Smart Power Monitoring Utility System Using Wireless Sensor Networks

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By

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To my family

ABSTRACT

The design and development of a Wireless Sensor Networks based Smart Grid for home utility system for power utility has been presented in this thesis. The system utilises wireless power monitoring devices and control units. The electronic wireless power monitoring devices have been designed to monitor electrical parameters such as voltage, current and power of the household appliances. The measured electrical parameters are transmitted to a central controller via the ZigBee node. The central coordinator has been configured around a laptop computer and receives all the transmitted data from different nodes. The computer stores the measured data and analyses them. The computer is also connected to internet and the website of the electrical power supply company is accessed. The real-time electricity tariff is available to the controller. Based on the tariff condition the controller can determine the off-peak and peak-electricity rate. The controller can decide to switch off the unimportant electrical loads at peak-tariff situation. This is implemented by sending the necessary command to the zigbee node connected to the appropriate load. The zigbee node can then switch off the load by sending an off-command to the triac which is used as the control device. The user has the options of controlling the electrical appliances in different modes. If the users would like to continue the load to be on during the peak-tariff condition, the option of a manual switch can be used to bypass the triac. The appropriate electrical loads can be monitored as well as controlled using the developed GUI available at the laptop. The complete information of the system is also available through a website and appropriate control action can be implemented through a secured access. The objective of the research is to lower the consumption of power during the peak-tariff condition and thereby saves electricity cost. A prototype has been designed, developed and extensively tested. This Thesis presents the current work, experimental results and concludes with possible future research opportunities.

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Chapter 1

Introduction

This chapter introduces and provides definition to the title of this thesis. The problem definition, motivation and outcome objectives for this research are discussed. Finally, the structure of the thesis is outlined.

1.1 Smart Grid Utility System

A Smart Grid is an integration of electrical and communication infrastructure using information technologies within the existing electrical network in an automated process to improve system efficiency [1]. The term "efficiency" means not only the reliability of the system but also the ability to automatically preserve, renovate and improve the system by utilizing Wireless Sensor Networks. Figure 1 below shows the key elements that the Smart Grid infrastructures should have, from generation to the utilisation.

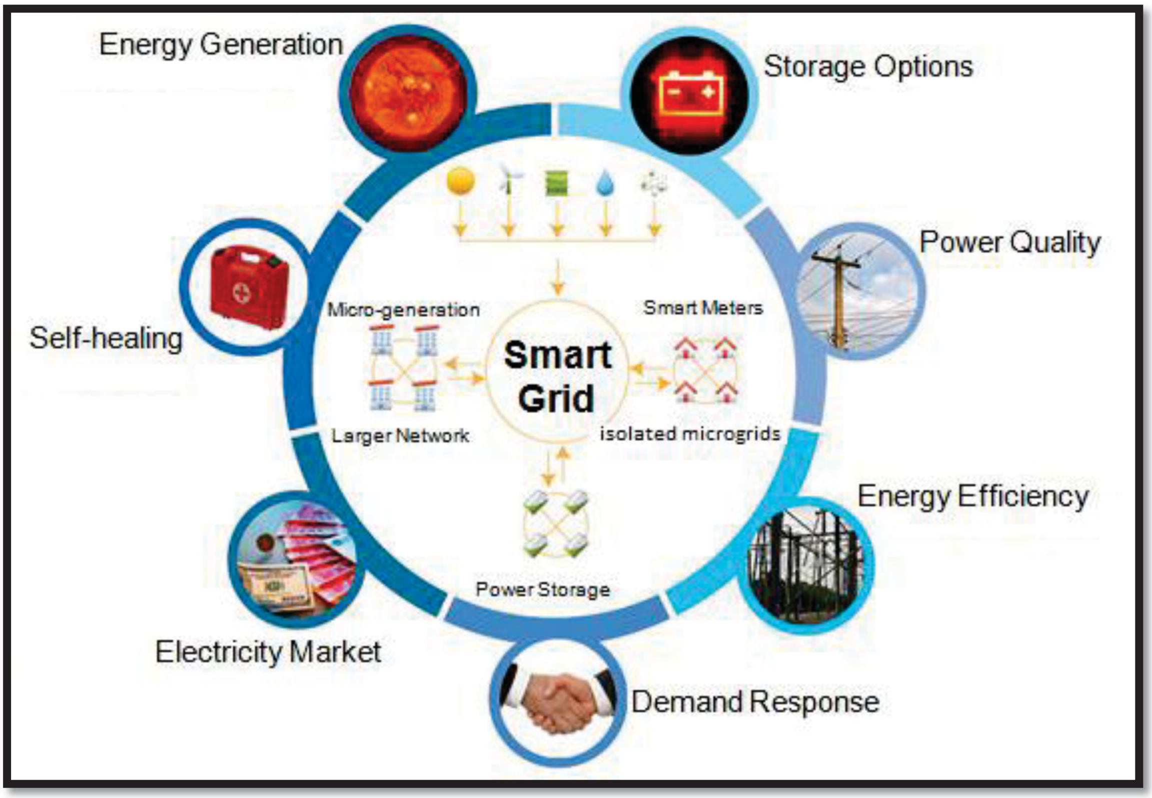


Figure 1: Key Elements of Smart Grid [2]

Smart Grids are digitally enabled to obtain and distribute information in order to improve the efficiency, reliability and sustainability of electrical devices. It involves the application of digital processing and communications to the power grid by replacing analog mechanical meters with digital meters, also known as Smart Meters. Smart Meters record usage in real time thereby improving electronic control, metering, and monitoring even for billing purposes. The Smart Grid enables information technology as a root to penetrate into today's existing electrical distribution system through information technology by using wireless sensor networks. Benefits of the Smart Grid include the ability to develop a utility's capacity to connect with and empower its users. The developed system is at the core of the enhanced relationship, providing many ways to instruct, invite and inspire the engagement with customers [3]. Users can take the benefit of better savings by monitoring and then controlling their power consumption enabling service providers to capitalize on new revenue and cost-saving opportunities. There are a number of benefits to using Smart Grid Technology; these include fault detection without the intervention of electrical professionals/electricians. Electrical grid reliability is also improved by reducing the frequency and duration of power outages and the number of power quality disturbances, including reducing the probability of regional blackouts [4]. Thus there is a more reliable supply of electricity and susceptibility to natural disasters or attack is reduced thereby improving the system's efficiency.

The Smart Grid term was coined in 2005 by S. Massoud Amin and Bruce F. Wollenberg [5]. The gaining importance and urgency of an integrated Smart Grid monitoring system using wireless sensors networks for advancements in metering of the electrical meters to provide more efficiency, reliability and options to the consumer. There are many companies and service providers that began installing Smart meters to the existing Electrical system. Smart meters are able to measure consumption accurately across different time periods in the one meter. They also have two-way communication abilities to enable remote meter reading, and to enable instructions to be sent to the meter e.g. to remotely disconnect a property. Smart meters' Advanced Metering Infrastructure (AMI) provide interface between the utility and its customers providing a bi-direction control mechanism, advanced functionality, real-time electricity pricing, accurate load characterization and outage detection or restoration [6].

The Smart Grid is essential to enable a future that is prosperous, customer empowered, energy reliable, secure and environmentally sustainable [7].

The project possibilities are wide-ranging. Maximising consumption without paying heavy costs has proven to be the most frequently employed and the most beneficial project.

At present, there are a wide range of sensors available on the market for similar projects like in irrigation supplies [8] and to check soil fertility. Recent advances in sensor technology, communication systems, and information technology have created generous opportunities to develop tools enabling remote monitoring in-case of emergency conditions. In projects like home monitoring for elderly care, various health monitoring sensors and activity recognition sensors are deployed in the home and can report any abnormality to care providers, and caregivers; allowing timelier and individually targeted preventive interventions [9]. The smart homes equipped with the wireless sensor networks will benefit both the consumers and service providers of the electricity.

1.2 Description of problem Domain

Electricity History

The form of energy which involves flow of electrons is called Electricity. Benjamin Franklin made one of the most important discoveries in human history - electricity in eighteenth century which is now the backbone of our planet and has enabled us to reach beyond earth into space to know what else is out there. It is one of our most widely used forms of energy and plays a crucial role in the unceasing development of human kind. Today our world revolves around it in a continuous loop. One of the most important areas of electrical knowledge is the study of the electrical power system [10]. Figure 2 shows the basic building blocks of an ‘Electric Power System’. Electric power systems are real-time energy delivery systems. They are not storage systems like water systems and gas systems. Electrical power systems have been in existence for many years. Alternating current (AC) power generation became widespread in the late nineteenth century. The alternating current system had an advantage of using step-up transformers for long distance distribution of electrical power to increase the voltages. All the electrical power systems distribute three phase alternating current. The primary sources for electricity generation are coal, natural gas, oil, nuclear power and other natural resources.

At present, the customer and the utility companies have continuous concerns regarding the operational efficiency of the power distribution and associated system because of magnificent power requirements. The application of the power systems have expanded rapidly since their development and continue to rise.

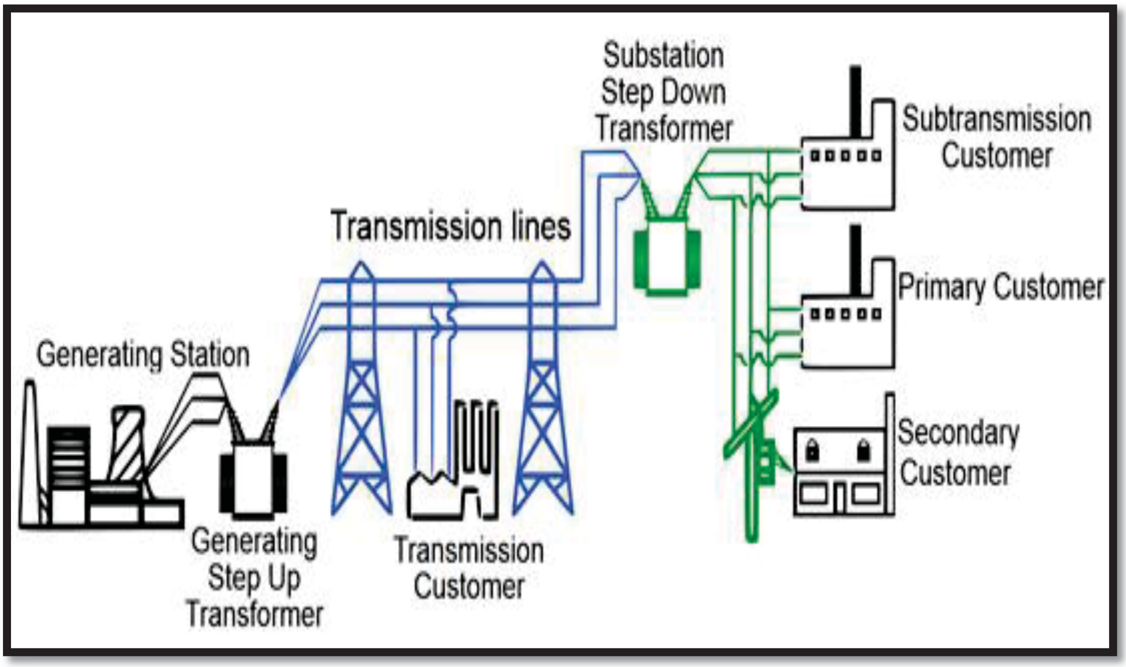


Figure 2: Building blocks of an Electric Power System [11]

Smart Grids are applicable in generation, transmission and distribution. Generation of the electricity can be done by using renewable sources of energy like water, solar energy and wind energy. There are some places in the world which use renewable sources of energy for the generation of the electricity. New Zealand is one of those countries. Increasingly hydropower, geothermal power and wind power are being used to produce electricity in New Zealand. The 70% share of renewable energy sources makes New Zealand one of the lowest carbon dioxide emitting countries in terms of electricity generation [12]. On the transmission side the Smart grids are useful in various applications like detecting a fault location automatically. This research is mainly based in the consumer side such as monitoring and controlling load appliances wirelessly through a GUI on a computer system.

