in steady state PQ parameters measurement and PQ event analysis like voltage variation, and waveform distortion, etc. On the other hand, researches on integrating power quality enhancement in smart meter after assessing PQ problem in real-time are left for further researches. The study of power quality control in real time is very important for low voltage network at customer's premises as it paves way for preventing power quality problem generated from customer's owed device injected to network and from network to customer's device and then meets both supplier and customer satisfaction. As it is very well known, PQ in the low voltage level and consumer premises, especially homes, is largely unmonitored and, uncontrolled, is not well understood. Specific monitoring typically takes place only after consumer complaints have been laid or abnormalities noticed. So power quality monitoring and controlling device in real-time at customer's service entrance needed.

Therefore, in our research we are going to integrating power quality controlling device in smart meter in order to enhance power quality in real time in addition to power quality monitoring and energy management function of smart energy meter.

1.6 Contribution of the Thesis

This study introduced a new system by incorporating a dynamic var counter in a smart meter based on GSM technology to monitor and control the power quality of end-users in real-time. Dynamic power factor correction designed based on capacitor bank connected in parallel to a load and thyristor switch for capacitor bank connection in order to overcome the problem faced by a relay and a contactor as a switch. A power factor of 0.9 or less is to be corrected; many electricity distributors are expected to maintain a minimum power factor of 0.9 for all installations. A Power Factor Regulator keeps track of the power factor and switches the capacitors in and out automatically, as the load on the system varies. The system also provides a low cost, reliable and real time reporting of power usage to supplier and end user; to control customer's energy consumption and reduce billing; link and detach the load from supply if there is overload and excessive power usage occurred. In addition, system design uses open source Arduino Uno to avoid programming and debugging difficulties faced by PIC or similar microcontrollers and it includes additional hardware components that help to reduce costs and GSM module to real-time monitoring.

❖ The advantages of switching with thyristor are:

- Suitable for real time power factor correction
- No high switch-on currents. Transient-free switching.
- Switching within one sinusoidal half cycle.
- Unlimited number of switching operations.
- Avoidance of drops in voltage

1.7 Methodology

The research methodology and research flow are presented as follows:

I. Author approach

Thesis is carried out through multiple stages starting from literature review about smart meter role in power quality management and real time monitoring, study existing power quality monitoring strategy and then performing design and the simulation of proposed system in proteus v8.6 tool to complete the thesis work.

II. Research design

a. Literature review:

A number of published ideas about power quality monitoring equipment and smart meter role in power quality monitoring in books, papers, articles, journals, lecture notes, materials have been reviewed.

b. Proposed framework: advanced smart meter design forwarded to improve the power quality management strategy weakness in real time base.

c. Building simulation environment:

This stage is critical to understand as it exhibit deep understanding of how and why each section of proposed system and components are chosen.

d. Simulation result:

The last stage is to grasp the relevant results of interest for research study. Using PROTUES software modeling and simulation of proposed smart meter have been carried out for the modeled load. Simulation short message service results display on virtual terminal consist of power quality parameter of supply and load information.

e. Simulation tools:

   Proteus is selected as it offers easy interface to Arduino board and IDE software, and GSM modem; possibility to develop and run this simulation environment; validity of the simulation results and the tools are highly reliable, robust and efficient.

f. Conclusion and recommendations: significant for the utility and end users have been made.

1.8 Thesis Organization

This thesis report is organized in five chapters. Chapter one discusses about the introduction section which included background, statement of problem, objective, scope and limitation of thesis, literature review, and contribution of the thesis, and methodology and other things have been studied. Chapter two, describes basics of smart metering and power quality monitoring.

Chapter three explains design principle of proposed smart meter, design implementation, circuit description and simulation tools. Chapter four shows the simulation results and discussions, lastly chapter five is conclusion and recommendation of the thesis.

Chapter 2

2. Theoretical Background of Conventional and Smart Meter

2.1 Conventional energy meter

Energy meters measure the instantaneous voltage in volts and current in amperes continuously to calculate energy consumption. There are two types of energy meter

i. Electromechanical energy meters, which operates by counting the revolutions of a non-magnetic metal disc. These numbers of revolutions are proportional to the energy used by the customer.

ii. Electronic energy meters, which display the energy used on an LCD or LED display [26].

These kinds of energy meters support only recording the amount of energy used during on-peak and off-peak hours. It has errors in conventional billing and doesn't have power quality monitoring capability.

There are errors and weakness in conventional billing because it manual operation [27]

- There is a chance of human error while taking manual energy meter reading
- Meter reading has no balance and verification procedure and
- Not updated of customer usage.
- The procedure is time consuming

2.2 Smart meter

2.2.1 Evolution of Smart Meter

The new digitalization era leads to the digitalization of electric power use and billing processes, leading to the development of prepaid smart energy meters with additional functionality with a specific feasibility study for realistic applicability ensuring optimal usage of electrical energy.

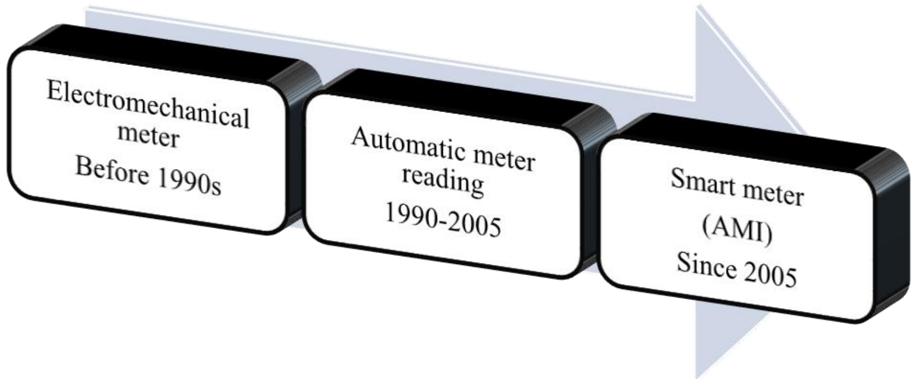

Figure 2-1 : Smart meter evolution in power industry

In 2005, the first generation of smart meters was launched, known as advanced metering infrastructure (AMI), by further enhancing contact between utility and consumers and time-sensitive billing. Smart meter goes a step better than reading automatic meter. It provides additional features including real-time reading, power outage detection, and power quality monitoring information, as well as enabling price-setting agencies to implement various end-user energy consumption prices based on daytime and season time. Such meters will take the read and send the information repeatedly in short time intervals to the data management unit of the utility meter, depending on information requirements. The meter data management unit will track the meters because smart metering system uses a two-way communication. Advanced metering infrastructures can detect power outages and monitor voltage profiles [28].

2.2.2 Smart Meter Function

Smart meter is one of the important smart grid infrastructure, is a microprocessor applications and network communication technology as the core of energy measurement, information storage and processing, real-time monitoring, automatic control, information exchange and other functions [9].Unlike smart meter multifunction table power meter ,because itself contains more powerful microcontroller(MCU),so it's like a mini computer ,automation and intelligent features richer ,more powerful, usually it will have some of the following major functions[4];

- Data collection function
- Data recording and storing function
- Load control function
- Programming function

- Billing function
- Display function
- Two-way communication function

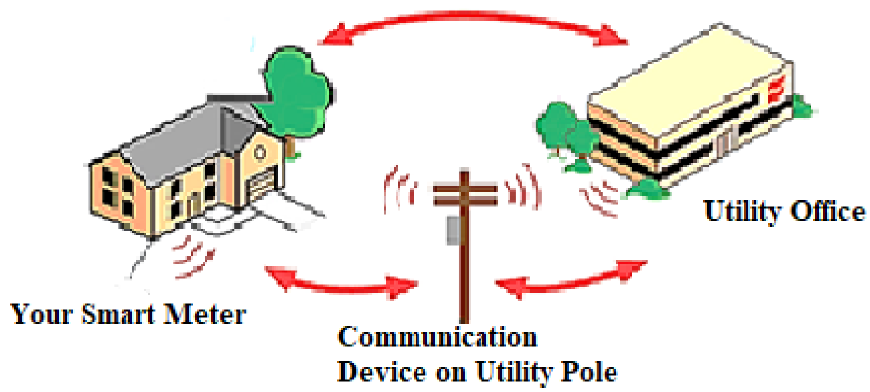

Figure 2-2: Smart Meter Working Principle

2.2.3 Advantage of Smart Meter

Both utility and customers are benefited by using smart meter as follows [32];

❖ Benefit for utility:

- Eliminates manual monthly meter reading
- Monitors the electric system in real time
- Encourages more efficient use of power resources
- Provides responsive data for balancing electric loads while reducing blackouts
- Enables dynamic pricing
- Avoids the capital expense of building new power plants
- Helps to optimize the profit with existing

❖ Benefits for customer:

- Provides accurate and real time consumption information
- More accurate billing
- Better and faster service
- Better power quality
- Automatic outage notification and recovery

2.3 Power Quality

Power quality is defined differently based on one's frame of reference the utility, end user of electric power, or manufacturer of load equipment. But as per IEEE Standard 1159 power quality defines as the concept of powering and grounding sensitive equipment in a manner that is suitable for the operation of that equipment [11].

A. Classification of Power Quality Phenomena

The electromagnetic phenomena that cause variations in the power quality are classified into different categories. One of the primary reasons for this categorization is to facilitate a more convenient way to solve the power quality issues based on the particular event under consideration. The IEEE standard 1159-1995, classifies the above electrical phenomena into seven major categories listed as hereunder [11].

- Transient
- Short duration voltage variation
- Long duration voltage variation
- Waveform distortion
- Voltage unbalance
- Frequency deviation
- Voltage fluctuation

B. Power Quality Standards

Waveform distortion and frequency variation range, individual and total harmonics distortion for voltage presented here as reference for simulation result.

I. Waveform distortion

Waveform distortion is defined as any steady-state deviation of the voltage and/or current waveform from an ideal sine wave of the power frequency. There are five primary forms of waveform distortion of which one or more events occur in a distorted voltage or current waveform.

i. Dc –Offset

Dc offset is the dc voltage or current component of the spectral contents in an ac voltage or current. This occurs mainly as the result of a geomagnetic disturbance or asymmetry of electronic power converters, such as half-wave rectification.

ii. Harmonics

Harmonics are sinusoidal voltage or current components of the waveform. They have frequencies that are integer multiples of the fundamental frequency.

iii. Inter Harmonics

interharmonics is a condition where a signal affects the main voltage waveform. It can cause display monitors to flicker and equipment to overheat. The main sources of interharmonics waveform distortion are static frequency converters, cycloconverters, induction furnaces, and arcing devices. Interharmonics can also cause communication issues.

iv. Notching

Notching is a drop in voltage as close to zero as permitted by system impedance caused by a momentary short circuit between two phases, during current commutation in the normal operation of power electronic devices. In other word, nothing is an intermittent disturbance that can affect voltage. It normally happens when light dimmers or arc welders are being used. Notching is a periodic voltage disturbance caused by the normal operation of power electronic devices when current is commutated from one phase to another. It results in data loss and issues with the transmission of data.

v. Noise

Noise is defined as unwanted electrical signals with broadband spectral content lower than 200 kHz superimposed upon the power system voltage or current in phase conductors, or found on neutral conductors or signal lines. Noise in power systems can be caused by power electronic devices, control circuits, arcing equipment, loads with solid-state rectifiers, and switching power supplies. Noise disturbs electronic devices such as microcomputer and programmable controllers. The problem can be mitigated by using filters.

II. Total Harmonic Distortion

Harmonics are components in the supply voltage or current which have sinusoidal wave shapes and with frequencies that are integer multiples of the fundamental frequency of the supply system. Harmonics can be evaluated individually by the relative amplitude of each component, or by evaluating the Total Harmonic Distortion (THD). One of the more common measure and indices of power quality is total harmonic distortion (THD). The basic themes of IEEE Standard 1159-1995 are twofold [11].

The IEEE Standard 519-1992 permissible voltage distortion that a utility can supply is tabulated as below.

Table 2-1: IEEE voltage distortion limits [12]

Bus Voltage at PCC(Point of common coupling)	Individual Voltage Distortion (%)	Total Voltage Distortion THD (%)
≤ 1 KV	5	8
1KV - 69 KV	3	5
69.001 KV - 161 KV	1.5	2.5
≥ 161.001Kv	1	1.5

Table 2-2: IEEE current harmonic distortion limits [12]

Isc/IL	11<h	11<h<17	17<=h<23	23<=h<35	35<=h
<20	4	2	1.5	0.6	0.3
20<50	7	3.5	2.5	1	0.5
50<100	10	4.5	4	1.5	0.7
100<1000	12	5.5	5	2	1
>1000	15	7	6	2.5	1.4

III. Power frequency variation

Frequency is a most important index for power quality and useful for load frequency control of power system. Digital measurement of power frequency using microcontroller based system is economical than using oscilloscopes. The frequency is required to be maintained at 50Hz ± 1%. This implies between 49Hz and 51Hz. Every 0.01 Hz of change in grid frequency corresponds to approximately 6% to 8% of power supply dropped in the grid [13].

C. Cause of Poor Power Quality

The main causes of poor power quality in low voltage are defined as [14], [15]:

- Voltage variations: because equipment operates less efficiently.
- Harmonic pollution: This causes additional stress on the networks and systems, causing them to operate less efficiently.it also cause to change power factor of supply.
- Excessive reactive power: because it charges useless power to the system. Most of loads are working with poor power factor less than 0.8 which implies the excessive reactive power has to draw to system.

D. Poor Power Quality Economic Impact

Some of the implications of power quality especially related to poor power quality are [14], [16];

- Increase in line & equipment current leading to additional ohmic loses;
- Increase in line & equipment current leading to blocked capacity and/or increased capital investment;
- Increased losses leading to higher operating temperatures and consequent reduction in life of equipment;
- Premature failure of equipment due to increased electrical and thermal stresses;
- Malfunction of equipment;
- Poor quality of production;
- Unplanned outages leading to loss of production

In Ethiopia, high voltage drop is the significant electric power supply problem, especially at residential usage. This is the cause for decreasing the performance of electric stoves and heaters that end users of electric power are forced to wait for a long time to make stew, to bake bread, and to boil water. Moreover, the working life of light bulbs, in addition to giving less-bright lights, is getting shortened due to under voltages.