Approximately 46% of the world's electricity is generated by the combustion of fossil fuel. At present, solid fossil fuel is the major fuel for electricity generation and is responsible for 58% of the electricity generated from all fossil fuels; natural gas accounts for about 23% and fuel oil for 19% [13]. It is worth mentioning that at its current rate, our consumption of fossil fuel is not sustainable and our supplies are rapidly dwindling.

The basic necessity for the application of a Smart Grid on the utility side has numerous reasons. At present, some electrical companies provide different tariff rates which vary throughout the day. Electricity is expensive during the peak time and is relevantly cheaper during off-peak time. The increasing demand for electricity will result in a significant change when the rates of electricity vary throughout the day everywhere in the world. The main concern is maximising consumption without paying heavy costs.

1.3 Aim and Scope of Research

The main aim of the research is to investigate the concerns associated with the power consumption on the utility side and comes with a solution to improve the efficiency of power by minimising power wastage and cost of power within an average household.

1.3.1 Smart Grid utility system

Figure 3 shows the block diagram of the developed system.

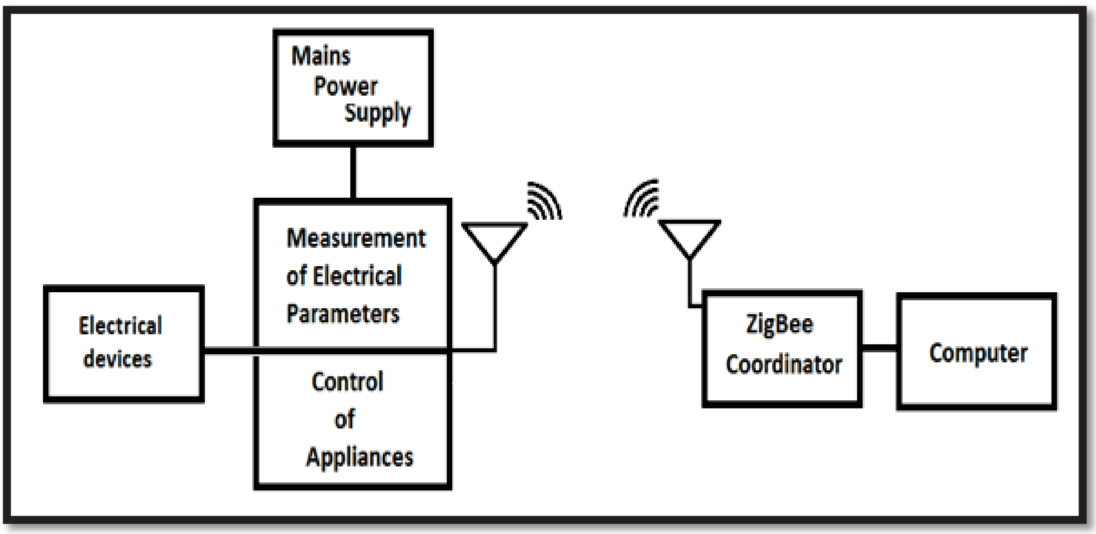


Figure 3: Block diagram of the developed system

The aim of this project is to develop an electronic networking system which integrates electrical devices and appliances found in almost all homes, so that the entire home can be monitored centrally or remotely. By monitoring the power continuously, users can control an individual appliance, or a set of appliances, based on the different tariff plans or time of use. Thereby reducing costs and increasing the efficiency of an average household system. The data collected from various sensors over the network in a smart home can be stored and integrated into a comprehensive record. It is a known fact that the use and implementation of wireless sensor networks drastically change from one application to another; the need for an in-depth study on performance parameters is vital [14]. There are a number of sensors available on the market, but making those sensors smart enough in the circumstance of a specific application is always a challenging task.

The basic principle of this project is to make the product compact and non-invasive in order for the user not to feel uncomfortable using it. To achieve this, a SMART component-based system of various integrated sensors all communicating via IEEE 802.15.4 wireless modules is developed and implemented. The use of wireless sensor networks in a Smart Grid utility is promising. It enables the utility to intelligently monitor, manage and optimize consumption in a safe environment [15]. The system depends on a set of a selected number of wireless sensors and a controller which relies on inputs from the sensors. The developed system is feasible, reliable, practical and scalable.

The original contribution of the thesis can be summarised as:

The initial design of the system was based on radio frequency wireless communication. In the later version the system has been developed using the ZigBee protocol.

Using a current transformer Smart electrical appliance monitoring unit has been developed. The developed unit determines the use, intensity and duration of use of the appliances. The data is then transmitted to the central controller using the ZigBee based wireless protocol. An intelligent algorithm has been developed to collect and analyse the use of the appliances.

By monitoring the load of a household in the database, an individual can analyse the day/night metering. Based on the different tariff rates provided by the electrical company, the user can decide what appliances need to be turned on during night time when the electricity is at a lower rate. The measurement of the electrical parameters through the end device connected to the appliance and the stored data into the database need testing at stages to make sure the system works and can be used reliably.

1.4 Research Objectives

This research aims to achieve the following objectives at completion:

1. Compilation of detailed specifications of sensor configuration.
2. Measurement of various electrical parameters such as current, voltage and power using sensor nodes.
3. Comparison of the received data or the measured parameters with the conventional power monitoring devices to check the accuracy of the developed system and explanation of the differences.
4. Establish the capability of controlling various high capacity load appliances using the proposed and developed approach.
5. Identification of areas for investigation for further improvement.
6. Complete documentation of the final data received, including complete component and signal listing, software information, and revised schematics.

These objectives will be used to determine a successful outcome of the research.

1.5 Outline of the thesis

A brief overview of each chapter is presented here as knowing where and when to expect specific topics and knowing how the information is organised in this thesis will help the reader to follow the material easily. This thesis is organized into eight chapters. Chapter one, the introduction, covers the general overview of the electrical power system and a brief overview of some of the basic concepts relevant to the electric power system. Uses of various techniques involved in saving power at the utility side are discussed in this chapter.

Chapter two provides important background information on the factors influencing today's existing power system. A brief discussion regarding the existing work on home monitoring, and power monitoring and controlling is discussed in this chapter.

Chapter three describes the existing wireless technologies and the comparison of ZigBee modules with various other wireless technologies like Wi-Fi, WI-Max and Bluetooth. The hardware and software configuration of the XBee coordinator with other

XBee end devices is also presented in detail in this chapter.

Chapter four presents the detailed work done showing the technology used to measure the electrical parameters of various household electrical appliances. The function of the ZigBee module is also presented in this chapter.

Chapter five explains the controlling technique used to control the power consumption of an electrical appliance within an average household thereby minimizing the overall consumption which will be beneficial to both the consumer and the service provider.

Chapter six explains the measurement technique and experimental results of the parameters that are monitored by using the project prototype. The functionality and benefits of the various types of communication techniques used in this project to monitor and control the power for various high loads in the household are discussed in this chapter.

Chapter seven concludes the work, summarising the developed system and future work is discussed briefly. C Sharp code used in the system is presented in Chapter 8 followed by the referencing used in this thesis.

Chapter 2

Literature Review

This chapter presents the survey done on existing technologies associated with the application of Smart Grid in the present power system in terms of power generation and consumption and existing technologies or techniques for measuring electrical parameters.

2.1 Existing Research/ The solutions

An electrical grid is an interconnected network which delivers electricity from suppliers to consumers after being generated at generating stations and transmitted via high voltage transmission lines to the substation from the distant sources [16]. The electricity is distributed to the individual users by the relevant distributing authorities or substations. Electric power is vital to present civilization. Economic prosperity, national security, and public health and safety cannot be achieved without it. Basic needs for food and shelter rely on electric power. Electricity has the capacity to deliver energy and information, thus yielding a cumulative selection of products, services, and applications in campuses, complexes, and communities [17].The world is changing constantly. Over time and due to excessive wear and tear of continued service, today’s existing electrical power system will start failing and to replace such a huge system, it would seem to be an impossible task in terms of labour and costs. Improvements in the electrical system can be done to improve the system’s reliability, efficiency, durability and sustainability [18]. There have been more power outages or blackouts since 1998 because of the aging system [19] and [20]. The worst blackout happened in India in July 2012 which left more than 620 million people without power across 22 states. Some of the states were blamed for the over-drawing of power from the grid which caused over-loading [21]. The drawbacks of the ageing infrastructure of the electrical power system in the USA and knowledge regarding the issues to fix the problems are discussed in [22]. Some assumptions are made by H. Cavdar in [23], that electricity can be used illegally by using fixed magnets (to change the electromagnetic field of current coils), mechanical objects (to reduce number of revolutions of the meter), use of external phase or free energy before the meter terminals and switching off energy cables at the meter box, and he presented a new method of using a smart meter with a smart resistance for remote real time detection to detect the usage of illegal electricity. Electricity demand is increasing as the population increases. Humans are globally relying on electrical technology. Congestion of the network on the transmission side is aggregating with the increasing growth thereby reduces customers access to power [24].

Although many governments have already invested in transmission facilities, the demand for consumption is also increasing on the consumer side. Fault in a transmission line is another big issue and detecting the fault location makes the system worse. This issue can only be resolved by the application of a Smart Grid. With the application of Smart Grids, the faulty sections in the distribution or transmission lines can be isolated by the use of fault indicators and the sections can be restored from alternate sources [25] thereby reducing outage times. The development of Smart Grid technology on the generation, transmission and consumer side, are exemplified in [26]. One method to resolve the issue of adverse weather conditions is to bury power lines which are discussed in [27]. A system can be defined as closed volume for which all the inputs and outputs are known. An arrangement of electronic components in which the inputs and outputs are known is called an electronic system [28]. The power system has served well throughout the 20th century but major developments are needed to bring it into the 21st century [1]. At present, the electrical power system is operated and controlled electromechanically. Although congestion over the electrical network is rising with its growth, it is envisioned that the electric power grid will move from an electromechanically controlled system to an electronically controlled network within the next two decades [5]. However, the electric power infrastructure, faced with deregulation (and interdependencies with other critical infrastructures) and an increased demand for high-quality and reliable electricity, is becoming more and more stressed. Methods to protect power system by utilising protective relays using spread spectrum radio communication are discussed in the literature [29]. To avoid costs of grid failure, penalties and other impairments, technology standardization can bring solutions with the introduction of a Smart Grid solution [30]. It is a vision of a better and safer future which will provide a healthier and intelligent electricity delivery infrastructure that responds to the requirements of and directly links with customers with reduced ecological impact. The Smart Grid system can integrate the solutions to make the electric grid more resilient to storms like Super Storm Sandy in America that left numerous people without Electricity. With the use of advanced sensing communication the implementation of projects based on Smart Grid technology are gaining importance in quantity, quality and use of the data available [31]. Projects related to Smart Grid started in early 2010 and are supposed to have finished the installation of equipment by the 2013-2014 timeframe [32]. Smart Grid technology will be beneficial by reducing and managing carbon dioxide emissions by leveling peak demand. On the residential side, there will be sufficient information for the electrical companies about the usage of individual households at any given time. Electrical service providers will be able to give price signals to individual users and information about the implications of their energy usage from where the user can decide what appliances need to be turned on and when [33]. A Smart Grid could detect areas of theft of current and take measures to cut off supply. Smart Grid utility systems will dramatically improve storage by utilising distributed resources and use of electricity [34]. The stored electricity in an elevated reservoir can be used to shift the time of buying of electricity depending upon the different tariffs provided by the electrical utilities. This system of storing electricity in terms of demand and supply will become more financially attractive when there are two different rates provided (peak and off-peak) [35]. The stored electricity is also used in charging plug-in hybrid electric vehicles (PHEVs) which provide extra support for grid operation by selling the power when it is required. PHEVs are scheduled for showroom floors by 2010 according to [36] which will help in reducing the nation's foreign oil bill. The task of adding other sources of energy to today's existing grid requires more elevated reservoirs for the storage of electricity and intelligent digital control which contains automatic control over problem analysis and automatic switching capabilities [37]. The applications of the Smart Grid system are essential for a prosperous and sustainable future. The momentum for realizing the "Smart Grid" vision has increased due to policy and regulatory initiatives for advancing and deploying relevant technologies. The Scope of Smart Grid in certain areas like central generation, delivery transmission and distributed energy resources and the characteristics of the Smart Grid are summarized in [38]. For an electrical utility, the combination of the right technology depends on the intelligence of the Smart sensors used. The concept was initially started with the idea of an advanced metering infrastructure (AMI) to improve load management at the consumer side and a self-healing sustainable electrical grid to improve supply reliability, efficiency and respond to natural disasters [39]. Some (not all) of the observability can be supplied by the AMI system. A unique vision regarding challenges, characteristics and features of a smart substation (future grid or smarter grid) are outlined and discussed in the [40] and [41]. There are many types of sensors available, even for use in irrigation and the measurement of water supplies which were not available before.