2.4 Power Quality Monitoring

Power quality monitoring is the process of gathering, analyzing, and interpreting raw Measurement data into useful information. A typical monitoring system measures voltage and electrical current, but ground quality may also be measured if unbalanced loads or harmonics are detected. There are a number of reasons to employ power quality monitoring. It allows plants to perform energy management, preventive maintenance, quality control, and saves money. Today, many end users have sensitive telecommunication or computer equipment that don't utilize PQM.

2.5 Dynamic Power factor correction

Variability in the power factor is one symptom of power quality. Utilities have installed a static capacitor bank on a secondary distribution line to improve the poor PF of a low voltage network. This is an ineffective, ineffective and unsustainable custom, because;

- It is very difficult and costly to fix and maintain mounted capacitor banks
- These static capacitor banks are constantly online and harm the distribution network by drawing large-line current at a time when domestic consumers are in low energy demand.
- Not efficient with very fast fluctuating load for these.

There is a different switching device for capacitor banks to compensate power factor assemblies. These devices Classified as follows are: electromechanical device (i.e. relay and contactor) and solid-state device (i.e. SCR, TRIAC, DIAC, etc.). Besides advantage, their drawback list is as follows;

❖ Relay has the following drawback

  - Has lower ampere capacity i.e. Max. 20A.
  - It is not economical to repair
  - Since it induces back emf, it generates transient voltage
  - Since it has delay in switching, power supply harmonics cannot be reduced.

❖ Drawback of contactor as a switch capacitor bank

  - Slow to switch they may not react quickly enough to sudden fluctuations in demand,
  - Contactor cannot reduce the harmonic content of the supply because of switching delay.
  - voltage transient due to inrush current cannot controlled in safe limits
  - there are mechanical contacts involved, arcing and sparking takes place and audible switching noise is produced.
  - Contactors undergo wear and tear over a period which leads limitations in number of switching operations.

Installing a dynamic power factor correction system at the customer service entry point recommended as an economical way of avoiding problems caused by a poor power factor. Dynamic (delay-free) power factor correction systems, among others, are fast reactive power compensation for dynamic loads with sudden and rapid demands of VARs and reactive power compensation without transients when switching to applications with high-sensitivity loads. This method benefits from the stability of the system voltage, avoids voltage drops, improves the efficiency of the customer's electrical system, reduces harmonic distortion, maximizes the power factor and significantly reduces flicker [7].

Dynamic power factor correction (DPFC), sometimes referred to as "real-time power factor correction," is used for electrical stabilization in cases of rapid load changes. DPFC uses semiconductor switches, typically thyristor, to quickly connect and disconnect capacitors to improve power factor.

Some of the advantage of dynamic reactive power compensation are listed below;

- Improvement of the power quality.
- Increase in available power (i.e. improved power network utilization).
- Decrease in transmission losses.

The advantages of switching with thyristor are:

- No high switch-on currents. Transient-free switching.
- Switching within one sinusoidal half cycle.
- Unlimited number of switching operations.
- Avoidance of drops in voltage.

2.6 International Industry Practice on Power Quality Monitoring

A survey was carried out cross the globe in 43 countries about the industry practice of monitoring power quality to build expertise and gather information to ensure the provision of good power quality service from utility to consumer. This paper has outlined some of the key findings of survey questions based on 114 responses.

The survey result revealed that, in some cases, the procedure is essentially universal across the world, with a few variations. Some of the findings of the survey could be found below [29]:

- 82 percent of network operators perform out continuous power quality monitoring using fixed monitors.

- Customers complaints was the main reason for power quality monitoring
- The selection of the installation location of the permanent monitor depends on the need to see the characteristics at the customer's site.
- Monitors are selected based on performance and not standards
- Every single utility uses just a few different models of PQ monitors
- In more than 90 percent of the cases, all the three phases are monitored and system current is more common than just specific customer current.
- The results of data processing are used for internal or external reporting on specific events
- Two thirds of voltage measurements are line-to natural voltages rather than line to line voltages.

A survey over some of the existing modern power quality monitoring systems and techniques that were developed over the past years conducted. It was noticed that some of the research was done to develop efficient quality monitoring systems and other to find the best location for meters in the electrical grid which will help to improve the PQM system. The power quality monitoring systems surveyed have been explained along with the different quality attributes they capture, such as flickers, voltage sags, etc. The monitoring scheme could be designed for real-time monitoring, long-term monitoring or both. It was noticed that some systems were designed for both which is considered as an advantage. An evaluation of the power quality monitoring systems was presented in form of comparison between the methods in terms of their advantages and disadvantages. The methods were varying between simple and complex or cheap and expensive. Some of the systems had tools and software that could be very expensive and hard to implement which was considered as drawback in the comparison. After comparing the methods and systems, it was found that the Data-Acquisition System for Power Quality Monitoring (SEMCE DAC) was the best example for power quality monitoring system as it has many advantages such as reduced cost and flexibility [30].

2.7 Analysis of Integrating Power Quality Monitoring in Smart Meter

The most advanced PQ analyzer in the market today provides three-phase high-performance PQ monitoring with built-in EN 50160 or IEEE Std. 1159 monitoring, statistics and reports. These Analyzers are more suitable to be installed at a fixed location and others designed to be used as portable equipment. Fixed equipment can usually be accessed remotely via standard communication technology and permanently monitors a single installation. Portable equipment, on the other hand, is normally installed at the desired location for a certain period of time, and then collected and mounted elsewhere. The price of this instrument however dictates that monitoring of all the points in the distribution network with these instruments is techno-economic point of view not feasible [8].

Hence, integrating power quality monitoring in smart metering can give advantages such as sharing dispersed equipment, installation, maintenance and communication networks. It measures parameter such as rms voltage, rms current, power factor, apparent power, active power, reactive power, and frequency, voltage and current total harmonics distortion, energy consumption and billing with low cost design, accurate and more precisions in measurement.

Generally, integrating power quality monitoring in Smart meters has great advantage over advanced power quality analyzer with respect to the following key point.

1. Monitoring location

Most of the monitoring placement specified is on the MV level network but Optimizing the number of analyzers of power quality and their positions at the LV level are still not solved. The usage of available data from smart meters and their correlation with data a smaller number of power quality instruments can provide a means of monitoring power quality in the LV distribution network in a more cost-efficient way [8].

Monitoring location should be at actual customer service entrance locations because

- It includes the effect of step-down transformers supplying the customer.
- To characterize the customer load current variations and harmonic distortion levels.
- It has the additional advantage of reduced transducer costs and provides indications of the origin of the disturbances.
- To reduce huge unnecessary volumetric data.

2. Data management

   The increased amount of power quality variation data being collected at central unit requires more advanced monitoring tools in order to easily handle analysis of these problems. Integrating power quality monitoring in smart meter helps to reduce unnecessary volumetric data. The integrated power quality monitoring system should collect only data from the measurement devices when there is problem or interference in order to identify the causes, instead of accumulating all the historical data [8], [24].

3. Reduce cost and flexible

   Integrating power quality monitoring into smart meters is a cost-effective solution, due to the existing smart meter hardware such as analog signal conditioning system, signal processing tool, communication interface and the power supply unit, instead of installing a power quality monitoring instrument at that location [9].

4. Continuous real time monitoring

   Smart meters implemented in power quality monitoring and having dedicated networks for the continuous online power quality monitoring in different countries around the world. Illustration for long term power quality monitoring with certain power quality parameters (i.e. harmonics, unbalance and flicker) were selected and monitored over selected periods of time. After the study it was found that the biggest change in the system or the key cause of disruptions was due to flicker parameters [31].

   There are four reasons that continue power quality monitoring should be good policy such as fast recovery, enhanced analytics, and accurate information and compliance benefits.

5. Offline and online data analysis

   It is suitable for offline and online measured data analysis due to it includes two-way communication technologies.

Chapter 3

3. Proposed System Design and Implementation

3.1 Design Principle of Proposed Smart Meter

The system architecture of integrating dynamic var compensation in smart meter based on Arduino and GSM is shown in figure 3-1. This thesis provides implementation done on Arduino UNO microcontroller using C language software to program the microcontroller, Arduino program to determine rms voltage, rms current, line frequency, power factor, real and reactive power, and THD for input voltage, energy consumed and prepare bill in birr and Proteus 8.6 used for simulation.

This system senses the power factor and with the help of microcontroller switches, required number of capacitors in the capacitor bank if power factor is less than 0.90. In this system, the reactive power will be generated by the bank of capacitors. Design and simulation will be done by using the LM 358, MOC 3023, Q7008LS, INA122, and Arduino Uno.

The system architecture can be divided into seven sections as

1. Voltage and Current Sensor
2. Zero Crossing Detectors
3. Arduino Board
4. GSM modem and Display
5. Thyristor Switching Circuit
6. Capacitor Bank
7. Load Control Unit

The description of each sections is separately introduced in circuit description section below:

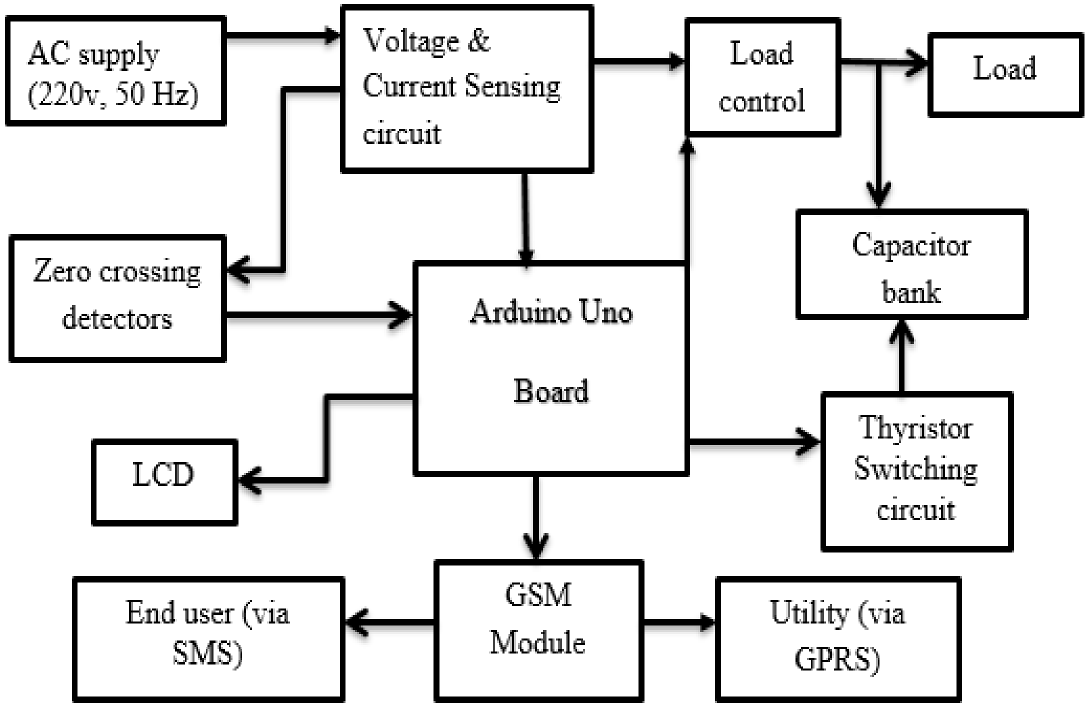

Figure 3-1: Block diagram of proposed system

3.2 Design Implementation

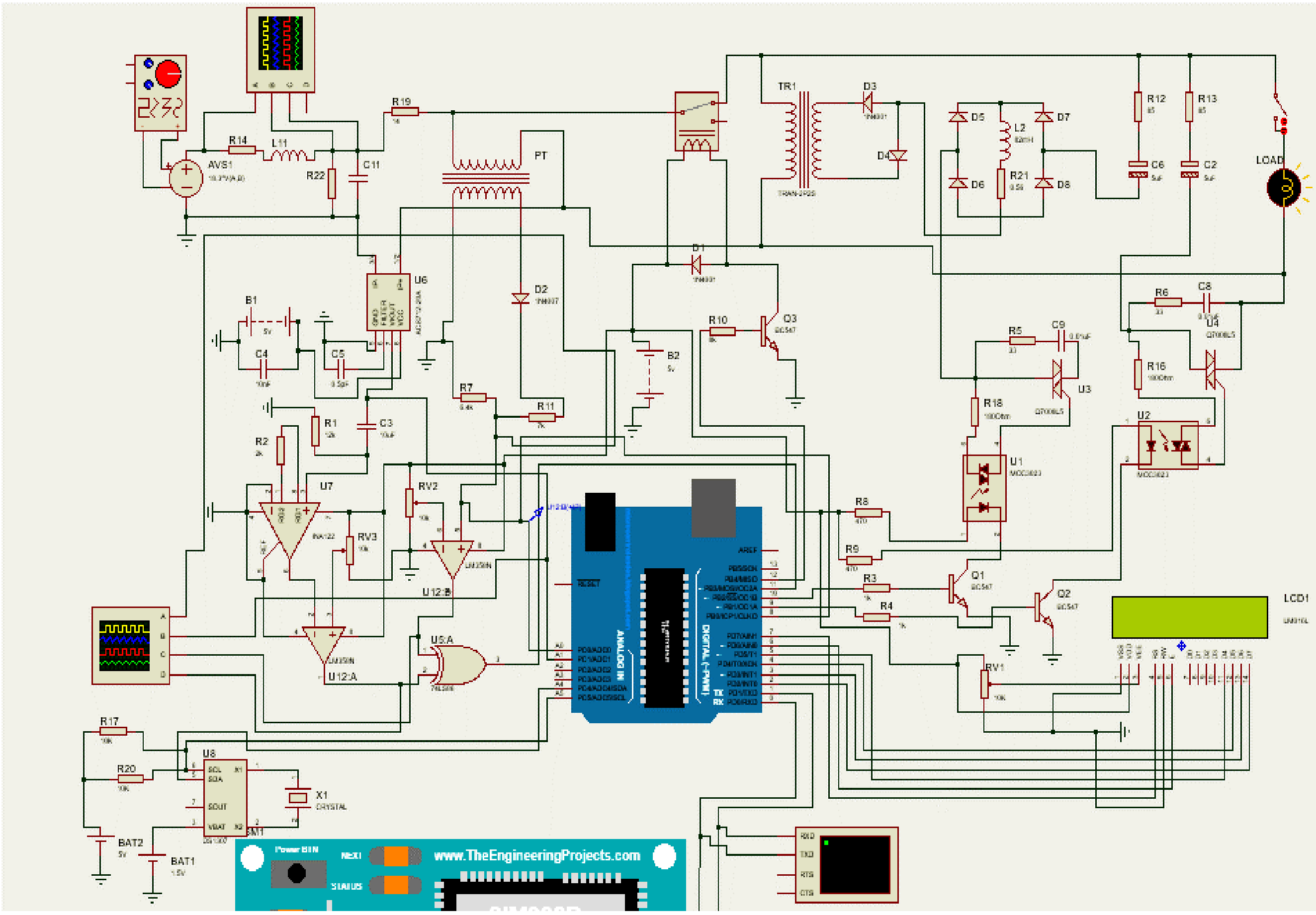

Figure 3-2: Proteus simulation of smart energy meter

3.3 Circuit Description

3.3.1 Ac source model

Figure 3-3 shows schematic diagram of ac source proteus simulation to generate 220V,50Hz ac with various possible power quality phenomena using RLC circuit.