Consumer behaviour is altered along with power system operations and the beginning of low-cost Smart sensors and the availability of two way communication along the network [42]. The first priority of every electric power utility company is “keeping the lights on”, which means protecting the system at all costs. Thus, improving system protection and control procedures together with strengthening cyber defenses may well be a key aspect of the Smart Grid development in the near term [7].

Research in to Smart Grid technologies has leapt forward in recent years. Projects like Smart Grids utilising Wireless Sensor Network technologies are being promoted by the US government as a way of addressing energy independence, global warming and emergency resilience issues. There are various wireless sensor network technologies that exist for the automation of an electrical utility system. A report on the revenue of Smart Grid sales of Smart Grid sensing, monitoring, control systems and related software sold to the worldwide Smart Grid sector is estimated at $6.3 billion by 2014 and double that to $13 billion by 2018. Software for home area network applications will bring revenue five times greater than $1.1 billion by 2014. While home energy monitoring has been popular in the past, subsidized Smart meter deployments will make more it cost effective. There are several challenges ahead in the path of Smart Grids such as security and reliability. An efficient algorithm is required on the transmission substations to reduce the computational cost for the instant delivery of multicast messages in less than 4 milliseconds [43].

Wired sensor networks (WSNs) have already reached and been deployed in many applications over the last decade; because of the wireless extension, Smart Grids have witnessed a tremendous upsurge in interest and activities in recent years. The advantage of having wireless sensor networks for automation and control is that the cabling cost can be eliminated, and the installation of the wireless system is fast. The application of WSNs in the Smart Grid is encouraging. The delivery response in WSNs is high with the minimal variance in packet delay for smaller network sizes. The consumer costs can be gradually lowered by the application of WSNs in energy management by turning ON/OFF appliance loads during peak hours and carbon emissions regulated with electricity usage during peak periods [44].

Fourth generation wireless technology is available in the market today. Z-Wave (sigma Designs) represents a 4G integrated wireless module which is ideal for adding control easily. It has the capability to monitoring home security and home control and energy management products [45]. New technology includes cutting-edge advancements in information technology, sensor, metering, transmission, distribution, and electricity storage technology, as well as providing new information and flexibility to both consumers and providers of electricity. Security of the network and the sensed information is a high priority. Electro Magnetic Interference can occur in wireless communication. Eavesdropping is a risk for the system's security. Some of the very important benefits and applications of wireless sensor networks for the automation in electrical system are discussed in [46]. It is a mandatory requirement of the system to properly secure the WSN implementation from the known threats like system hacking, eavesdropping. The ZigBee Alliance, the wireless communication platform is presently examining Japan's new smart home wireless system implication by having a new initiative with the Japanese government that will evaluate use of the forthcoming ZigBee Internet Protocol (IP) specification and the IEEE 802.15.4g standard to help Japan create smart homes that improve energy management and efficiency [47]. The XBee/XBee Pro RF modules are designed to meet the ZigBee 802.15.4 standard. In this project, the XBee S-2 has been used for the wireless communication between several nodes from the coordinator to the end devices or vice-versa. The ZigBee modules have reliable communication of up to 100m and receiving current of up to 55mA at the operating voltage of 3.3V. The communication between two or more nodes can be unicast or broadcast. The X-CTU software is provided free from the Digikey website for testing and configuration of the XBee. The applications of the ZigBee module include a wireless network to synchronize street lamps which can be configured as a router because of the mesh capability of the ZigBee. The typical distance between street lights is approximately 40 to 60 meters. Communication can be easily achieved using the ZigBee protocols and the range can be extended by using a mesh network [48]. There are expectations that Smart meters will be equipped in 65 million households by 2015 and that is a realistic estimate based on the size of the home energy management market [49]. Smart Grid and wireless sensor networks provide an intelligent function that advance interactions of agents such as telecommunication, control and optimization to achieve adaptability, self-healing, efficiency, cyber security and reliability of power systems while reducing the cost and providing efficient resource management and utilization. A wide range of smart meter research has been carried out during the last decade. Various architectural design and development methods of Smart

Grid utility systems for effectively managing and controlling household appliances for optimal energy harvesting have been presented [50] and [51].

In order to connect various domestic appliances and have wireless networks to monitor and control based on the effective power tariffs have been proposed [52] and [53], but the prototypes are verified using test bed scenarios. Also, smart meter systems like [54], have been designed for a specific usage related to a particular geographical location Different Information and Communication technologies integrating with smart meter devices have been proposed and tested at different houses in a residential area for optimal power utilization [54] and [55], but individual control of the devices are limited to specific houses. Considering performance and cost factors related to the design and development of smart meters and also predicting the usage of the power consumption have been demonstrated [56], [57] and [58]. However a low-cost, flexible and robust system to continuously monitor and control based on consumer requirements, are at the early stages of development.

Although many governments, companies and departments are trying to resolve the issues regarding the load-demand on today's existing grid infrastructure, it is the responsibility of the individual to save as much power as they can in the sense of proper utilization, like switching off unused appliances such as light bulbs and standby electronic appliances (microwave oven, TV, room heater, AC etc.). The cleaning of the appliances also helps in improving efficiency, so filters of some devices like air conditioners and vacuum cleaners should be cleaned because the blocked airflow in these appliances can stress the system [59]. Another example of saving energy is illustrated in [8] in which the University of Colorado has earned $500,000 in revenues by diverting 10,000 tons of waste from local landfills in an award winning recycling program. Use of renewable sources of energy like solar power and wind energy, are strongly encouraged. Methods of power generation by personal means are reported in [60]. The project possibilities are wide ranging. In the 21st century, the most lucrative projects are energy conservation and reduced energy consumption. In this research, a low-cost, flexible and real-time smart power management system which can easily integrate with the home monitoring system like [61] is presented.

2.2 Electrical parameters measurement: Existing techniques

Before the research and development of the Smart power monitoring utility system, it is important to do research on the various approaches or techniques used in the measurement of electrical parameters such as voltage, current and power. Voltage, current and power are the fundamental electrical quantities that are important in every phase from power system to VLSI chips. Voltage is the basic electrical parameter which is used to get the output from all types of sensors like a temperature sensor, pH sensor and voltages produced by nerve cells. Voltage is the potential energy source of the electric power system. The unit of voltage is the volt (V) named in honour of Allessandro Giuseppe Antonio Anastasio Volta (1745–1827), the Italian physicist who invented the battery. Electrical voltage is denoted by “e” or “E” [62]. There are two types of voltage: direct and alternating. Alternating voltage is commonly used in electrical power systems. At the large scale, in power transmission, measurements of high voltages are used. At the medium scale, such as in power mains, industrial operations and laboratories, voltage measurements are used. There is a need for proper instruments to measure those high voltages [62] and [63]. Relevant work has been done for the measurement of high voltages using step down transformers and potential dividers in [64] and [65]. The measuring of electrical parameters (voltage, current and power) using a six-port coupler is presented in [66]. The measurement of non-sinusoidal voltage using integrated harmonic measuring instrument (HMI) is proposed in [67].

The voltmeter is the common method of measuring voltage. Other basic methods include multimeters and oscilloscopes. A multimeter is a device which has the capability of measuring current and resistance. An oscilloscope allows voltages to be measured by displaying the output waveforms on a CRT or LCD display. An oscilloscope is used to measure time varying signals with the graphical representation of voltage across time. Presently, oscilloscopes can produce many different signals like the RMS value, average value, peak to peak value, frequency, and mean value of the signal or waveform [68].

In this research, there are many sensitive components such as the XBee which have limited power handling capability. To minimize the risk of damage to the sensitive unit, test signals should be very small when electrically connecting these components. The voltage measurements are also of very low values. The testing of these sensitive components can only be done by selecting the known current as an input, measuring the resulting voltage, and calculating resistance. Some methods of measuring low level voltage and the delta method of measuring resistance are discussed in [69].

The flow of electrons in a wire is known as current. The main cause of the flow of electrons is voltage through a complete or closed loop electrical circuit. The resistance in the circuit will reduce the amount of current flow and will cause heat to be produced. The unit of current is the ampere, usually called amps. The electrical current is denoted by the letter "I" [70]. Current sensing is a more difficult problem as the current waveforms are associated with harmonic contents that create a wider range of frequencies. For the current measurements, shunt resistors, Hall Effect current sensors and current transformers are the widely known methods [70]. The approach of measuring compensative current by separating small amounts of total magnetic flux produced by the measured current so that this magnetic flux is strictly proportional to the measured current is discussed in [71]. Current shunt resistors, also known as ammeter shunts, are the low resistance precision resistors used to measure AC or DC electrical currents by the voltage drop those currents create across the resistance. A wide range of precision shunts, designed for use with kilowatt-hour meters and other high-current applications, where a high level of accuracy is required, are available on the market today. The basic model of a shunt resistor is shown in figure 4 in which voltage drop across the shunt resistor R_{sh} is measured and the measured output voltage is proportional to the current and its frequency.

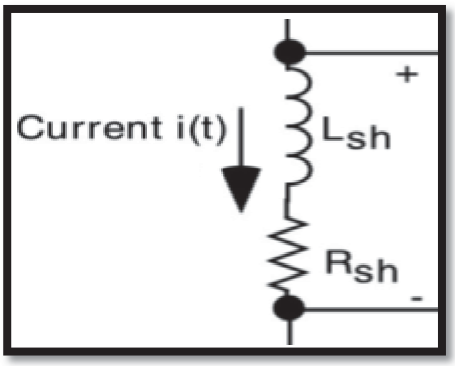


Figure 4: A Simple model of a Shunt Resistor

Various types of current shunts are discussed in [72]. Current flowing in a conductor generates a magnetic field and there are methods to use that magnetic field to measure the current which created it. Rogowski Coil (1912) delivers a terminal voltage proportional to the current passing through its loop. A range of methods for current measurements using electro mechanical ammeters, thermal type ammeters, multimeters, oscilloscopes and virtual instruments are presented in detail in [73]. The new energy meters installed in the U.S. residential market need to measure a maximum current up to 200A.

2.3 Conclusion

To develop an electronic networking system which integrates devices and appliances found in almost every home so that the entire home can be monitored centrally or remotely. Recent advances in sensor technology, communication systems, and information technology have created generous opportunities to develop tools enabling remote monitoring in case of emergency conditions. It is necessary to develop the key elements of the Smart Grid to quicken the standards. In home monitoring has the added benefit of evaluating individualized health status and reporting it to care providers and caregivers alike; allowing timelier and individually targeted preventive interventions [9]. The smart homes equipped with the wireless sensor networks will benefit both the consumers and the providers of the electricity. It is a known fact that the use and implementation of wireless sensor networks drastically change from one application to another; the need for in-depth study on performance parameters is vital. Other applications of wireless sensor networks such as vehicular traffic, thermal energy harvesting, inventory management in the packed gas industry, are reported in [14]. While several sensors are readily available off the shelf, making them "intelligent" so that the developed system can be capable of sensing overloads, and analyse that problem with a solution of rerouting power to reduce potential outage, is always a challenging task. Integration and data handling are the key issues of a wireless sensor network.

In this research an electronic system has been used extensively to get all the electrical parameters in such an automated fashion that power of an individual appliance can be controlled wirelessly, based on different tariff rates provided by the electrical companies. The wireless sensor networks integrated with the ZigBee modules used for the collection of data are described, and this research is still on-going with other projects like smart home monitoring for elderly care. By monitoring the power continuously and reporting any abnormal situation, the system frees human labour and thus reduces labour costs and increases efficiency by notifying service providers quickly. The data collected from various sensors over the network in a Smart home can be stored and integrated into a comprehensive record. By monitoring the load of a household in a database, an individual can analyse the day/night metering by utilising energy consumption based on individual parameters or preferences. The developed system can be easily installed in the household with no damage or modification to the existing electrical system or infrastructure. The user can decide which appliances, depending on their individual consumption, need to be turned off/on during night time when the electricity is at a lower rate.

The developed system consists of the integration of various sensors and communicates via standard RF protocols. The system depends on a set of a selected number of wireless sensors, and a controller which relies on inputs from the sensors. This system will consist of a proof-of-concept that is feasible, reliable, practical and scalable.

The original contribution of the thesis can be summarised as:

1. The initial design of the system was based on radio frequency wireless communication. In the later version the system has been developed using the ZigBee protocol.
2. A current transformer based Smart electrical appliance monitoring unit has been developed. The developed unit determines the use, intensity and duration of use of the appliances. The data is then transmitted to the central controller using the ZigBee based wireless protocol.
3. An intelligent algorithm has been developed to collect, analyse and control the use of the appliances.

Chapter 3

Wireless technologies for System Set-Up and the comparison

In this chapter, comparison between the existing wireless technologies like Wi-Fi, WiMAX, Bluetooth and ZigBee is discussed. The configuration of the proposed technology is also shown at the end of the chapter.

3.1 Introduction

Any type of information which can be shared or sent over the air via electromagnetic waves, without any physical connection between sender and receiver is called wireless communication. Depending on the various applications, wireless technology is applicable almost everywhere in today's life, allowing freedom of movement for the users: from home to factory, from traffic control to environmental and home monitoring. Although wireless technology is applicable over short distances, but even for long range communication it is beneficial as the cable network complexity is reduced thereby reducing operational costs. Although wireless technology has been deployed for more than 30 years [74] through the use of proprietary radios, over the last few decades many wireless technologies have been developed to deal with issues such as cost and network complexity. Power consumption is minimal for sending small bits of the data. A survey shows wireless technologies used in industrial automation and the most exploited were WiFi, WI-Max, Bluetooth, and ZigBee. It is very important to select a suitable wireless technology for the intended application. In this section of the research, brief key features for the above mentioned wireless technology are illustrated.

Wireless technologies

Depending on the requirements of different applications, every technology has its own features and strengths. The following sections show a brief comparison of wireless technologies based on the requirements of robustness, low consumption of power and throughput data rate.

3.1.1 Bluetooth wireless technology (IEEE 802.15.1)

Bluetooth (named after Danish King, Harold Bluetooth) [75] technology is the first wireless technology designed to be a short range wireless communication which has an operating frequency band within the unlicensed ISM 2.4 GHz. It is an ad hoc, terrestrial wireless standard. It uses the frequency hopping spread spectrum (FHSS) modulation technique in which data is sent on a radio channel that frequently changes frequency according to a predetermined code [76]. This avoids a collision between other wireless technologies such as Wi-Fi or Bluetooth which are using the same band of 2.4 GHz ISM [77]. It is commonly used in handheld devices maintaining a high level of security without the use of cables for the transfer of data between devices. Bluetooth supports realistic data rates up to 600Kbps and consumes less power when compared with other wireless technologies [78]. Common applications include hands-free headsets for voice calls, printing and fax capabilities, and synchronization for PCs and mobile phones at low power and lower cost [79]. A fundamental strength of Bluetooth wireless network is the ability to simultaneously handle data and voice transmissions, which provide users with a variety of innovative solutions. Bluetooth uses CSMA/CA to avoid collision with other wireless networks when using a shared channel. The data rate in Bluetooth technology for low energy technology is up to 1 Mbps [80].

Depending on the version, data rates can vary such as version 1.2 has data rate of up to 1 Mbps, version 2.0 has data rate of up to 3 Mbps and version 3.0 has data rate of up to 24 Mbps. The range for Bluetooth wireless technology depends on many factors such as the type of mobile device, environmental conditions, transmission speed, etc. Range may vary depending on class of radio used in an implementation [77]:

- ❖ Class 3 radios – have a maximum range of 1 metre with the maximum power output of 1mW.
- ❖ Class 2 radios – most commonly found in mobile devices – have a range of 10 metres, but in most cases 5 - 10 metres with the maximum power output of 2.5mW.
- ❖ Class 1 radios – used primarily in industrial use cases – have a range of 100 metres, but in most cases 20 - 30 metres with the maximum power output of 100mW.

3.1.2 Wi-Fi (802.11)

Wi-Fi (Wireless Fidelity), the term coined for Wireless Local Area Network (WLAN) operates on high frequency radio waves at 2.4 GHz or 5 GHz bands for transmission of data from source to destination. The range of a Wi-Fi network can be several hundred meters between two places of data transmission. It is commonly intended to be used for mobile computing devices, such as laptops, and in other Internet access devices such as routers and modems [80], but at present, the applications of Wi-Fi networks are increased beyond the PC to Internet gaming, and basic connectivity of consumer electronics such as televisions and DVD players. In terms of power consumption, improvements have been made to Wi-Fi in recent years, but it still is not suitable for coin cell operation as it is using high speed throughput for large data transfer [81]. There are four generations of Wi-Fi products available which are IEEE 802.11a/b/g/n [82]. These four generations of Wi-Fi are defined by a set of features that relate to performance, bandwidth and frequency as shown in the table 1:

Table 1: WiFi Generations [83]

Wi-Fi Generation	Maximum Bandwidth (in Mbps)	Frequency Band (in GHz)	Range (in m)
802.11a	54	5	15
802.11b	11	2.4	45
802.11g	54	2.4	15
802.11n	300	2.4 and 5	55

3.1.3 WiMAX (802.16)

WiMAX operates on 802.16 standards which were approved by IEEE in 2001. The frequency range is approximately 50 kilometers, dependent on the central radio base station, and the data rate is up to 70-80 Mbps. It falls under the category of Wireless Metropolitan Area Network Class (WMAN) [84] and [85]. The frequency bands in WiMAX are 2-11 GHz and 10-66 GHz by which it is capable of working non-line of sight and line of sight within these two frequencies ranges respectively [75]. The interference is minimal which makes it similar to Wi-Fi networks. The only difference between WiFi and WiMAX is that instead of using smaller wireless LANs, WiMAX creates a larger wireless MAN by interconnecting smaller wireless networks. WiMAX provides a wireless alternate to cable and wireless access. The speed of a WiMAX network is faster than 3G cellular. Its applications provide mobile broadband connectivity across different locations through a variety of devices. The security is provided via station authentication and encryption.

3.1.4 ZigBee (802.15.4)

ZigBee operates on IEEE 802.15.4 standard and is a commonly used wireless technology that can be used for short range multimedia transmission. The ZigBee standard is being promoted and developed by ZigBee alliance which contains more than 200 members including companies like Texas Instruments, Philips and Samsung.
[86]. The frequency bands for a ZigBee network are 868 MHz, 915 MHz and 2.4 GHz. The applications of Zigbee along with Bluetooth include health care and medical applications [87] and [88]. Zigbee modules are able to support mesh networking by interconnecting various nodes with each other providing greater stability. The number of nodes can be up to 65,000 per network. The main applications where ZigBee modules are used include Smart grid/Smart energy, lighting controls, home automation systems, medical devices and remote controls [89]. The communication system used in the operation of ZigBee is based on the Direct Sequence Spread Spectrum (DSSS). The IEEE 802.15.4 standard is a simple packet data protocol for light weight wireless networks and specifies the Physical (PHY) and Medium Access Control (MAC) layers for multiple Radio Frequency (RF) bands. The data transmission over a ZigBee network is very reliable at up to 100 metres when compared to other discussed technologies, while consuming a very small amount of power. ZigBee communications can reach up to 500 m, with a data rate of up to 250 kbps, for a typical power consumption of 125 to 400 μW[77]. ZigBee wireless technology is far superior to both Wi-Fi and Bluetooth in terms of energy conservation [90] therefore it was preferred for this project.

3.2 Comparison of ZigBee, WiFi and Bluetooth

In comparison with existing wireless technologies, Bluetooth, WiFi and ZigBee are considered to be intelligent enough to deliver the performance and low cost which is required in present wireless applications. The key features of the wireless technologies mentioned in this chapter allow users to select the most suitable technology for their applications. Table 2 shows the comparison between these three wireless technologies, on the basis of their frequency range, technology, performance, range, power consumption etc. ZigBee wireless technology cannot be applied to high data implementations applications such as audio/video streaming and graphic web browsing because of their high bandwidth requirements. Bluetooth and WiFi are not suitable for battery powered applications because of their high power consumption characteristics.

Table 2: Comparison of Wireless Technologies

	Bluetooth	WiFi	WiMAX	ZigBee
STANDARD	802.15	802.11a/b/g/n	802.16	802.15.4
DATA RATE	1 Mbps	11 & 54 Mbps	70-80 Mbps	upto 250 Kbps
OPERATING RANGE	10 meters	50-100 meters	Upto 50 Kilometers	10-100 meters
POWER CONSUMPTION	Medium	High	High	Very Low
SECURITY	Yes	Yes	Yes	Yes
COMPLEXITY	Medium	High	Very High	Low
LATENCY	2.5ms	1.5ms	5-40ms	20ms
NETWORKING TOPOLOGY	Ad-hoc, very small networks	Peer-Peer or Point to Hub	Mesh	Ad-hoc, peer to peer, Star or Mesh
OPERATING FREQUENCY	2.4GHz	2.4-5GHz	2-66GHz	2.4GHz, 950MHz 868MHz
APPLICATIONS	Used in Handheld devices like PDAs, Phones, Laptops and Headsets	Broadband Internet Access, WLAN	WMAN	Monitoring and Control Applications, Home Automation, Lighting Control
ADVANTAGES	Low Cost	Speed	Speed and Range	Speed, Range, Power Consumption and Cost
DISADVANTAGES	Range	Cost	Cost	???