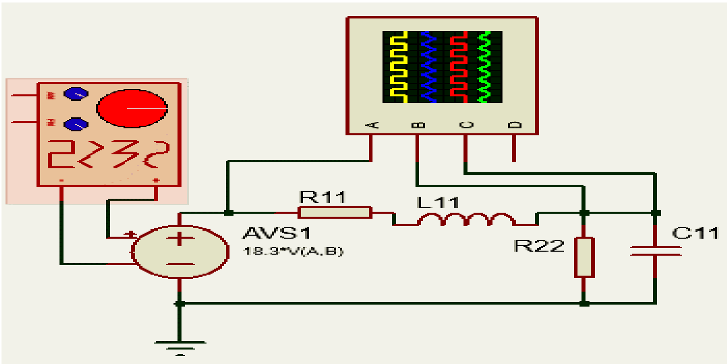

Figure 3-3: Proteus simulation of AC source

3.3.2 Load model

System design specification is based on supply 220V,50Hz. Most of customer's load is inductive and resistive in nature today. So, the implementation uses inductive and resistive load. Load model are selected based on thyristor switching circuit rated current. Two loads are assumed for simulation purpose which have resistive nature as shown in figure 3-4, and series combination of resistive and inductive nature impedance as shown in figure 3-5.

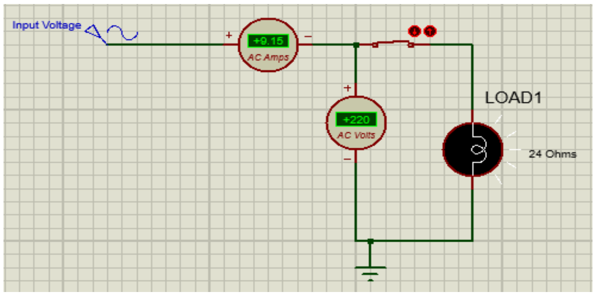

Figure 3-4: Pure resistive load model

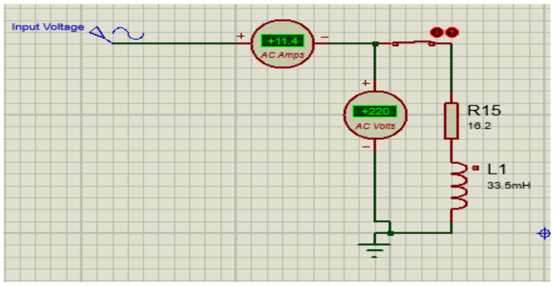

Figure 3-5: R-L load model

3.3.3 Sensing circuit section

1. Voltage sensing circuit

Figure 3-6 represents the circuit developed for the measurement of the supply voltage. The output Vout from the circuit can be fed directly to the Arduino.

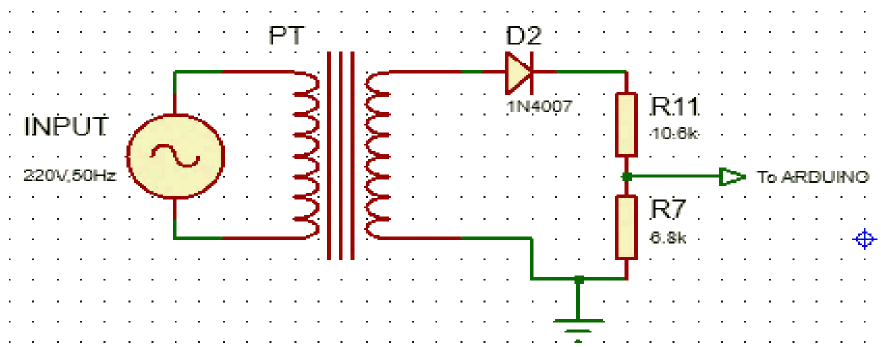

Figure 3-6: voltage sensing circuit diagram

The supply voltage to be measured is 220V. However, ADC of Arduino read only rated for voltages between 0 and +5V on any input pin. To do so, the supply voltage to be measured is applied at the input terminals of potential transformer (PT) steps down the supply voltage from 220 V AC to 12V AC. Then a diode (D2) is used to rectify the negative part of the voltage. After rectification 12V ac voltage was once again lowered by a voltage divider circuit using R11 and R7 to 5V.

2. Current sensing circuit

Figure 3-7 below represents the circuit for the measurement of the load current. It is similar in functionality to the circuit for measurement of voltage.

The current transformer (CT) stepped down the current down from line current to a more tolerable level to Arduino. Then the burden resistor converts the stepped down current to a limited voltage for the Arduino to read. This voltage will then be converted into suitable calibrated value.

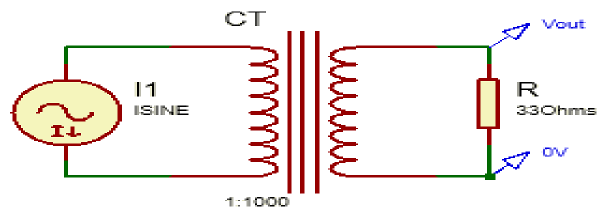

Figure 3-7: CT circuit with proteus

Figure 3-8 below represents the ACS712 current sensor module for the measurement of the load current.

In this design, ACS712-20A current sensing module used to simplify simulation. The sensor outputs an analog output voltage that corresponds to the current flow which ranges from 0-5V. This module designed for range 0-20A loads current and sensitivity of 100mV/A.

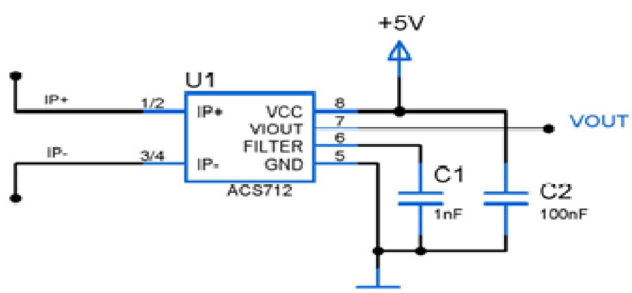

Figure 3-8: ACS712 Current Sensor Module(courtesy www.google.com)

3.3.4 Load control section

Figure 3-9 below represents load control circuit with relay. The working principle is microcontroller sends digital control signal to relay circuit and then disconnect the load from main supply if there is overload and unusual usage of energy consumption.

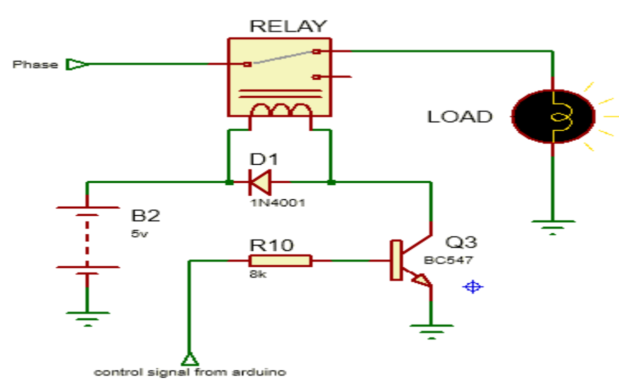

Figure 3-9: Load Control Circuit with relay

The transistor (BC547) used for interfacing microcontroller with relay, and diode is available in order to protect the transistor and microcontroller from back emf generated in the relay coil. The required value of diode is 1N4148 for fast switching action.

3.3.4 Power factor correction

Power quality is enhanced by improve power factor. This reduce reactive power consumption. Dynamic power factor correction (DPFC), sometimes referred to as "real-time power factor correction," is used for electrical stabilization in cases of rapid load changes. DPFC uses semiconductor switches, typically thyristor, to quickly connect and disconnect capacitors to improve power factor. This block is a new feature added to existing smart meter. It has three sub blocks.

1. Capacitor Bank

Capacitor bank design consideration: A capacitor bank has to go through different abnormal system conditions, during its life span. To with stand these abnormalities at optimum manufacturing cost, the capacitor banks are rated with following allowable parameters. A capacitor bank should continue its service with in the following limits.

- 110 % of normal system peak voltage.
- 120 % of normal system rms voltage.
- 135 % of rated KVAR.
- 180 % of normal rated rms current

The capacitor bank design considerations must be avoiding adverse effect of over correction such as, power system becomes unstable, resonant frequency is below the line frequency, and current and voltage increase. The sizing of capacitors is determined based on the required KVAR demand by the load network.

Hence $\mathrm{C} = \frac{\mathrm{KVAR}}{\omega * \mathrm{v}^2}$ ……………………………………………………… (3.1)

Where, C is capacitor value

KVAR is capacitor reactive power rating

$\omega = 2 * \pi * \mathrm{f}$ ………………………………………………………. (3.2)

Where: f- is supply frequency

v - is voltage rating.

Case 1: Resistive load specification:

- ✓ Supply: 220V,50Hz, single phase
- ✓ $\mathrm{R = 24ohms, I = 9.15\ Amps,\ power\ factor(PF) = 1.0}$
- ✓ $\mathrm{AppP = 2013VA = Activepower = 2.013KW}$

Case 2: Inductive load specification:

- ✓ Supply: 220volts,50Hz, single phase
- ✓ Load impedance has resistor $\mathrm{R = 16.2ohm}$ and inductor $\mathrm{L = 33.5mH}$ value.
- ✓ $\mathrm{I_{load} = 11.4amp}$
- ✓ $\mathrm{apparent\ power(S) = V_{rms} * I_{rms} = 220\ volt * 11.4\ amp}$

  $\mathrm{= 2508VA = 2.5KVA}$
- ✓ $\mathrm{Active\ power(P) = 2000W = 2KW, power\ factor(PF) = 0.80\ lagging}$
- ✓ $\mathrm{intial\ PF = 0.80, \theta_1 = 36.9°}$
- ✓ $\mathrm{Targeted\ PF = 0.90, \theta_2 = 25.84°}$

Then capacitor bank value calculates using equation 2 as follows,

$$\mathrm{KVAR = Q_C = P(tan\theta_1 - tan\theta_2) = k * P} \ \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots (3.3),$$

$$\mathrm{Q_C = 2000 * (0.75 - 0.484) = 540VAR}$$

$$\mathrm{C = {}^{540}/_{(2 * \pi * 50 * 220^2)} = 36uF}\ .$$

This implies 36uF capacitor needed to achieve targeted power factor. In this design, the capacitor bank consists of a group of seven ac capacitors in order to get 36μF, all rated at 400V, 50Hz. The value of capacitors is similar and it consists of seven capacitors 5μF. All the capacitors are connected in parallel to one another and the load. The capacitor bank is controlled using the triac module and is connected across the line. The operation of a triac connects the associated capacitor across the line in parallel with the load and other capacitors.

2. Zero Crossing Detector(ZCD)

ZCD is a voltage comparator that detect the zero crossing point of input signal waveform with reference value (0 volt) and then output converts to square waveform with different amplitude about 4V. It can be used to measure the phase angle between voltage and current.

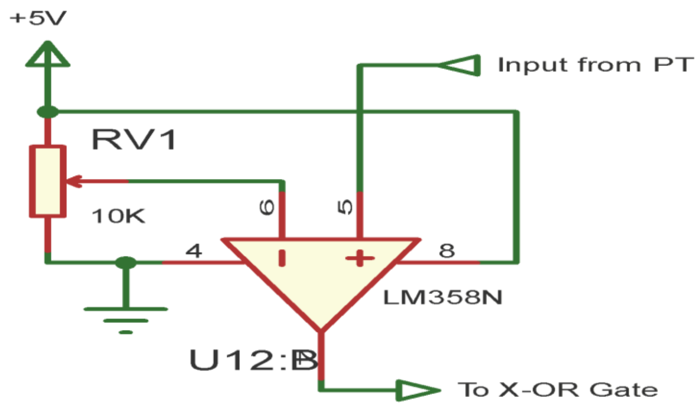

Figure 3-10: voltage zero crossing detector

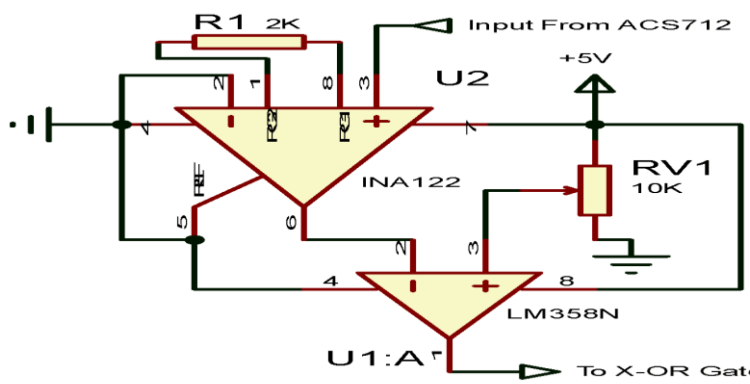

Figure 3-11: current zero crossing detector

3. X-OR Summer circuit

Table 3-1: truth table of XOR gate

XOR gate output		
Output	V	I
0	0	0
1	0	1
1	1	0
0	1	1

Figure 3-12 below represents X-OR summer circuit with two input from voltage zero crossing detector and current zero crossing detector.