Bluetooth is primarily a cable replacement for point-to-point communication between consumer devices, and WiFi technology is a network technology developed for data-intensive communication such as audio/video streaming and graphic web browsing. ZigBee technology is capable of providing large scale low power networks and devices that could run for years on inexpensive batteries. WiFi and Bluetooth have much higher power requirements, therefore the battery running time will be a lot shorter. In this research XBee is used mainly for the wireless communication to monitor and control a different set of home appliances depending on the power consumption.

3.3 ZigBee

The Figure 5 shows the XBee module which has been used in this research for communication between coordinator and end devices. XBee Series 2 is used in this research for the wireless communication between the centralized controller and the connected end devices.

The operation of an XBee module requires a 3.3V DC power supply at 50 mA. It has 20 pins out of which seven pins can be used as analog input; nine pins can be used as digital I/O and two channels for PWM [91].

The communication is carried out without the use of a micro-controller and the data processing is done at the central controller.

In the following section the ZigBee module configuration and how to initiate communication between the end device and the coordinator is discussed. This configuration is used for this project.

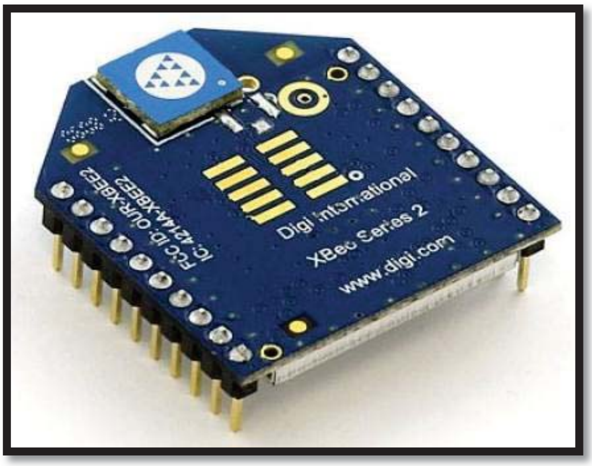


Figure 5: XBee Chip Series 2

3.4 XBee Configuration

The XBee modules are required to be configured individually before they can be used. The Digi website provides free software X-CTU (XBee Configuration and Testing Utility) which is required for the configuration of the XBee modules. The following Figure 6 shows the layout of the X-CTU program.

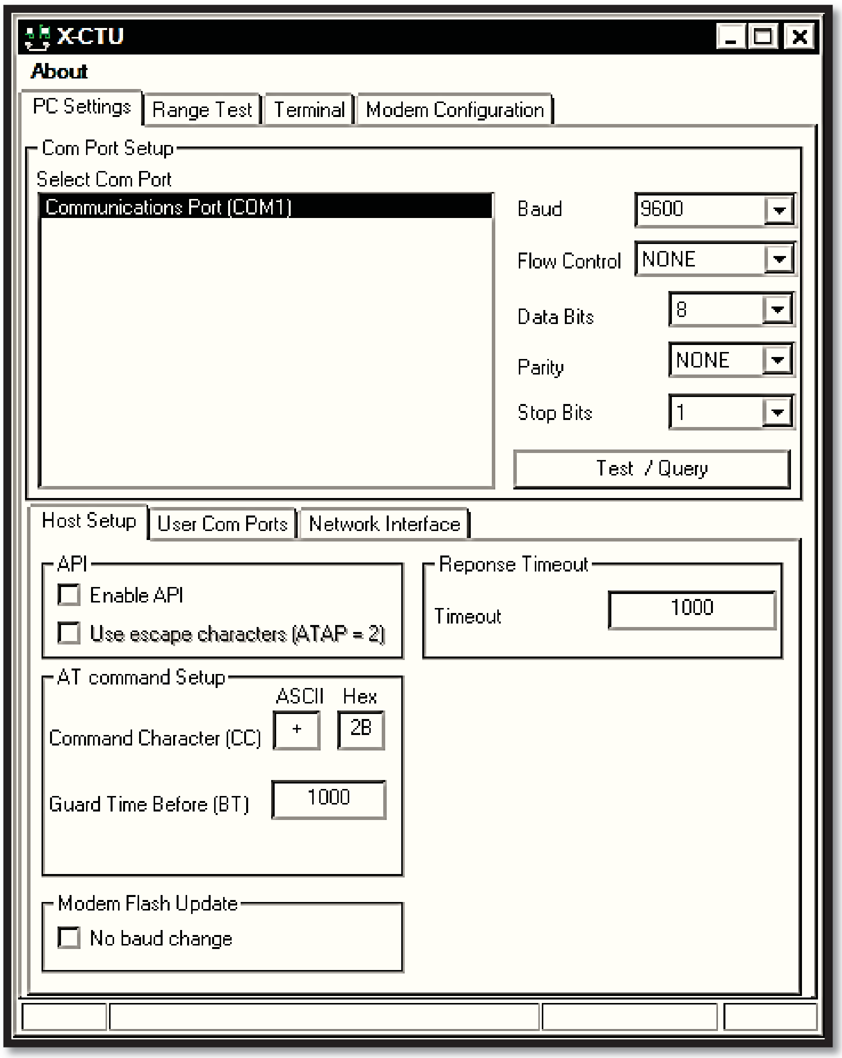


Figure 6: XCTU Configuration tab

The software program consists of 4 main tabs: PC Settings, Range Test, Terminal and Modem Configuration. The PC Settings tab allows the user to select the XBee modules, for configuration, from the range of plugged in devices. The Range Test tab allows the user to test the range of wireless communication between two XBee modules. The Terminal tab allows access to the computers COM port with a terminal emulation program. This tab also allows access to the radios' firmware using AT commands. The Modem Configuration tab allows the user to modify the program to configure the XBee coordinator and end devices. For the configuration of the coordinator and the end device modules, the mandatory requirement is ZigBee Explorer with a USB. The picture of ZigBee Explorer and relevant USB cable is as shown in Figure 7.

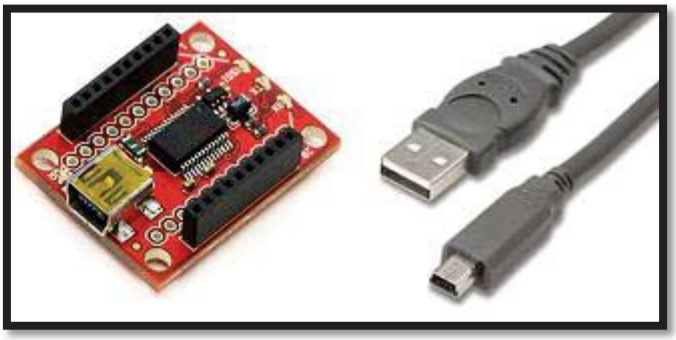


Figure 7: XBee Explorer and USB Cable

3.4.1 Configuration of the Coordinator

The coordinator is initially configured to start a communication network. The coordinator always listens to the end devices and receives the incoming data and sends it to the computer through a USB cable connected on a serial port. A developed program is installed on the computer that is used to read and store the serial data for further processing according to the application [15]. Using the Modem configuration tab on X-CTU program, select the modem type as XB24-B and the Functional set as ZNET 2.5 COORDINATOR API with a version of 1147. Set a unique PAN – ID e.g. 2345 for the network. Set the baud rate to a value of 9600 and the sampling rate to 14 (hexadecimal) which is 20ms in decimal value. This means that after every 20ms, the coordinator will receive data from the end devices using the same PAN – ID in the network. To start the configuration, select the "Write" tab on the X-CTU and wait until it is finished successfully. Figure 8 shows the screenshot of a configured coordinator:

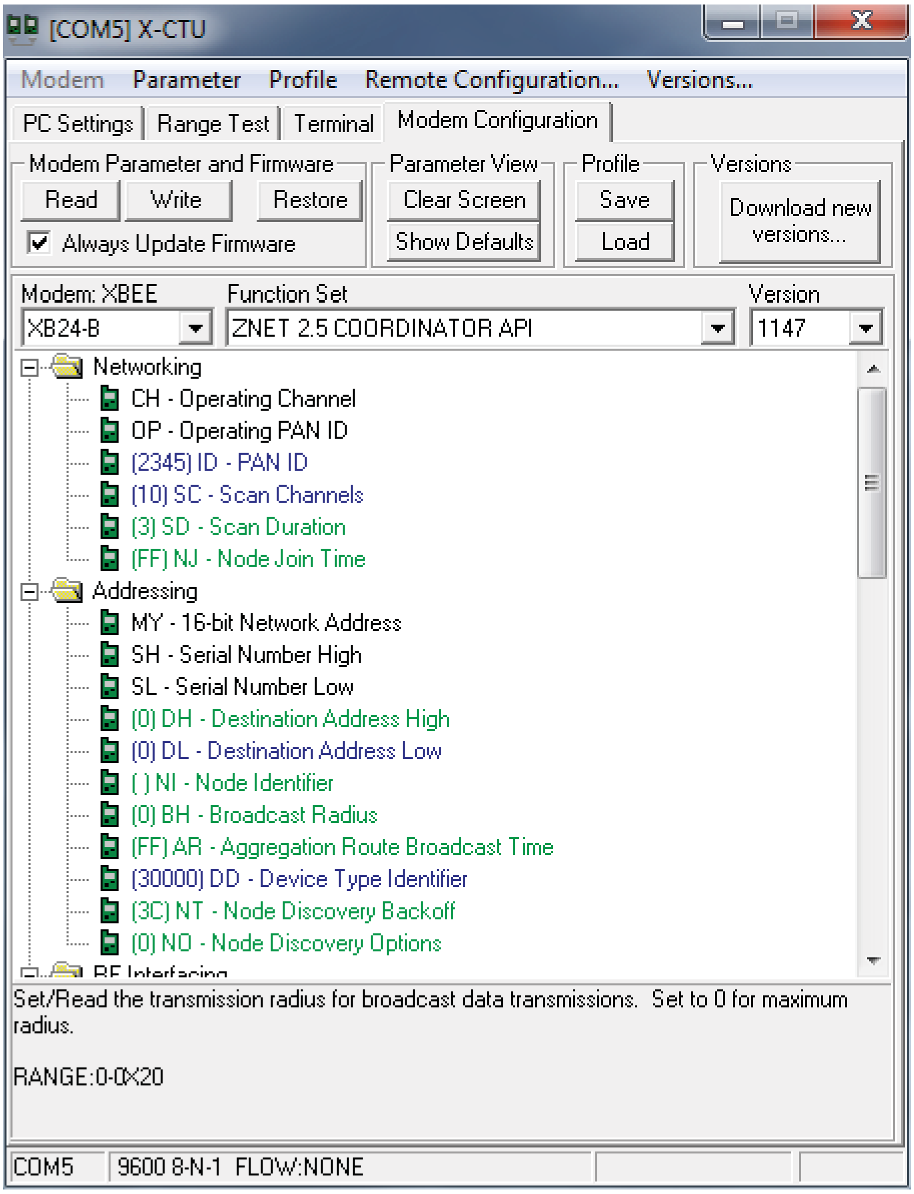


Figure 8: Screenshot of XBee Coordinator Configuration

Close the X-CTU program after the coordinator is successfully configured. This configured coordinator will then manage the whole communication within the network. It will receive data from all the active end devices and send it to the computer via the USB cable which will store all the information for further processing [92].