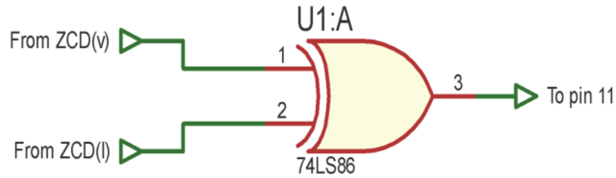

Figure 3-12: X-OR summer circuit

XOR gate output will be ‘1’ just when the inputs (ZCD (V) &ZCD (I) output) have different signals so when the load is resistive XOR gate output is ‘0’ because both voltage and current phases start and ends in the same time, but when the load is inductive or capacitive XOR output is ‘1’ because there is phase shaft between voltage and current.

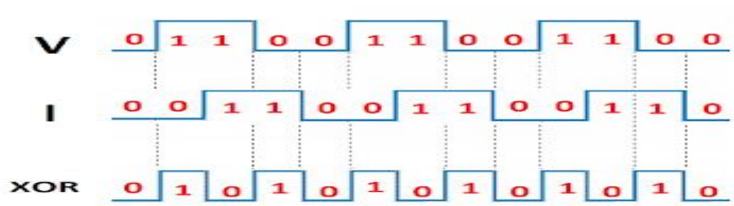

Figure 3-13: XOR-output with voltage (v) &current (I) input

XOR gate output is given to Arduino digital pin 11 in order to detect time difference because gate output has digital value. Hence, we can find the power factor by measuring the "ON-time" or “high “of XOR output, and the power factor calculated as follows.

$$\mathrm{PF} = \cos(\mathrm{duration} * \mathrm{f} * 360°) \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \quad (3.4)$$

Where:

PF = Power Factor, f= Frequency

Duration =Time difference between two phases and/or XOR output ON-time

After measuring power factor, microcontroller switched on required capacitor value if power factor is less than 0.90.

4. Thyristor Switching Circuit

Thyristor (TRIAC) switch for capacitor bank connection to the load without delay. The Optocoupler (MOC3023) used as isolator between microcontroller and triac because of triac is connected to high voltage. Microcontroller control signal/pulse are connecting to pin 2 of MOC3023 through NPN transistor.

The transistor (BC574) used as Optocoupler driver, it need input base current maximum rating 10mA and output collector current 100mA which is enough to drive Optocoupler. Microcontroller has digital high and low output. Transistors are suitable for such type of output than Optocoupler. Optocoupler has capability of supply up to 100mA to trigger triac gate in order to switch on/off required capacitor value.

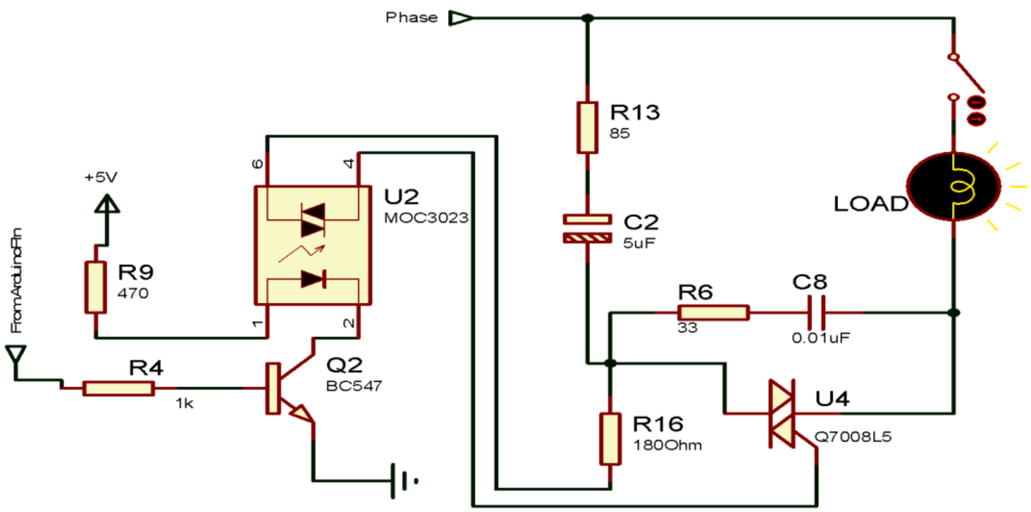

Figure 3-14: Capacitor bank with triac switching circuit

5. Capacitor switching transient limiter

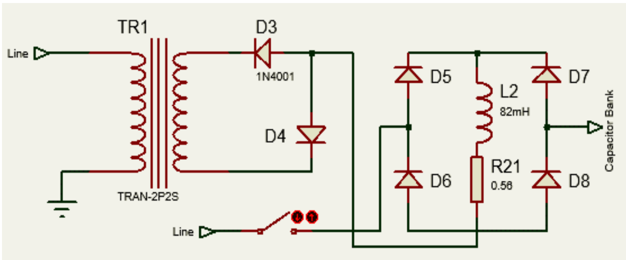

Figure 3-15: Capacitor switching transient limiter circuit

The operating condition of the circuit has two states: the charging suppressive mode and the steady state with its initial transient (freewheels mode). During the charging suppressive mode, a pair of diode strings conducts automatically and then it provides high impedance at the instant of switching on in order to suppress the capacitor energizing transients (inrush current). All diodes of the bridge rectifier conduct simultaneously and the limiter freewheel during the steady state with its initial transient; therefore, the limiter acts as a short circuit and has no effect.

The freewheeling effect in the limiter helps to avoid transient over voltage appears across the switching device at the instant of de-energization. In this study, adding capacitor switching transient limiter at each seven group of capacitor bank is costy. So it has to be design by grouping capacitor bank in step.

3.3.5 Arduino Uno

Arduino key features are:

1. Arduino boards are able to read analog or digital input signals from different sensors and turn it into an output such as activating a motor, connect to the cloud and many other actions.
2. Board functions control by sending a set of instructions to the microcontroller on the board via Arduino IDE (referred to as uploading software).
3. Unlike most previous programmable circuit boards, Arduino does not need an extra piece of hardware (called a programmer) in order to load a new code onto the board. You can simply use a USB cable.
4. The Arduino IDE uses a simplified version of C/C++, making it easier to learn to program. Arduino provides a standard form factor that breaks the functions of the micro-controller into a more accessible package.

Features of Arduino Uno board-

- It is based on ATmega 328P microcontroller
- Input voltage range is 5-7.12V.
- Digital I/O pins is 14 (of which 6 pin provide PWM output) and 6 analog input pins.
- 32KB flash memory 0.5KB used by boot leader.
- 16MHz clock speed and DC current for I/O pin 40mA

Arduino Uno was used as the heart of the system controller unit. Once actuated, it receives signals from all sensors, processes these signals and saves the value while sending the processed information or command out when necessary. Flowchart shown below represents microcontroller operation.

A. Measurement Parameter Data Calculation

I. RMS Voltage and Current Measurement

Voltage and current analog signals are given to Arduino pin A0 and A1. Then Arduino ADC convert theses analog signal to digital sampled value. The ADC on the Arduino is a 10-bit ADC meaning it has the ability to detect 1,024 (2^10) discrete analog levels. The ADC reports a ratio metric value. This means that the ADC assumes 5V is 1023 and anything less than 5V will be a ratio between 5V and 1023.

$$\frac{\text{Resolution of ADC}}{\text{system voltage}} = \frac{\text{ADC reading}}{\text{analog voltage measured}} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (3.5)$$

The 10-bit ADC of the Arduino on a 5V system, we can simplify this equation:

$$\frac{1023}{5} = \frac{\text{ADC reading}}{\text{analog voltage measured}} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (3.6)$$

e.g. If the analog voltage is 2.12V, the ADC report as a value

$$\frac{1023}{5V} = \frac{X}{2.12V} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (3.7)$$

$$ADC\ report\ value\ as\ X = 434$$

It then needed to be converted back into a voltage number when we analyze it

$$\text{AC voltage} = \text{Vrms}$$

$$= \frac{ADC\_value}{\sqrt{2}} * \frac{220\text{V}}{1023} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots . (3.8)$$

Multiplication factor: Multiplication factor set to algorithm to minimize error which is $\sqrt{2}$

$$AC\ voltage = \frac{ADC_{value} * \sqrt{2}}{\sqrt{2}} * \frac{220}{1023}$$

The same method used for current measurement because we give voltage signal for Arduino analog pin by converting load current to voltage using ACS712 current sensor module.

The only difference is current value get as follows

$$\text{Irms} = (\text{adc value} * \frac{0.707}{2}) * 1000/\text{mVperAmp} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (3.9)$$

Where, mVperAmp is sensitivity of current sensor module.

Implementation considered half second sampling in order to get accurate value; increasing number of sample gives more accurate result in microcontroller case. Voltage and current rms value could retrieve by programming Arduino microcontroller.

II. Frequency Counter

Frequency Counter is an electronic device which is used to measure the frequency of a signal. We generally use an oscilloscope to depict the signal, calculate the time period of the signal and finally convert it to calculate the frequency of the signal. But, oscilloscopes are very expensive and everyone cannot afford it. Hence, a simple digital frequency counter can be built which might come in handy to measure the frequency of a clock signal. In this thesis, an Arduino based digital frequency counter is designed to measure the frequency of an incoming signal.

$$\mathrm{F(Hz)} = \frac{1000000}{\mathrm{pulseHigh\ duration} + \mathrm{pulseLow\ duration}} \dots\dots\dots\dots\dots\dots\dots\dots.. (3.10)$$

Output signal of voltage sensor inputted to digital pin of Arduino. This digital pin detects rising and falling edge of input voltage pulse to measure signal frequency using pulseIn function.

III. THD Measurement

One of the more common indices for power quality is total harmonic distortion (THD): The ratio of the RMS value of the sum of the individual harmonic amplitudes to the RMS value of the fundamental frequency. In this thesis, THD used to measure and analysis power quality problem. In order to determine the total harmonic distortion, the discrete fourier series expansion has been used.

For pure input sine wave, individual harmonics and THD have to be zero.

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{V_1^2} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (3.11)$$

Where,

- V_1 = fundamental rms voltage,
- V_n = n^{th} harmonics of voltage amplitude

IV. Power and Energy Calculation

Microcontroller programmed to calculate power , energy consumed and preparing bill as follows and retrieve these values via serial pin 1(T_x) and pin0 (R_x) to GSM module and LCD display:

$$\mathrm{Apparent\ Power(VA)} = \mathrm{Vrms} * \mathrm{Irms} \dots\dots\dots\dots\dots\dots\dots\dots.\dots\dots\dots\dots\dots\dots\dots\dots\dots (3.12)$$

$$\text{Active Power(Watt)} = \text{AppPower} * \cos\theta \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.13)$$

$$\text{Reactive Power(VAR)} = \sqrt{(\text{AppPower}^\wedge 2 - \text{active power}}{}^\wedge 2) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.14)$$

$$\text{Energy Consumed(KWH)} = \left(\frac{\text{Active power}}{1000}\right) * \text{elapsed Hour} \ldots\ldots\ldots\ldots\ldots (3.15)$$

V. Billing calculation:

$$\text{Total birr} = \text{total energy consumed} * \text{electricty tariff} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.16)$$

Flow chart

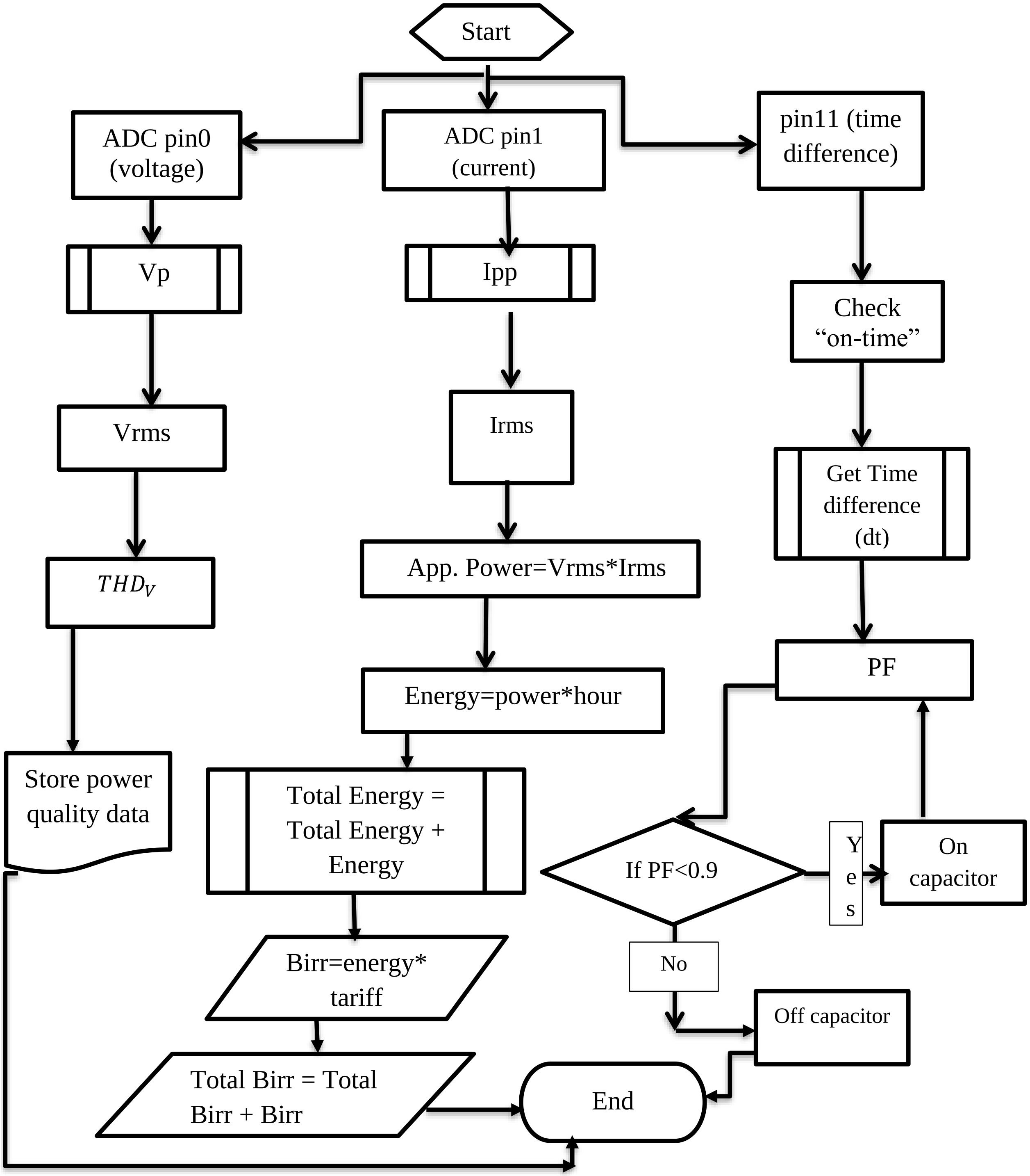

Figure 3-16: Flow Chart of Microcontroller Operation

3.3.6 LCD Display Section

Liquid Crystal Display screen is an electronic display module for displaying text or characters. A 16x2 LCD means it can display 16 characters per line and there are 2 such lines. In this LCD, each character is displayed in 5x7 pixel matrix. LCD mounted with smart meter to display measured parameters and useful for local load monitoring.

Figure 3-17: 16*2 LCD display

3..3.7 GSM Module Shield

The values of Vrms, Irms, voltage variation, frequency variation, total harmonics distortion, power, and energy consumed, total energy cost, relay trip status, immediate PF and PF corrected value are available at the serial port of the ATmega328 microcontroller. So using serial communication, it is possible to retrieve these values live for any other operation. SIM900 GSM module is bidirectional communication technology used to transmit and receive these data between end users and supplier. The Arduino GSM Shield allows connecting your Arduino board to the internet using the GPRS wireless network, make/receive voice calls and send/receive SMS messages. SIM900D model of GSM Module shield used, just plug this module onto Arduino board, plug in a SIM card from an operator offering GPRS coverage and communicate with the board using AT commands. The SIM900D is a complete Quad-band GSM/GPRS solution in a SMT module which can be embedded in the customer applications. GSM module is implemented by using virtual terminal.

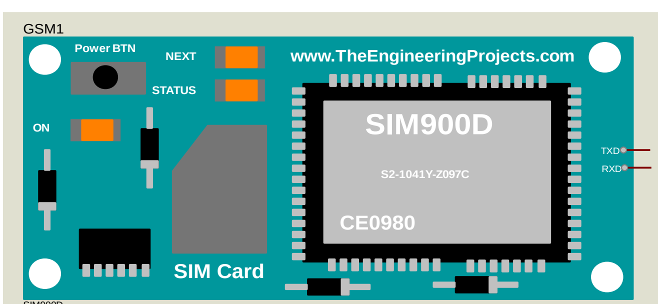

Figure 3-18: SIM900D GSM Module

3.4 Simulation Tools

Simulation carried out on proteus software with Arduino IDE software. Proteus 8.6 software is used for system schematic design and IDE software used to program Arduino microcontroller using C programming language. Then hex. File is generated from this software. The hex. File is uploaded to Arduino Uno microcontroller in order to system work as required.

- Proteus 8.6 Software

Proteus is a fully functional procedural programming Language created in 1998 by Zanella. It is a software package for computer aided design, simulation and electronic circuit design. Proteus incorporates many functions delivered from several other Languages: C, Basic Assembly, Clipper /d Base.

Proteus includes hundreds of functions for

- Accessing file system
- Sorting data
- Manipulating dates and strings
- Calculating logical and mathematical expression.

- Arduino Software (IDE)

The open-source Arduino software (IDE) makes it easy to write code and update it easy to write code and upload it to the board. It runs on windows, Mac OS X and Linux. This software can be used with any Arduino board**.**

Chapter 4

4. Results and Discussion

4.1 Introduction

In this chapter the results of the simulations of proposed smart meter are presented and discussed with reference to the aim of the study, which was to study and analysis of smart meter in power quality management and real time monitoring. The two sub-aims are: – first, power quality real-time monitoring performance of smart meter present and discussed, and the second, real-time power quality enhancement capability of smart meter presented and discussed. In addition, representation of real time energy consumption data and billing simulated and discussed. The power quality monitoring parameters are: RMS voltage, RMS current, apparent power, active power, reactive power, line frequency, power factor, and voltage total harmonics distortion. Dynamic Power factor correction integrated within smart meter considered as power quality enhancement scheme [**Error! Reference source not found.**].

The simulation was done using the Proteus software and Arduino Uno as core for system as shown above [Figure 3-2]. System designed based on supply voltage 220V,50Hz AC and then tested with two loads as shown above [Figure 3-4] and [Figure 3-5]. Supply voltage is supplied to load and all measurements are collected using the proposed smart meter. The voltage and current sensor circuits, atmega328 microcontroller, dynamic power factor correction scheme, LCD and GSM module were all tested and successfully interfaced in proteus environments. The Arduino Uno is loaded and configured with the Arduino code shown in [Appendix]. Development, testing and verification of the code is done in IDE 1.8.1 version. The smart meter results can thus be analyzed with respect to the following parameters:

- Accuracy of voltage and current sensor output signals waveform
- Real time power factor correction
- Real-Time Representation of Power Quality Phenomena
- Real-time Energy Consumption Data

As the design was specifically chosen to allow for parameter measurement, the performance of the system measurement is verified based on absolute percentage error (APE) to present the accuracy of the measurement [33]. The absolute percentage error (APE) can be expressed as follow:

$$APE = \left(\frac{x_i - x_m}{x_i}\right) \times 100\% \quad \ldots \ldots \ldots \ldots \quad (4.1)$$

Where: X_i - is actual value and x_m - is measured value.

4.2 Results of the Simulation

4.2.1 Waveform of Voltage and Current sensor output signals

In order to ensure that the meter is accurate in determining the power factor, energy consumption, and power quality phenomena. First ensure that it is able to measure the voltage and current waveform with sufficient accuracy. The sampled outputs from the voltage and current sensor are recorded for one complete cycle of supply frequency. The sampled values are used to retrieve the real supply voltage.

Accordingly, when pure sinusoidal signal waveform given to voltage sensor the digital oscilloscope displays the rectified half wave output signal waveform as shown in figure 4-1 below. As a result, it is readily visible that there is phase delay on zero crossing point of supply voltage signal waveform.

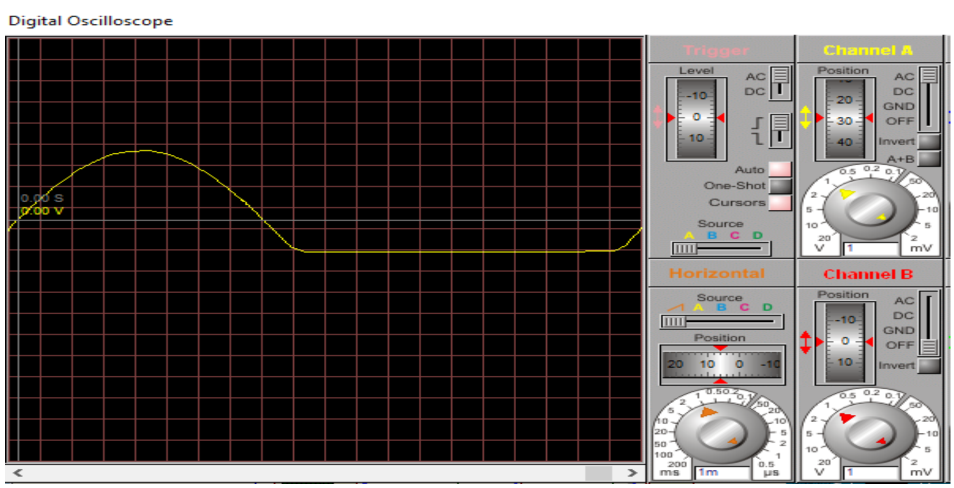

Figure 4-1: Voltage Sensor Output for Supply Voltage Signal Waveform

The following table 4-1 shows the corresponding value for above figure waveform, as supply voltage magnitude varies the measured supply voltage for voltage sensor varies, and the error increases as the supply voltage increases or decreases from the nominal voltage (220V). The measured values of supply voltage are the values which show maximum deviation from the actual value.

Table 4-1: Supply Voltage RMS Magnitude Variation Measurement

supply voltage (V)	Measured voltage (V)	Error (%)
0-6	0	-
100	92.90	7.1
150	146.45	2.36
174	170.97	1.74
210	205.38	2.2
220	216.77	1.45
230	220	4.34
245	220	10.20

The following figure 4-2 shows, when a pure sinusoidal input signal waveform given for a current sensor the digital oscilloscope displayed that a sinusoidal output waveform. As a result, the output waveform is similar with the input waveform.

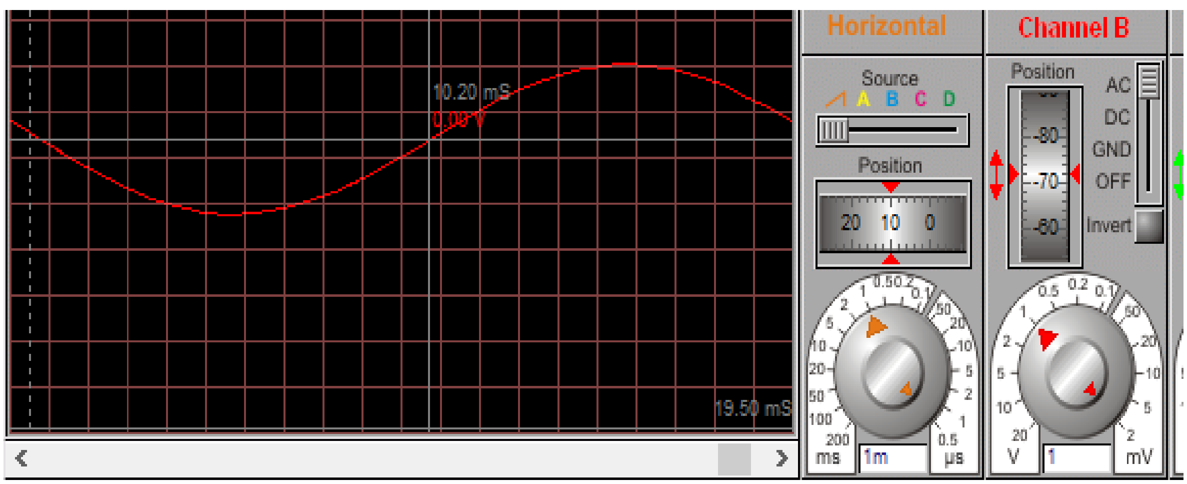

Figure 4-2: Current Sensor Output Waveform for an input current

Table 4-2 shows the measured output current magnitude and the error variation depending on the resistive and inductive load. Hence, for an inductive load the measured output current and error is higher than the resistive load. The measured current value shows maximum deviation from the actual value.

Table 4-2: Load RMS Current Magnitude Variation Measurement

Load Type	Actual current (A)	Measured output current(A)	Error (%)
Resistive	9.16	9.23	-0.76
Inductive	11.40	11.80	-3.5

4.2.2 Real Time Power Factor Correction

The first step of power factor correction is to measure real time power factor. Schematic shown in figure 3-10, figure 3-11 in the previous section is used for power factor calculation which measures time difference between zero crossing point of voltage and current signal square waveform.

The actual power factor for resistive load power factor is 1.00 and for inductive load is 0.80. The real time power factor measurement for resistive and inductive load represented in a waveform in the simulation result shown in figure 4-3 and figure 4-4 below respectively. The blue color square waveform represents output of voltage zero crossing detector whereas green color square waveform represents current zero crossing detector on digital oscilloscope.

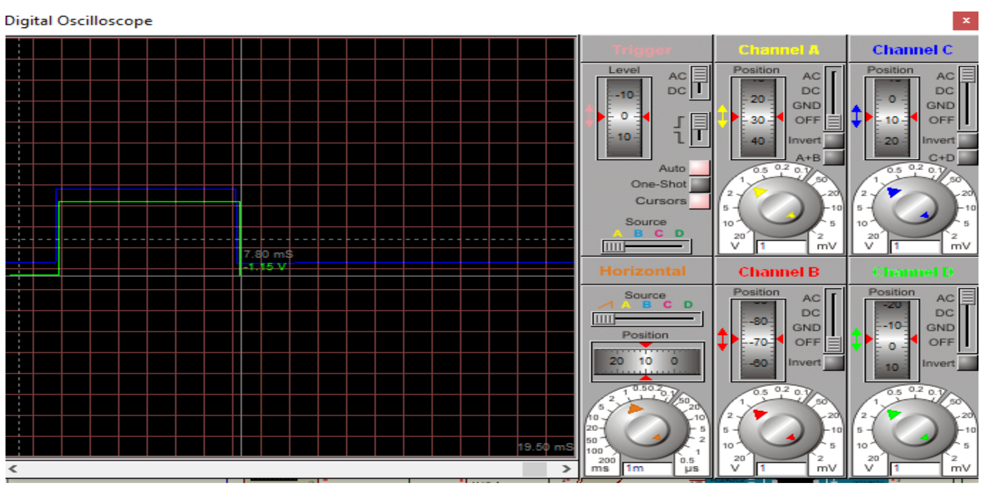

Figure 4-3: Power Factor Measurement for Resistive Load

Figure 4-3 shows real time power factor measurement for resistive load in waveform. The voltage and current ZCD output square waveform almost in phase each other implies there is no phase delay between the two signals. Hence, power factor is one for resistive load. The measured value is 1.00.