3.4.2 Configuration of the End Device

The configuration of the end device is carried out by following a similar procedure as the coordinator, again using ZigBee USB Explorer. Using the Modem configuration tab on X-CTU program, select the modem type as XB24-B and the Functional set as ZNET

2.5 ROUTER/END DEVICE AT with a version of 1247. The PAN – ID for the end devices should always be same as the coordinator in the network e.g. 2345. The value for Destination High (DH) and Destination Low (DL) should be the same as the Serial High (SH) and Serial Low (SL) of the coordinator. The registers D0, D1, and D2 have to be set to 2, which mean that the selected pins will read the analog inputs. Set the register D3 to 4, which means that this pin will read the digital input. Select the same baud rate and sampling as the coordinator, 9600 and 14 (hexadecimal) respectively. To start the configuration, select the "Write" tab on the X-CTU program and wait until it is finished successfully. The end device will be configured to join a network when powered on. After the end device joins a network it will attempt to discover an endpoint on the trust center that supports key establishment by sending a match descriptor request to the coordinator. If the trust center responds with a match descriptor response, the end device will attempt to perform key establishment. If everything is setup correctly, wireless communication can be established between coordinator and end device. This type of communication is referred to as a point to point or point to multi-point communication. The screenshot showing the configuration of XBee End Device is as shown figure 9.

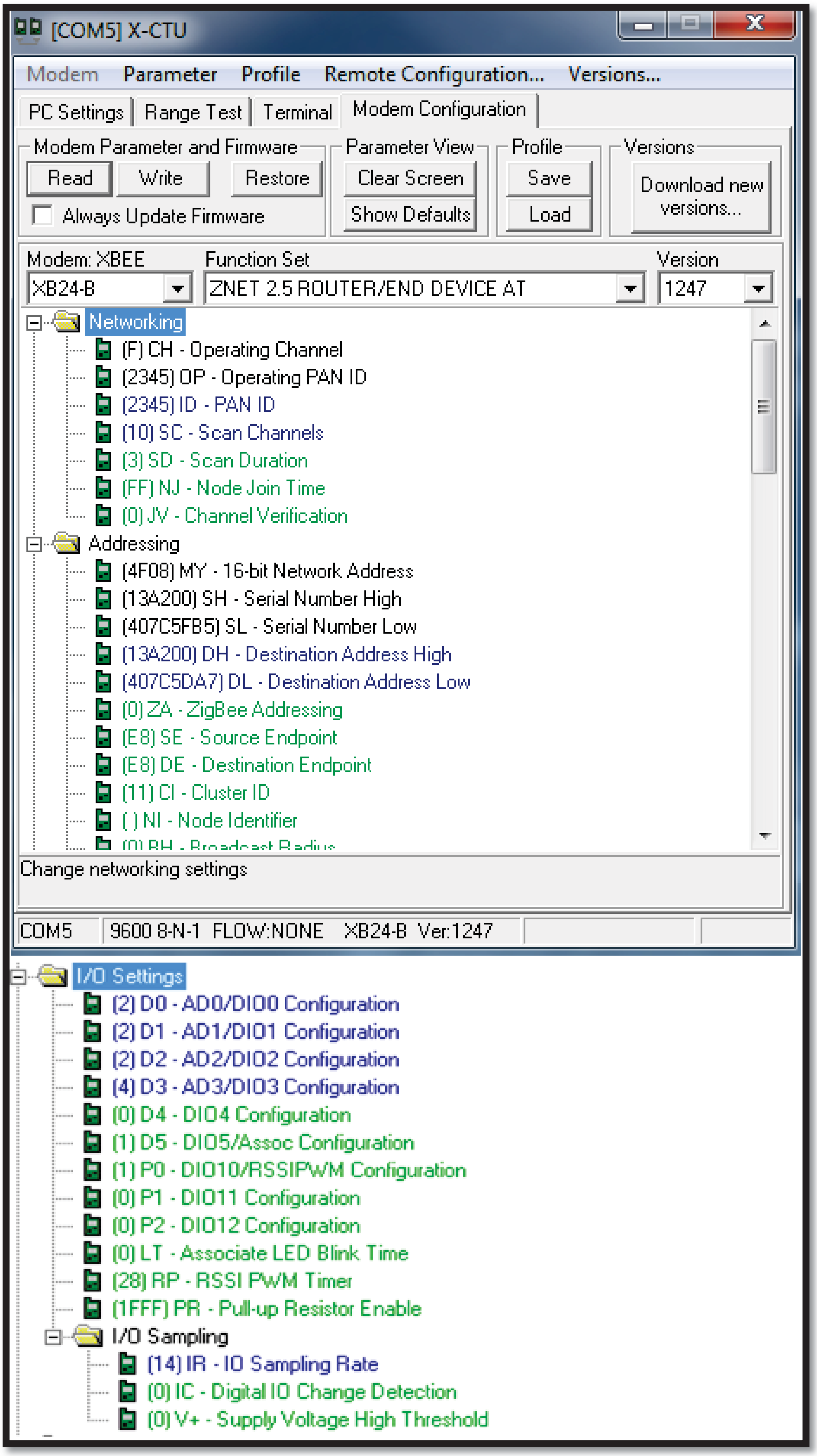


Figure 9: Screenshot of XBee End Device Configuration

3.4.3 Software and Algorithm for XBee Data Reception

Communication between the XBee Coordinator and XBee End Device is wireless, transmitted in the unlicensed 2.4GHz frequency band. Data Collection is based on the Sampling rate used in the XBee Configuration. For this research, the Sampling rate is set at 14ms. So the data packet is coming at the receiver unit after every 14ms.

The flowcharts in Figure 10, 11 and 12 displays the Configuration, Communication and Packet Identification and Extraction of data between XBee Coordinator and Xbee End Device.

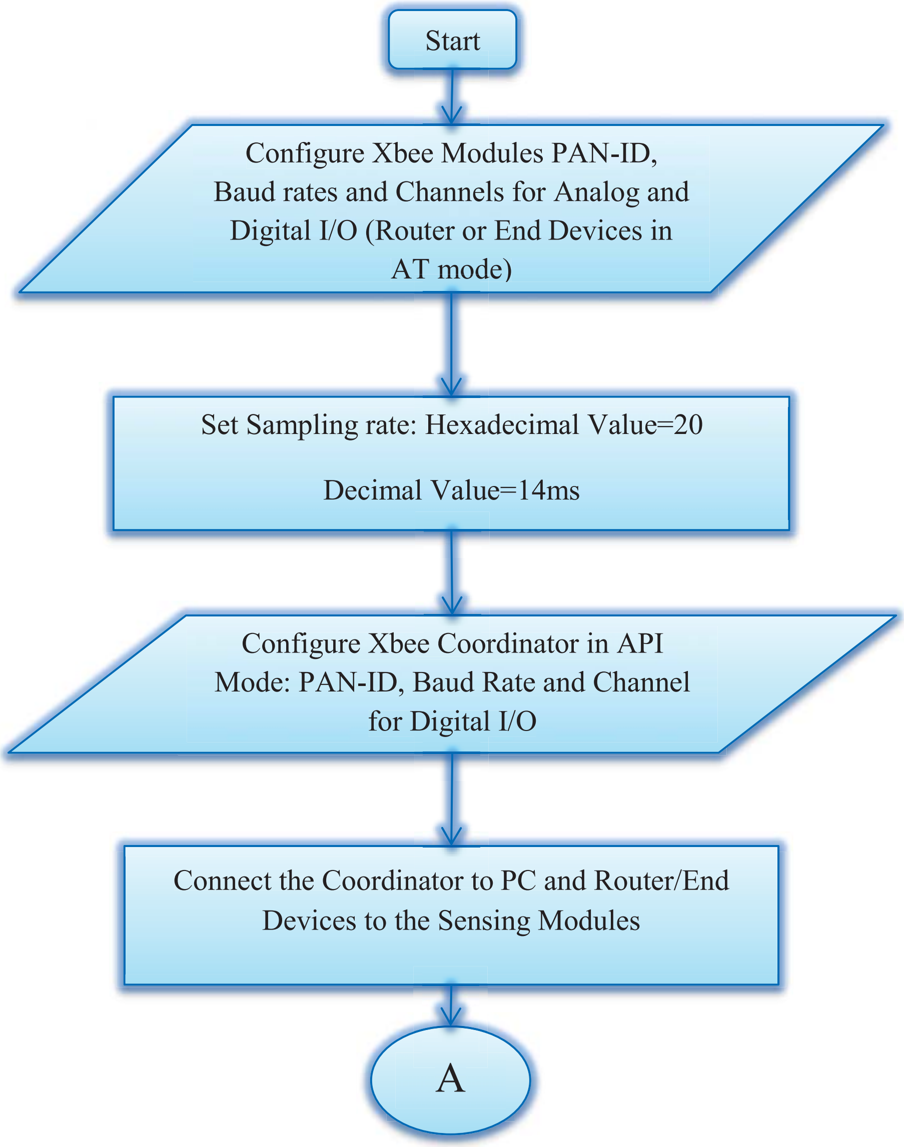


Figure 10: XBee-Coordinator Configuration Algorithm

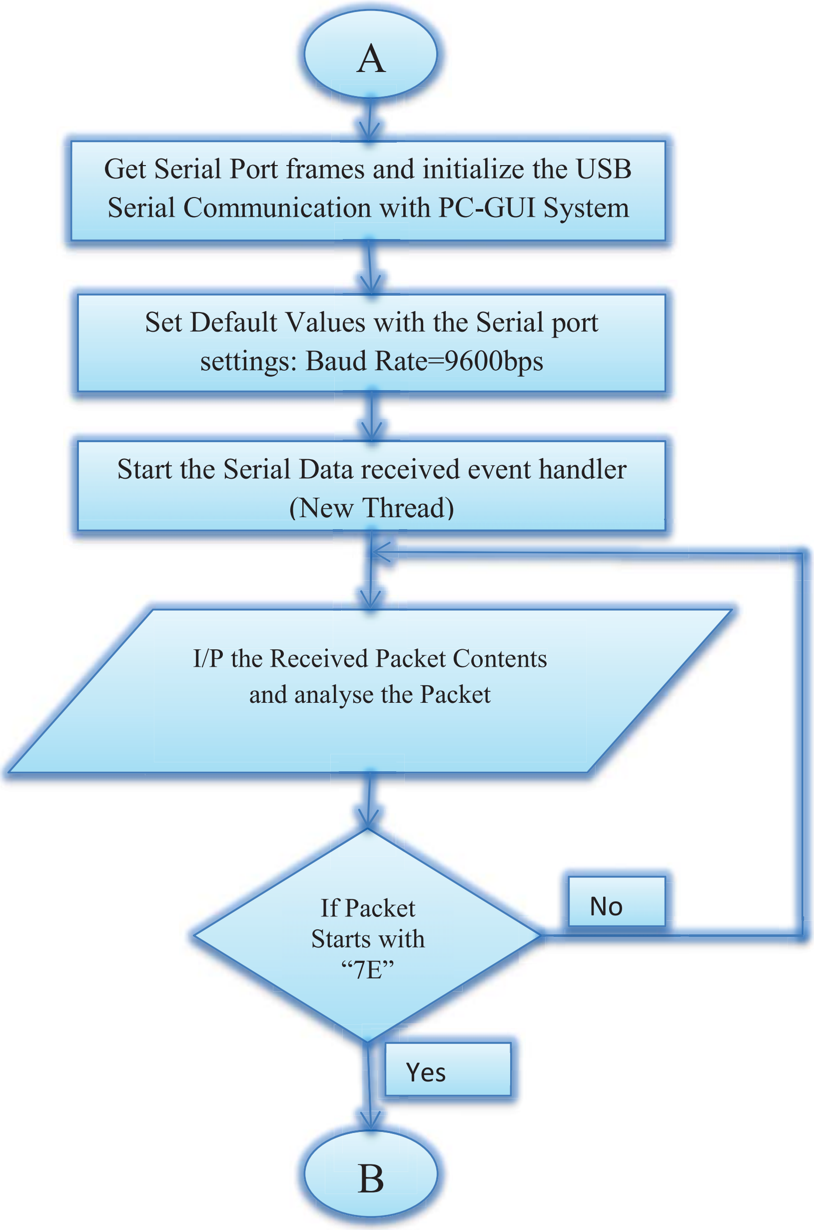


Figure 11: XBee Data-Packet Identification

Algorithms were written for the XBee Communication and for the software program used in the computer. Figure 11 shows the algorithm used for the data identification. Each packet of information in XBee data frame starts with "7E" in a frame when "7E" appears again that means this is the start of next data bit. The developed system software is based on the Current and Voltage sensor data which are designed to measure the Electrical Parameters of the appliances. The output data frames are transmitted through XBee End Device to the Coordinator and analysed.