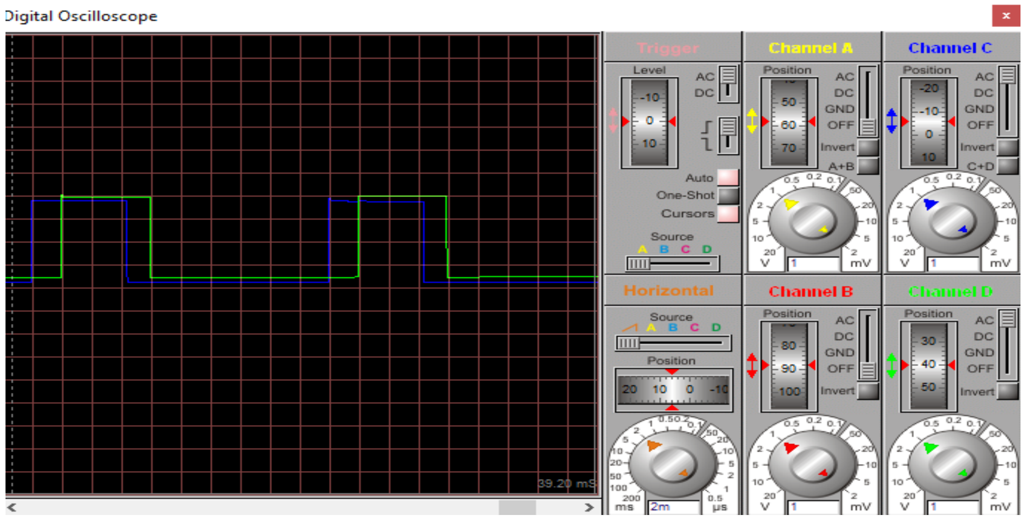

Figure 4-4**:** Power Factor Measurement for Inductive Load

Figure 4-4 shows that real time power factor measurement for inductive load in waveform. The voltage and current ZCD output square waveform out phase each other. The measured time difference between two signal is 2080ms and power factor is 0.79. However, the expected power factor value was 0.80.

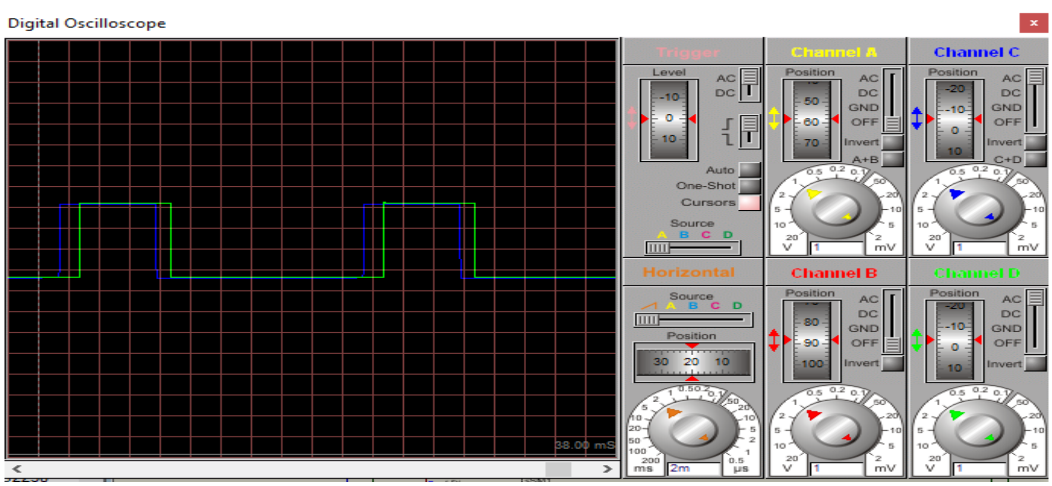

Figure 4-5: Improved Power Factor Measurement for Inductive Load after Compensation

Figure 4-5 shows the improved power factor measurement after compensating capacitor added for the above inductive load. Still there is time difference between to waveform even after power factor correction because targeted PF is to set the desired value 0.90. The measured time difference between zero crossing points of two signal waveforms reduced to 1422ms after compensating capacitors added but measured PF value is 0.89.

The following table 4-3 summarizes the measured real time power factor value of waveform represented in figure 4-3, figure 4-4 and figure 4-5. As shown in the table 4-3, the power factor measurement for inductive load is 1.25% error before compensation and 1.1% error after compensation. But for resistive load it works fine.

Table 4-3: Real-time Power Factor Measurement in the without and with Compensation Capacitors

	Without Compensating Capacitors			With Compensating Capacitors		
Load Type	Actual PF value	Measured PF value	Error (%)	Desired PF Value	Measured PF Value	Error (%)
Resistive	1.00	1.00	0	1.00	1.00	0
Inductive	0.80	0.79	1.25	0.90	0.89	1.1

Table 4-4 shows apparent power and active power value before and after compensating capacitors added simulation result. Apparent power drawn from the distribution network was higher, which is 2508VA and active power was 2000W with PF 0.80 without compensating capacitors. After the compensating capacitors added the measured apparent power reduced to 2471.85VA and active power increased to 2228. 88W.

Table 4-4: Apparent and Active Power Measurement without and with Compensating Capacitors

	Without Compensating Capacitors		With Compensating Capacitors	
Load type	Apparent power (VA)	Active power (W)	Apparent power(VA)	Active power(W)
Inductive	2508	2000	2471.85	2228.88

4.2.3 Real-Time Representation of Power Quality Phenomena

In order to add power quality monitoring ability to the smart meter without compromising the accuracy of the energy meter, the following power quality phenomena may be detected by the meter:

- Power frequency variation
- Individual harmonics distortion up to third order

Accordingly, by varying the input frequency range from 48 up to 52Hz real-time detection ability of proposed meter tested in simulation is shown in table 4-5 below. It shows the meter reading gives an error of 1%. However, it reads a bit higher for frequency greater than nominal frequency (50Hz) again it reads lower than it.

Table 4-5: Measured Frequency by Proposed Meter for various Input Frequency

Actual/Input Frequency(Hz)	Measured Value(Hz)	Error (%)
48	48.38	-0.8
49	49.60	-1.2
50	49.83	0.34
51	51.26	-0.5
52	52.37	-0.7

The following table 4-6 shows total harmonics distortion (THD) detection ability of proposed meter for a given supply voltage in the simulation. Here, resistive and inductive load are considered to show harmonics effect of power factor correction scheme integrated with proposed meter. The two supply voltages considered are nominal voltage (220V) and under voltage (174V). When a pure sine wave signal given to a system both individual and total harmonic distortion measurement has to be zero, but as observed from the simulation result there is some error.

Table 4-6: Supply Voltage Total Harmonic Distortion Measurement for Resistive and Inductive load.

Load Type	Supply voltage (V)	Measured harmonics1	Measured harmonics2	Measured harmonics3	Measured THD_V (%)
Resistive	220	219.96	0.08	0.21	0.10
	174	167.58	0.11	0.28	0.13
Inductive	220	219.96	0.08	0.21	0.10
	174	171.83	0.10	0.27	0.12

4.2.4 Real Time Energy Consumption Data

One of typical function of smart meter is billing function. Energy metering accuracy is crucial in ensuring the integrity of a billing system. It depends on elapsed time to record power rating of known load.

Accordingly, the accuracy of the meter was determined from the deviation of the measured time from the expected time. For testing the accuracy of the energy meter, the known loads given in table 4-7 were used. The result shows the error in the inductive load reads twice of the resistive load. In fact, the accuracy of the meter was less than the standard value (0.2%).

Table 4-7: Accuracy of Proposed Energy Meter

Load Type	Load Power (W)	Expected time(s)	Measured time(s)	Error (%)
Inductive	2200	3600	3598	0.06
Resistive	2013	3600	3599	0.03

Table 4-8 shows the energy consumption parameters for continuous real time monitoring ability of smart meter represented in one-hour data with 10 minutes' interval PQ data aggregation standard. For resistive load a nominal voltage value 220V at 50Hz, current 9.15A and power 2013W, there is a variation in voltage, current and power measurement value as shown in table 4-8.

Table 4-8**:** One Hour Measured Data with 10 Minutes' Interval for Voltage, Current and Power

Date	Time(min)	Voltage(v)	Current(A)	Power factor	Power(W)
20/7/2020	09:00	217.85	9.27	1.00	2034.12
>>	09:10	215.48	9.23	1.00	2040.55
>>	09:20	213.76	9.28	1.00	1990.71
>>	09:30	216.34	9.20	1.00	2022.59
>>	09:40	217.65	9.27	1.00	2034.56
>>	09:50	215.65	9.23	1.00	1991.00
>>	10:00	216.85	9.18	1.00	2020.45

Furthermore, figure 4-6, figure 4-7, and figure 4-8 shows the measured voltage, current or power data respectively plotted against time for a considerable period of time so as to get proper visual representation for variations in each measured quantity tabulated in the above table 4-8.

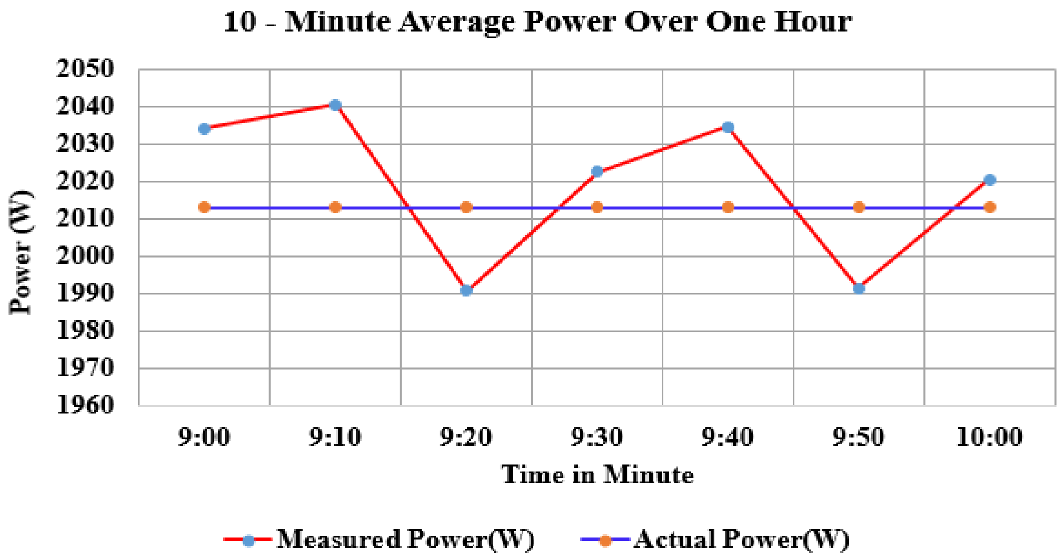

Figure 4-6: 10-Minute Average Power Consumption plot over 1 Hour

Figure 4-6 shows the measured average power consumption value maximum deviation from actual value. The meter reading gives an error of 0.45% highest. However, it reads a bit higher or lower in subsequent 10 minutes' intervals. As result, measured average power consumption fluctuated around actual value of 2013W.

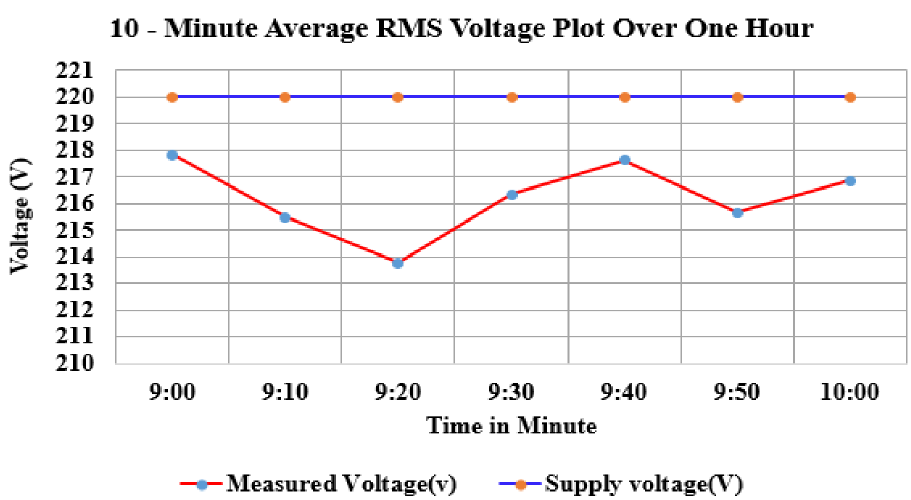

Figure 4-7: 10-Minute Average Rms Voltage Plot Over 1 Hour

Figure 4-7 shows the measured supply voltage value maximum deviation from actual value. As result, the measured supply voltage fluctuated around actual value of 220V. The meter reading gives an error of 0.98% highest. However, it reads a bit higher or lower in subsequent 10 minutes' intervals.

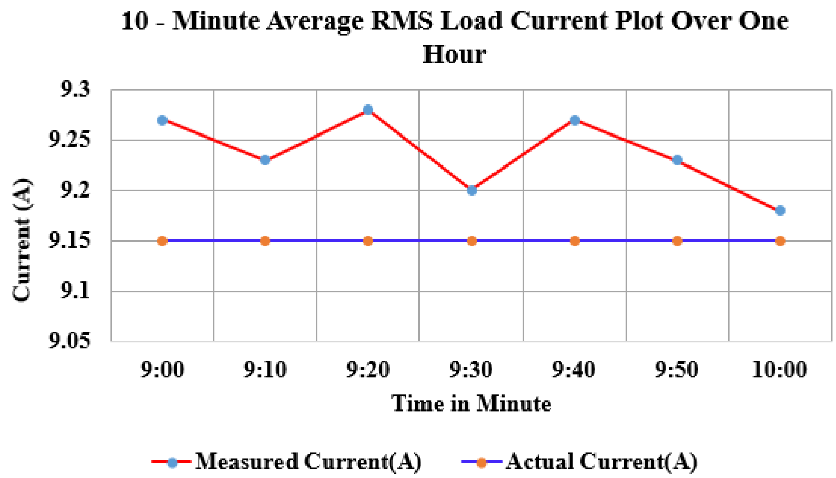

Figure 4-8: 10-Minute Average Load Current Plot Over 1 Hour

Figure 4-8 shows the measured load current value maximum deviation from actual current value. The measured average load current fluctuated around actual value of 9.16A. The meter reading gives an error of 0.87% highest. However, it reads a bit higher or lower in subsequent 10 minutes' intervals.

GSM Module Simulation Result

Finally, all measured power quality parameters such as RMS voltage and RMS current, active, reactive and apparent power, frequency, power factor, THD of voltage, total energy consumed and bill are sent to customers and utility via SMS as show in figure 4-9 below. Utility can access more detail meter measurement via GPRS network or other advanced communication technology to have detail power quality parameters measurement, events record and analysis capability.

Figure 4-9 shows virtual terminal simulated result of measured PQ parameter SMS message sent via GSM module for customer and utility.