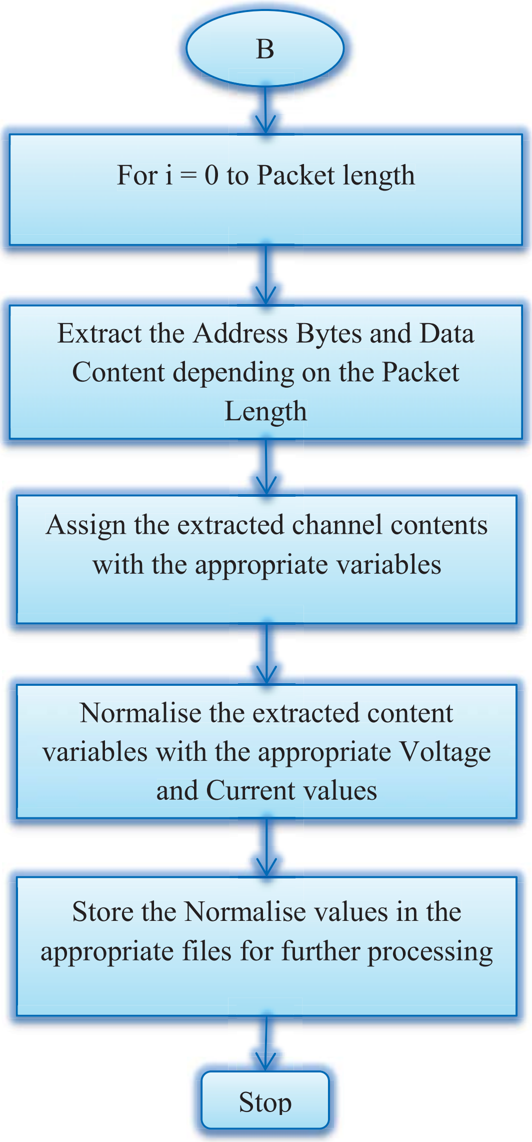
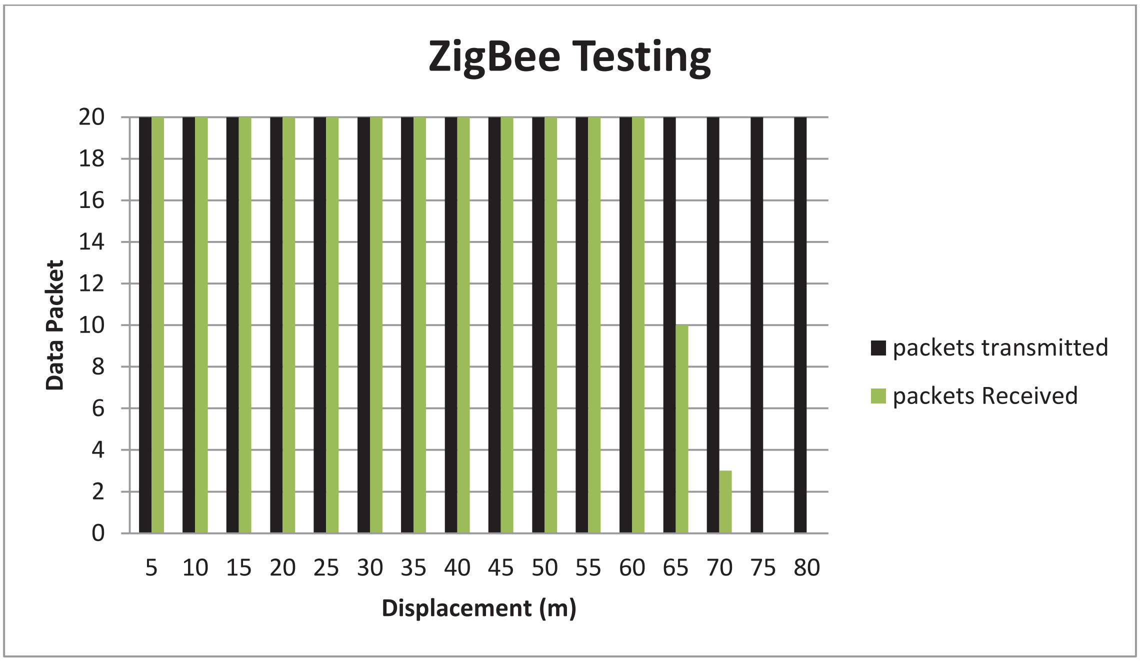


Figure 12: Extraction of Data Bytes for further processing

Figure 12 above shows the algorithm used for the extraction of data frames. The Xbee coordinator which is connected to the computer via USB cable receives and stores the information in the computer data-base. C-Sharp program is used for the processing of data received and the output results are displayed on the GUI.

3.5 ZigBee Feasibility

To determine the strength of the signal in a network a series of tests can be done with respect to the change in direction and displacement between the coordinator and the end devices. Two ZigBee wireless modules, one configured as coordinator and the other as an end-device are setup. A 3.3 V DC supply is provided for the operation of the XBee end device. With every test, twenty sample data packets are transmitted by the coordinator to the end-device. The reliability of the transmission is determined based on the number of received respond data packets with respect to the number of transmitted data packets. The coordinator is connected to a personal computer via USB cable. The test was repeated after increasing the distance by 5m after the completion of every test. The experimental results showing the reception of data packets during transmission are displayed in the Graph1. As stated by Digi, the range of ZigBee wireless module is approximately 60 m indoor/urban area [93]. This statement was found to be correct according the result obtained from the experiment. As shown in the figure, the transmitted data packets were received in full at 60m and below. However, the signal strength drops significantly when the displacement increased above this limit. The number of packets received successfully is reduced by half at 65 m and dropped to zero at 75 m.



Graph 1: Testing the strength of ZigBee radio signal with respect to the changes in the displacement between coordinator and end device

3.6 Conclusion

After comparing the wireless technologies, ZigBee wireless transmission is considered to be very reliable when it operates within the recommended range. ZigBee was found to be very robust to external interferences (no evidence of fluctuations in the signal strength was found) as compared to the other technologies. There is a minimal delay for the reception of data when the displacement is increased beyond 50 m but this is negligible. In general, to ensure reliable data transmission it is recommended to limit the range to below 50m which is suitable for the use of the ZigBee standard in a home environment.

Chapter 4

Measurement of Parameters

This chapter discusses the measurement technique used in this project for the measurement of control parameters such as current and voltage. The type of transformers used for the measurement and their relevant characteristics in relation to the input sources are also discussed in detail.

4.1 Introduction

There are continuous fluctuations in the patterns of alternating voltages and currents with respect to time as the polarity and direction changes. Those patterns are known as waveforms. To display these waveforms and their respective outputs, an oscilloscope is the required instrument. Sensors are required to measure the voltage and current from a system, so the output of those sensors can be displayed on the oscilloscope. The generated signals from the sensors need amplification as the generated signals are very small, so suitable operational amplifiers are used in the circuit. In this chapter, the medium voltage that exists in normal household mains power is stepped down by using a voltage transformer and the low voltages that are generated by the voltage sensor are measured with respect to the input mains voltage. Electrical current and voltage are the key elements, from the consumer point of view, to measure power consumption of various appliances in a house. This chapter focuses on the power monitoring technique used to monitor the power consumption in the house and the appropriate technique to control it. The designed system has been tested in different households for measuring voltages and current readings of the electrical appliances. Fundamental to the developed system is the ease of modelling, setup and use.

4.2 System Set Up

Figure 13 shows the functional description of the developed system to monitor electrical parameters and control appliances based on the consumer requirements. At the low level module, Wireless Sensor Network integrated with ZigBee modules of a mesh structure exists to capture the sensor data based on the usage of the household appliances and stores that data into the computer database for further processing. Collected sensor data is low level information that contains the status of the sensor as active or inactive and the identity of the associated sensor.

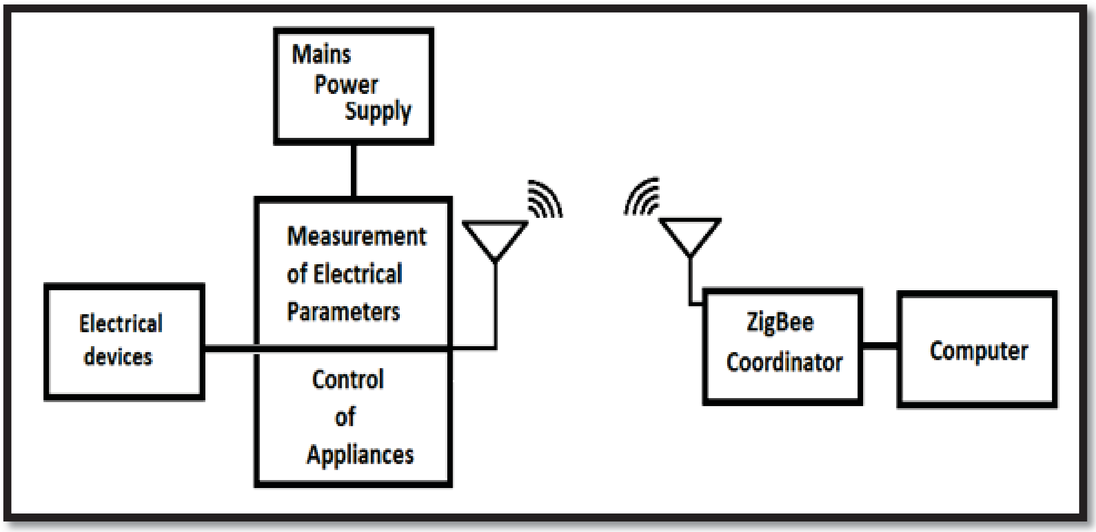


Figure 13: Functional block diagram of the system

The low level module consists of a number of sensors interconnected to detect usage of the electrical appliances. The fabricated sensing unit communicates at 2.4 GHz (Industrial Scientific and Medical band) through radio frequency protocols and provides sensor information that can be used to monitor the electrical parameters on a regular basis. Figure 14 given below shows the basic block diagram of the implemented circuit. The transformer block consists of voltage and current transformers. The step down voltage transformer is used to convert the mains 220 V to the 10 V signal and the current transformer, ASM010, is used to get the current in the Line wire connected to the load via current transformer circuit. In the electrical circuit block, the operational amplifier, LM324, is used to amplify small signals along with other small components like the rectifier, capacitors and gain resistors of certain values. The analog signal outputs are then fed to the analog channels of the ZigBee chip for further communication.