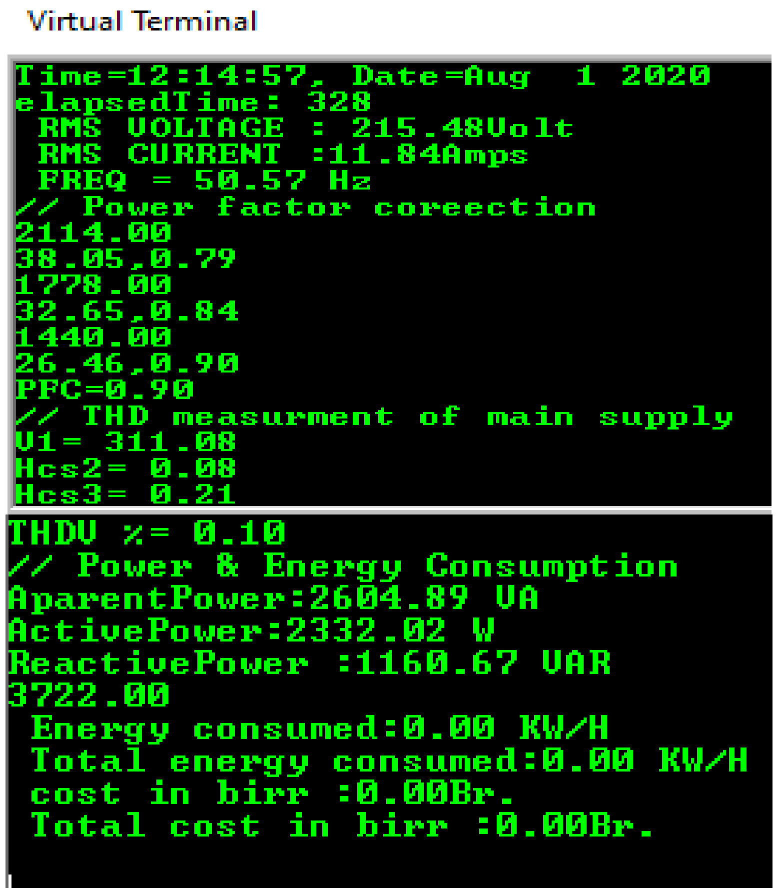

Figure 4-9: Typical Message Sent to User’s Cellular Phone via GSM Module

4.3 Discussion of Results

4.3.1 Accuracy of Voltage and Current Signals Waveform

According to the electric energy meter with accurate metering, voltage and current finally inputted to the metering chip does not has waveform distortion so that metering of the electric energy meter is enabled to be more accurate.

In line with hypothesis voltage waveform measurement result includes the effect of step-down transformers supplying the customer as shown in figure 4-1 and the customer’s current variation levels which is mainly due to monitoring location located at customer service entrance implies one of major significance of smart meter in power quality monitoring at customer premises as shown in figure 4-2.

As shown in figure 4-1, the phase delay on zero crossing point of voltage signal waveform may be due to the effect of step-down transformers and half wave rectifier, noise introduced into signal from the circuit component such as from the processor core, from the I/O ports of the processor, etc. The RMS voltage measured value for different supply voltage illustrated in table 4-1. For the particular case shown in table 4-1, the supply voltage was 220 V at 50Hz, whereas the measured value was 216.38 V. It was observed that the measured value of the voltage sensor output was fluctuating around the value of the supply voltage. There was no meter reading for range 0-6V in the power line. The error in the range up to 100V and greater than 220V was significantly higher. the meter reading gives an error of 4V highest. However, it reads a bit higher in some seconds again reads lower in some seconds.

The result provides a new insight into the relationship between voltage sensor and load type for supply voltage measurement. In system design, voltage sensor circuit has to be designed with sinusoidal waveform and variable resistor to cope up variable load impedance in order to minimize the error.

The current measured waveform has sinusoidal form which equivalent to pure sinusoidal waveform as shown in figure 4-2. The load RMS current measured magnitude value for different actual current values illustrated as shown in table 4-2. The meter reading gives an error of 400mA highest from actual value. However, it reads a bit higher in some seconds again reads lower in some seconds. According to manufacturer ACS712-20A current sensor module has a resolution of 100mVperAmp and it has a noise of 11mV which means there will be a noise of 110mA. As a result, their average value gives significantly less error, especially for resistive load we can say that it gives almost accurate reading. This result supports the theory that to minimize the error as many as possible samples have been taken.

4.3.2 Real-Time Power Factor Correction

Integrating dynamic power factor correction or real time power factor correction scheme in smart meter is one of new features added in proposed meter. The result indicates real-time power factor correction simulation was efficient and reliable which would able to implemented practically. In line with theory integrating DPFC in smart meters is a cost-effective solution with great flexibility, due to the existing smart meter hardware instead of installing PFC system at each equipment and different distribution system location.

As shown on table 4-3, power factor measurement is really a sophisticated because here the time delays are within millisecond and microsecond range. For inductive load some measurement error appears but resistive load meter works fine. This measurement error caused by phase shift between supply voltage and load current measurement error since power factor equals to cosine of phase shift.

There is significant improvement on apparent power and active power value after compensated capacitors on as shown in table 4-3. Power factor is the relationship between active power and apparent power. In line with hypothesis the integrated real time power factor correction system enhanced power quality. This reduced reactive power consumption. Power factor correction enhanced power quality by reduce voltage drop, and harmonics content from supply. Most people agreed that PFC and solid state devices increase harmonics content. However, as observed the simulation result the voltage drop and harmonics content reduced when dynamic power factor correction switched on. On reverse, voltage drop and harmonics content increase a bit higher when dynamic power factor correction switched off. It is briefly shown in table 4-4 that the apparent power drawn from the distribution network reduced after capacitor bank on is likely due to reduced current draw in installation. The capacitor bank which can limit energy losses in the system by the joule effect (limit voltage drop) given the reduction in the current carried in the installation. Essentially, the compensation system was effective implies after installing the capacitor bank, the inductive load gained 0.25kw power which is 12.5% from the initial value. Hence, the improved PF value is near to 0.90 which has good electrical efficiency. The triac switches capacitor bank automatically without introducing any harmonics into circuit and it also reliable, delay free switching mechanism which makes the proposed smart meter preferable. Especially, in Ethiopia there is higher voltage drop at end users. The proposed smart meter can solve this problem with help of new features added.

4.3.3 Real-time representation of power quality phenomena

Power frequency variation and supply voltage total harmonic distortion measurement was successfully simulated in order to add power quality monitoring ability to proposed smart meter without compromising the accuracy of energy meter.

As shown in table 4-5, the meter frequency reading gives an error of 1% highest for both resistive and inductive loads. This frequency measurement error is due to distortion introduced from voltage sensing circuit output.

The measured individual harmonics up to 3rd and total harmonics distortion for voltage illustrated as shown in table 4-6. The measurement value expected to be zero for both individual harmonics and total harmonics distortion. The measured value, however, is non-zero which caused by reading value fluctuation of fundamental voltage and fixed error (noise). As a result, the accuracy of measurement was found to be better than 0.5%.

The result contributes a clearer understanding of the problem lies in the difficulty to measure injected harmonics content and power frequency variation at consumers premises in real–time. This real-time monitoring may be assist towards rapidly identifying problems and decrease the time to resolve them. Moreover, the complaint ambiguities on poor power quality source between utility and customers will be solved because the true picture of power quality data record by proposed meter.

Due to weakness of system design, the result cannot confirm clear analysis of harmonics distortion. The methodological choices were constrained by proteus software and Arduino. Proteus could not give freedom to generate varies supply voltage and harmonics source as input to verify the output of the proposed meter. In addition, sinusoidal voltage waveform must be inputted to Arduino with appropriate number of sample to get more accurate result instead of half wave waveform signal analysis. It is beyond the scope of this study to analysis frequency variation, harmonics distortion in waveform and other power quality events in more detail.

4.3.4 Real-time Energy Consumption Data

The error in the meter reading has a direct bearing on the energy bill the customer has to pay. The excess payment a customer has to make on account of the error in the meter reading provides the customer with a better understanding of the meter's performance. The energy consumption measurement was found 0.06% error due to obtained accurate current and voltage values as shown in table 4-7. If we assume the cost per unit of electricity as 1 pu and considering an error of 0.06 % per kWh, the excess energy bill will be 0.0006p.u. Per kWh of energy consumed. Assuming an average cost per unit of birr. 10, the excess bill charged will be birr. 0.006 per kWh. Hence, for a typical household consuming 500 kWh a month, the extra payment to the utility on account of the error will be only birr 3 per month. The accuracy measurement of this energy meter affected by

a. Fluctuation of the reading value, represented in percentage % from actual value (reading).
b. The phase shift between voltage and current affects the accuracy since power equals voltage multiplied by current multiplied by the cosine of the phase angle.
c. a fixed error(noises)

The accuracy of the meter was found to be better than standard value (0.2%) while there is some error for voltage and current measurement.

The result supports theory the proposed meter has continuous real time monitoring capability which tested with standard PQ data aggregation time interval. The meter tested to display one-hour data and it compute continuously the average rms values of voltage and current and the average power over a time interval of 10 minutes.

The performance of meter to measure power quality parameter such as voltage, current, power factor and power of main circuit in continuous and real-time monitoring illustrated as shown in table 4-8. These data discrepancies may be due to the incorrect calibration of the instruments. Average Power measurement error occurs due to fluctuating of the reading value of RMS voltage and RMS current from actual value. In addition to that, the phase shift between voltage and current affects the measurement of power since power is product of voltage current and cosine of the phase angle. Supply voltage and current measurement fluctuation occurred due noise introduced into signal from the circuit component such as from the processor core, from the I/O ports of the processor, etc.

Finally, the GSM module protocol was chosen for its simplicity, reliability, global coverage, and low cost of communication. All measured data sent to GSM was tested with help of virtual terminal. The simulation result/message helps utilities control load remotely and monitoring power quality data of customers in real time. It enables two-way communication which makes both customer and utility are active participant in power industry, especially, for the customers it helps to manage their power quality problem and energy consumption. LCD helps to display power quality parameter, and energy consumed and bill locally at installed place. RTC helps to update real time data for PQ data aggregation.

Chapter 5

5. Conclusion and Recommendation for Future Work

5.1. Conclusion

This thesis focuses on integrating power quality monitoring and enhancement in smart meter. Besides the basic objective of this thesis, integrating dynamic power factor correction in system is a novel hardware architecture make proposed meter preferable than existing smart meter on power quality enhancement performance in context of developing country. Proposed smart meter give advantages such as sharing dispersed equipment, installation, maintenance and communication networks which assist towards rapidly identifying problems and decrease the time to resolve them.

This thesis has described the design of single phase smart electricity meter with dynamic power factor correction based on Arduino Uno and GSM module. The efforts are made to describe the working of sensors and communication strategy in the proteus simulation environment. The detailed analysis of performance of proposed smart meter for various power quality parameters has been made based on actual measurements. It is shown how all measured parameters contribute to performance of smart meter. The proposed meter is provided for different analyzing parameter, and showed how these translate into overall performance of smart meter under number of different potential applications.

The performance of the system measurement is verified based on absolute percentage error (APE) and shown the results to be appropriate. Voltage and current waveform measured with sufficient accuracy implies the meter is accurate in determining power quality parameters, energy consumption, and power quality phenomena. Accuracy of measurement for frequency variation, power factor, active power, energy consumption, and supply voltage total harmonics distortion was found less 1% error, which mainly is due to fluctuation of the reading value, the phase shift between voltage and current and a fixed error(noises). Frequency variation and voltage harmonics distortion measurement was done analytically implies the problem lies in the difficulty to measure injected harmonics content and power frequency variation at consumers premises in real time solved. Necessary data sent to customers via GSM was tested with help of virtual terminal.

Furthermore, it is observed from the work that power quality enhanced such as stabilize supply voltage, reduced harmonics distortion and consumption of electricity becomes much more efficient by using dynamic power factor correction scheme and applying capacitors for the correction of power factor and shown the achievement is mainly due to power factor monitoring was sophisticated and thyristor switch for capacitor connection without mains supply distortion and delay free.

Proteus software and Arduino Uno were constrained for methodological choices. It is observed that proteus software cannot allow flexibility to generate varies supply voltage and harmonics distortion source as input to verify the output of proposed meter. Power quality phenomena measurement such as voltage variation, frequency variation, and harmonics distortion measurement analysis was restricted to empirical and digital oscilloscope based analysis due to methodological choice. Hence, supply voltage and load current waveform accuracy was then checked using digital oscilloscope. But frequency variation and harmonics distortion measurement was carried out analytically.

5.2. Recommendation for Future Work

In this research benefits of integrating power quality monitoring and enhancement in smart meter and the performance of smart meter under different parameter is analyzed. Some simulations are also done to demonstrate the benefits of integrating power quality monitoring and enhancement in smart meter for power quality management system and real-time monitoring.

It recommended that industrial customers are highly benefited if they use this proposed smart meter because they cost a lot of many for reactive power.

However, there are lots of tasks left open for next researches. The hardware implementation and three-phase mode design with Capacitor Switching transient limiter should be performed in future.

It recommended that waveform capture, remaining power quality phenomena record, data logger and robust programming code should be performed in future to get better result for detail analysis of the performance of the proposed meter. It should be given more time, and allocate budget to do so.

Another thing, this thesis paves the way for further research on how to improve harmonics analysis methodology which will reduce the computational power. Voltage and current sensing circuit should be designed in optimized way which will minimize measurement error.

The communication technology used for the smart meter should be modified in future which will helps utility to get appropriate recorded PQ data in order to analysis in detail because Arduino can support a range of different communication protocols.

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Appendix

Arduino Source Code for simulation of Proposed Smart Meter

Description: Integrating PQ monitoring and PQ enhancement in smart meter based on GSM module and Arduino Uno

Last Edited: 25-AGUST-2020

```
#include <SoftwareSerial.h> //importing serial software Library file

#include <LiquidCrystal.h> // Importing LCD Library file

#include <Wire.h>

#include <TimeLib.h>

#include <DS1307RTC.h>

#include <EnergyMeter.h>

/*

 * RS: Pin 12

 * EN: Pin 11

 * D4: Pin 5

 * D5: Pin 4

 * D6: Pin 3

 * D7: Pin 2

 */

 LiquidCrystal lcd (7, 6, 5, 4, 3, 2); //lcd display pin

 char mobileNumber; // Will hold the incoming character from the GSM shield
```

```
SoftwareSerial SIM900(0,1);

DS1307RTC;

//bool DateTime;

const char *monthName[12] = { "Jul",
"Aug","Sept","Oct","Nov","Dec","Juna","Fab","May","Apr","Mar","Jun"};

tmElements_t tm;

const int voltageSensor = A0; // voltage pin

const int currentSensor = A1; // current pin

int mVperAmp = 100; // use 100 for 20A Module

int pin11 = 11;

const int cap1=10;

const int cap2=9;

const int Fpin=8;

const int relaypin=12;

float angle;

float pf_max = 0.00;

float angle_max = 0.00;

float rads = 57.29577951; // 1 radian = approx 57 deg.

int k=0;

double sumKWH = 0.0000;

double KWH = 0.0000;//energy consumption in Kilo watt hour
```

```
double birr=0.0000;
double sumBirr=0.0000;//Total cost in birr
float Voltage = 0.0000;//AC supply peak voltage
float vrms = 0.0000;//AC supply rms voltage
float current = 0.0000;//load peak current
float irms = 0.0000;//load rms current
double AppPower = 0.0000;// apparent power
double ActiveP=0.0000;// active power
double ReactiveP=0.0000;//reactive power
float frequency; //storing frequency
float THDV=0.0000;//voltage total harmonic distortion

void setup ()
{
  bool parse=false;
  bool config=false;
  // get the date and time the compiler was run
  if (getDate(__DATE__) && getTime(__TIME__)) {
    parse = true;
    // and configure the RTC with this info
    if (RTC.write(tm)) {
```

```
    config = true;
  }
 }
 Serial.begin(9600);
 SIM900.begin(9600);
  delay(200);
  SIM900.print("AT+CLIP=1\r"); // turn on caller ID notification , to get missed call number
  delay(100);
Wire.begin();
//RTC.begin();
if (parse && config) {
   Serial.print("Time=");
   Serial.print(__TIME__);
   Serial.print(", Date=");
   Serial.println(__DATE__);
 } else if (parse) {
   Serial.println("DS1307 Communication Error :-{");
   Serial.println("Please check your circuitry");
 } else {
   Serial.print("Could not parse info from the compiler, Time=\"");
   Serial.print(__TIME__);
```

```
    Serial.print("\", Date=\"");
    Serial.print(__DATE__);
    Serial.println("\"");
  }
 lcd.begin(16,2); // Display Columms, Rows and Size
   lcd.clear();
  pinMode(voltageSensor,INPUT);
  pinMode(currentSensor,INPUT);
  pinMode(pin11, INPUT);
  pinMode(Fpin,INPUT);
  pinMode(cap1,OUTPUT);
  pinMode(cap2,OUTPUT);
  pinMode(relaypin,OUTPUT);


}
 void loop()
{


bool getTime( int Hour,  int Min, int Sec);
bool getDate( int Day,char Month[], int Year);
  unsigned long time;
```

```
  time=millis();
  Serial.print("elapsedTime: ");
  Serial.println(time);
 rmsvalue();
 Fvalue();
 capswitch();
 thvalue();
 energy calculation ();
 gsm();
 relayoff();
}
bool getTime(const char *str)
{
  int Hour, Min, Sec;

  if (sscanf(str, "%d:%d:%d", &Hour, &Min, &Sec) != 3) return false;
  tm.Hour = Hour;
  tm.Minute = Min;
  tm.Second = Sec;
  return true;
}
```

```
bool getDate(const char *str)
{
  char Month[12];
  int Day, Year;
  uint8_t monthIndex;

  if (sscanf(str, "%s %d %d", Month, &Day, &Year) != 3) return false;
  for (monthIndex = 0; monthIndex < 12; monthIndex++) {
    if (strcmp(Month, monthName[monthIndex]) == 0) break;
  }
  if (monthIndex >= 12) return false;
  tm.Day = Day;
  tm.Month = monthIndex + 1;
  tm.Year = CalendarYrToTm(Year);
  return true;
}
void getpf()
{
float rads = 57.29577951; // 1 radian = approx 57 deg.
float degree = 360;
```

```
float Frequency=50;

float tit;

float factor = 1* pow (10,-6); // Multiplication factor to convert nano seconds into second

int k;

 for (k = 0; k <=4; k++) // Perform 3 measurements then reset

  {

    tit=pulseIn (pin11, HIGH);

  angle = (tit*factor*degree*Frequency);

   if (angle > angle_max) // Test if the angle is maximum angle

     {

      angle_max = angle; // If maximum record in variable "angle_max"

      pf_max = cos(angle_max/rads); // Calc PF from "angle_max"

     }

  }

   if (angle_max > 360) // If the calculation is higher than 360 do following...

   {

    angle_max = 0; // assign the 0 to "angle_max"

    pf_max = 1; // Assign the Unity PF to "pf_max"

   }

   else if (angle_max == 0) // If the calculation is higher than 360 do following...

   {
```

```
    angle_max = 0; // assign the 0 to "angle_max"
    pf_max =1; // Assign the Unity PF to "pf_max"
   }
   //Serial.println(" // Power Factor Correction");
   Serial.println(tit);
   Serial.print(angle_max, 2); // Print the result
   Serial.print(",");
   Serial.println(pf_max , 2);
   lcd.clear();
   //lcd.println("pf correction");
   lcd.setCursor(0,0);
   lcd.print("PF=");
   lcd.setCursor(4,0);
   lcd.print(pf_max);
   lcd.print(" ");
delay (5);
 angle = 0; // Reset variables for next test
  angle_max = 0;
}
void capswitch()
{
```

```
Serial.println("// Power factor correction");
getpf();
//Serial.print("PF=");
if(pf_max<0.90)
{
 digitalWrite (cap1, HIGH);
 getpf();
 lcd.setCursor(0,0);
 lcd.print("PF=");
 lcd.setCursor(4,0);
 lcd.print(pf_max);
 //delay (5);
 if(pf_max<0.90)
 {
  digitalWrite(cap2, HIGH);
  getpf();
  Serial.print("PFC=");
  Serial.print(pf_max);
  Serial.println("");
  //lcd.print(" ");
```

```
  lcd.setCursor(0,1);

  lcd.print("PFC=");

  lcd.setCursor(5,1);

  lcd.print(pf_max);

   }

   else if(pf_max>=0.91)

   {

     digitalWrite(cap1, HIGH);

     digitalWrite(cap2, LOW);

     }

  }

  else

   {

     digitalWrite (cap1, LOW);

     digitalWrite (cap2, LOW);

     }


 }

// overload controlling

void relayoff ()

{
```

```
  current=getVPP (1);
  if(irms>=20)
  {
 digitalWrite (relaypin, HIGH);
  Serial.println("Dear customer! you are using overload");
  }
  else {
    digitalWrite (relaypin, LOW);
    }
  }

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 half 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)/1023.0;
 return result;
}
//to calculate rms voltage and current value
void rmsvalue()
{
 // getting voltage from Input PIN
  Voltage = getVPP (0);
  vrms = ((Voltage)*(220/5)); //find ac supply voltage
   Serial.print(" RMS VOLTAGE: ");
   Serial.print(vrms);
   Serial.println("Volt");
    // getting current from Input PIN
  current = getVPP (1);
  irms = (((current/2) *0.707)*1000/mVperAmp)-2.5;
   Serial.print(" RMS CURRENT:");
   Serial.print(irms);
```

```
  Serial.println("Amps");
   lcd.setCursor(1,0); // set the cursor at 1st col and 1st row
 lcd.print(vrms);
 lcd.print("v ");
 lcd.print(irms);
 lcd.print("A");
}

//to calaculate line frequency
void Fvalue()
{
 int pulseHtime;            //integer for storing high time
  int pulseLtime;            //integer for storing low time
  float pulseTtime;          // integer for storing total time of a cycle
pulseHtime=pulseIn(Fpin,HIGH);     //read high time
pulseLtime=pulseIn(Fpin,LOW);      //read low time
pulseTtime = pulseHtime+pulseLtime;

frequency=1000000/pulseTtime;    //getting frequency with Ttime is in Micro seconds
//lcd.clear();
lcd.setCursor(0,0);
```

```
 lcd.print("FREQ= ");
 lcd.setCursor(7,0);
 lcd.print(frequency);
lcd.print(" Hz");
   Serial.print(" FREQ = ");
 Serial.print(frequency);
 Serial.print(" Hz ");
 Serial.println(" ");
  delay(10);
  }

  //to calculate supply voltage  harmonic distortion
 void thvalue()
 {
  float an1,an2,an3,bn1,bn2,bn3;
  float Hdv1,Hdv2,Hdv3;
  Voltage=getVPP(0);
  vrms=Voltage*(220/5);
```

```
 an1 =(vrms*1.414)*(sin(1*2.0*3.14*50.0*(0.02)));   // calculating An for first/fundamental
Harmonics

 bn1= (vrms*1.414)*(cos(1*2.0*3.14*50.0*(0.02)));


 an2 =(vrms*1.414/2)*(sin(2*2.0*3.14*50.0*(0.02)));    // calculating An for 2nd  Harmonics

 bn2= (vrms*1.414/2)*(cos(2*2.0*3.14*50.0*(0.02)));


 an3 =(vrms*1.414/3)*(sin(3*2.0*3.14*50.0*(0.02)));    // calculating An for 3rd Harmonics

 bn3= (vrms*1.414/3)*(cos(3*2.0*3.14*50.0*(0.02))); // squr root of an and bn


Hdv1=sqrt((an1*an1)+(bn1*bn1));

  Serial.println("// THD measurment of main supply");

  Serial.print("V1= ");

  Serial.print(Hdv1);

  Serial.println(" ");

  lcd.print(" ");

  lcd.setCursor(0,0);

  lcd.print("V1=");

  lcd.setCursor(4,0);

  lcd.print(Hdv1);

  lcd.print("V");
```

```
Hdv2=(sqrt((an2*an2) +(bn2*bn2))/(Hdv1*Hdv1)/2)*100;
  Serial.print("Hcs2= ");
  Serial.print(Hdv2);
  Serial.println(" ");

Hdv3=(sqrt((an3*an3)+(bn3*bn3))/(Hdv1*Hdv1/2))*100;
  Serial.print("Hcs3= ");
  Serial.print(Hdv3);
  Serial.println(" ");

THDV=(sqrt(((an2*an2)+(bn2*bn2))+((an3*an3)+(bn3*bn3)))/(Hdv1*Hdv1)/2)*100 ;
  Serial.print("THDV %= ");
  Serial.print(THDV);
  Serial.println(" ");
  lcd.print(" ");
  lcd.setCursor(1,1);
  lcd.print("THDV % = ");
  lcd.setCursor(9,1);
  lcd.print(THDV);
   lcd.print(" ");
 }
```

```
 // energy calculation form input value
void energycalculation()
{
   //power calculation
    float timeconsumed;
   AppPower=(vrms * irms );
   Serial.println("// Power & Energy Consumption");
   Serial.print("AparentPower:");
   Serial.print(AppPower);
   Serial.println(" VA");
   ActiveP=(AppPower*pf_max);
   Serial.print("ActivePower:");
   Serial.print(ActiveP);
   Serial.println(" W");
  ReactiveP=sqrt((AppPower*AppPower)-(ActiveP*ActiveP));
  //ReactiveP=AppPower*sin(angle_max/rads);
   Serial.print("ReactivePower :");
   Serial.print(ReactiveP);
   Serial.println(" VAR");
   timeconsumed=millis();
```

```
Serial.println(timeconsumed);
KWH= (ActiveP/1000) *((timeconsumed/1000)/3600);
Serial.print(" Energy consumed:");
Serial.print(KWH);
Serial.println(" KW/H");
 sumKWH = KWH;
Serial.print(" Total energy consumed:");
Serial.print(sumKWH);
Serial.println(" KW/H");
 birr=getReading();
 Serial.print(" cost in birr :");
 Serial.print(birr);
 Serial.println("Br.");
  sumBirr = birr;
Serial.print(" Total cost in birr :");
Serial.print(sumBirr);
Serial.println("Br.");
Serial.println(""); // print the next sets of parameter after a blank line
 lcd.clear();
lcd.setCursor(1,1); // set the cursor at 1st col and 2nd row
lcd.print(AppPower);
```

```
  lcd.print("VA");
   delay(10);
  lcd.clear(); // clear the screen
  lcd.setCursor(1,0); // set the cursor at 1st col and 1st row
  lcd.print(KWH);
  lcd.print("KWH ");
  lcd.setCursor(1,1); // set the cursor at 1st col and 2nd row
  lcd.print(birr);
  lcd.print("Br.");
  delay(10);
  lcd.clear(); // clear the screen
  lcd.setCursor(1,0); // set the cursor at 1st col and 1st row
  lcd.print(sumKWH);
  lcd.print("KWH total");
  lcd.setCursor(1,1); // set the cursor at 1st col and 2nd row
  lcd.print(sumBirr);
  lcd.print("Br.total");
  delay(300000);
  lcd.clear();
 }
float getReading()
```

```
{
 float solution;

 if( KWH<=50){
 solution =  0.2730*KWH; // based on Ethiopia electricity energy tariff
 }

else if(KWH>=51&&KWH<100)
{
   solution=13.6500+(0.6644*KWH);
}
  else if(KWH>=100)
   {
     solution=66.4400+(1.3436*KWH);
     }
  return solution;
}
// Used to send Total Energy Consumption Billing to Customer
void sendBilling()
{
 SIM900.println("AT+CLIP=1\r");
```

```
   SIM900.println("AT+CMGF=1");    // Setting the GSM Module in Text mode
   delay(100);
  SIM900.println("AT+CMGS=\"+251xxxxxxxxx\"\r"); // Sending Energy Consumption to Customer's Mobile Number
   delay(100);
    SIM900.print(" Dear customer,Your Energy Consumption is :");
     SIM900.print(sumKWH);
     SIM900.print("Billing is Br. ");
     SIM900.print(sumBirr);
    delay(100);
  SIM900.println((char)26); // ASCII code of CTRL+Z
   delay(100);
}
void RecieveMessage()
{
  SIM900.println("AT+CNMI=2,2,0,0,0"); // AT Command to receive a live SMS
  delay(1000);
 }
void gsm()
{
 if (Serial.available()>0)
```

```
  switch(Serial.read())
 {
   case 's':
     sendBilling();
     break;
   case 'r':
     RecieveMessage();
     break;
 }
if (SIM900.available()>0)
  Serial.write(SIM900.read());
}
```