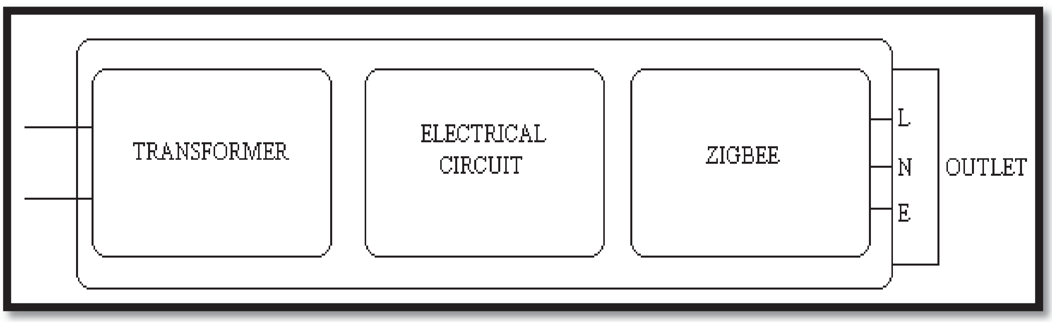


Figure 14: Basic block diagram of the circuit

The XBee Coordinator, a Smart sensor, collects data from the sensing units (XBee end Devices) and forwards it to the computer system for data processing. The proposed sensing unit also displays the time of use of any appliance connected to the sensing unit as shown in figure 16. This operation is based on the detection of current flow to the regularly used connected appliances such as a microwave, water kettle, toaster, room heater, television and dishwasher. The output of the electrical appliance monitoring sensor unit is either ON or OFF based on the use of the connected electrical appliance. Normally, one electric sensing unit is required to sense each electrical appliance.

To minimize the requirement of many sensing units, the sensing unit is designed in such a way that two electrical appliances can be connected to one sensing unit in a single power inlet. This will also help in reducing the overall cost of the system. Intelligence in the sensing unit is provided to detect the activity of the particular device and whether it is ON or OFF. The sensing unit has been tested by connecting a water kettle and toaster through different analog channels of the ZigBee.

The input signal from the sensors are integrated and connected to the XBee module (end device). The measured parameter i.e. Voltage and current are wirelessly transmitted to the XBee Module (coordinator). The coordinator is connected through USB cable of the centralized controller or computer, through which data is stored in the computer database.

By analysing the power from the system, energy consumption can be controlled. A tariff plan can be installed to run various appliances at peak and off peak tariff rates. It can be controlled either manually or automatically.

The smart power metering circuit is connected to a mains 240 V/50 Hz supply. Figure 15 shows the circuit diagram of the Smart voltage and current sensing circuitry.

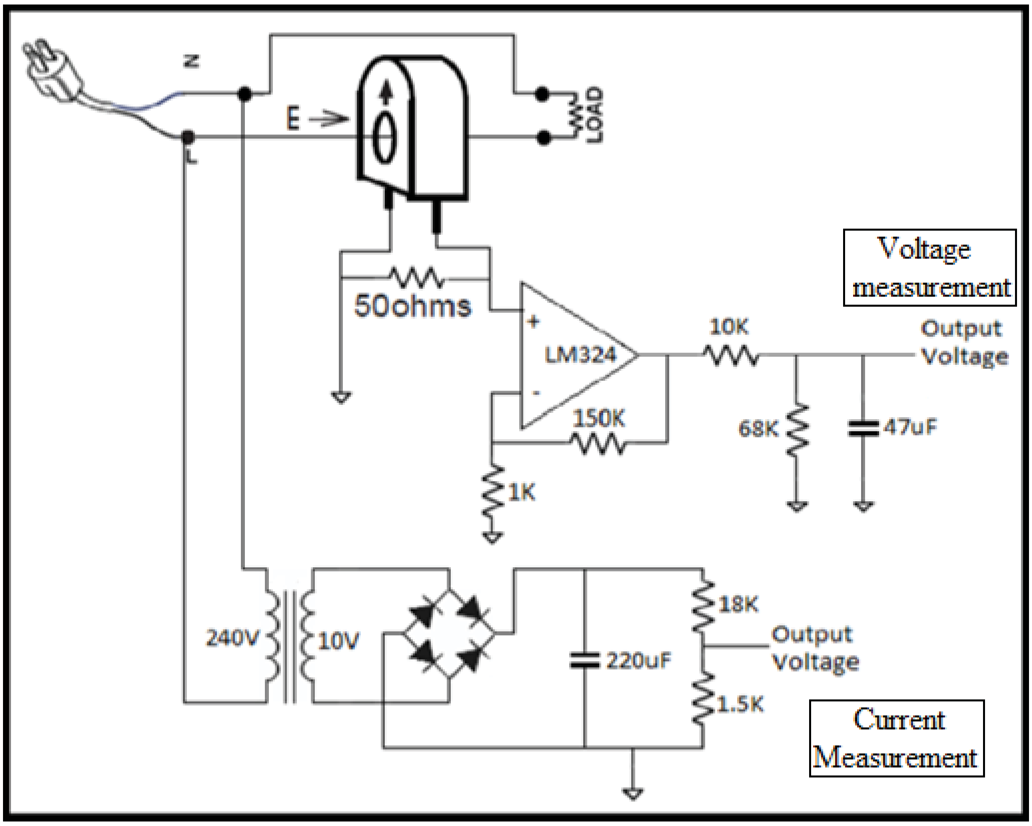


Figure 15: Designed smart voltage and current sensing circuitry

An example is shown below in figure 16, in which an Electrical Room Heater and a Light Bulb are connected to the sensing unit, and the monitored information by the XBee end devices is sent wirelessly to the system coordinator. The output results can be seen on the GUI on the computer system.

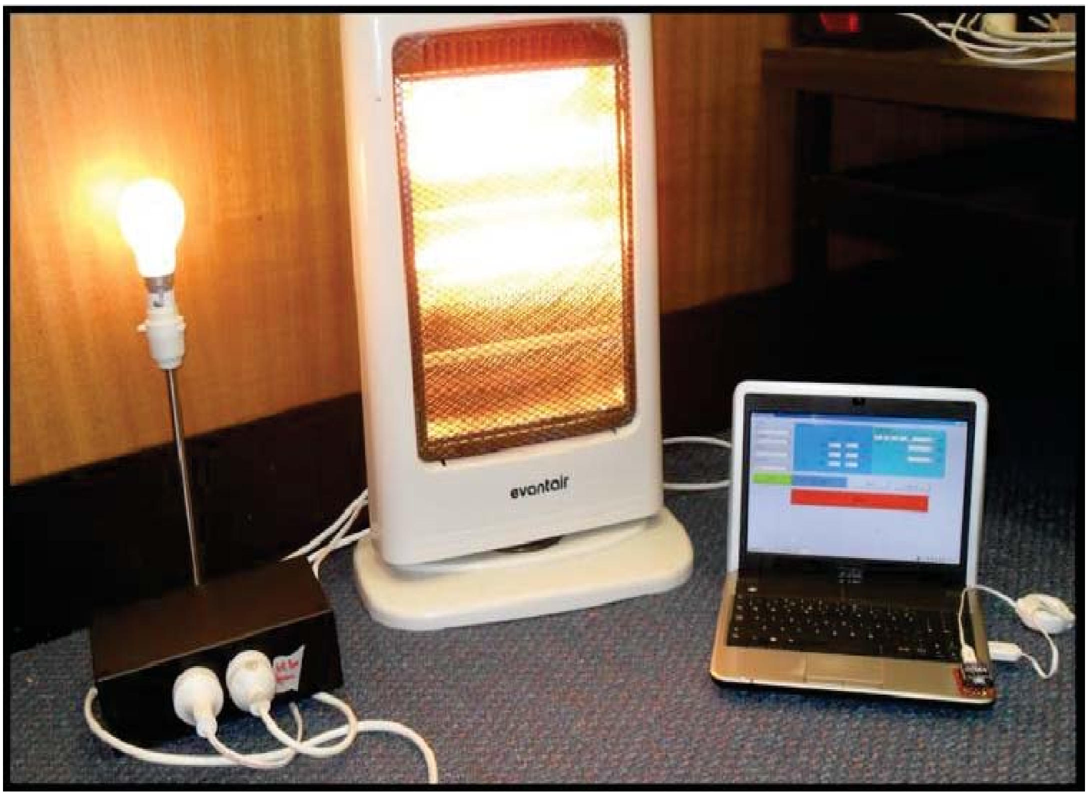


Figure 16: Sensing Unit connected to room heater and electric bulb

4.3 Voltage measurement

Transformers are used to transform alternating current energy from one voltage into another voltage [94]. Transformers come into two basic categories: Step-up and step-down. A step-up transformer has more turns on its secondary winding than its primary winding and is used to increase the AC voltage into a high AC voltage. The amount that the voltage is stepped up depends on the ratio of number of turns on the primary and secondary.

For any transformer,

$$\frac{V_{secondary}}{V_{primary}} = \frac{N_{secondary}}{N_{primary}}$$

On the other hand, a step-down transformer has more turns on its primary winding than on its secondary winding and is used to decrease the voltage into a lower voltage. Transformers are used in many applications such as power supplies, electrical power distribution (from a generated voltage of 11kV to higher values of 132kV, 220 kV, 400 kV, 500 kV and 765 kV for the long distance power distribution), signal coupling in communication systems (as an impedance transformation device to allow maximum transfer of power from the input circuit to the output device) and in measuring input voltages. The basic operation of a transformer is based on the principle of mutual inductance, which occurs when two or more coils are in close proximity [95] and are coupled by magnetic induction. The primary winding is always energized by a sinusoidal voltage signal and the secondary winding feeds the load. The energy transfer from the primary winding to the secondary winding is through the medium of the magnetic field. There is no change in the frequency of the signal.

In this research, the voltage step-down transformer- 44127, manufactured by MYRRA [96] is used. As compared to the other voltage transformers, this voltage transformer has the striking feature of two bobbin compartments including self-smothering plastics. It has a very light weight of 100 grams which makes the sensing unit easy to use. It has a secondary voltage of 2 x 6 V on its output secondary pins and a secondary current 2 x 167 mA. The No load voltage of the 44217 transformer is 2 x 10.4Vrms and the rating is 2VA [97].

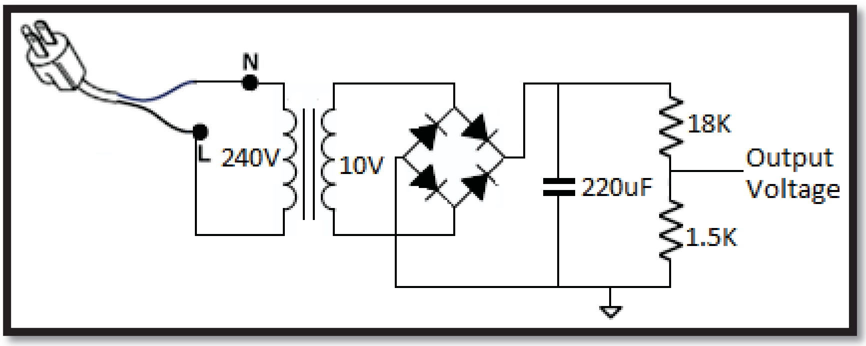


Figure 17: Voltage Transformer circuitry

Figure 17 above shows the circuit design layout for voltage measurement. The step down voltage transformer is used to convert input supply of 240 V to 10 V RMS AC signal which is rectified using a full wave rectifier. The full wave rectifier allows unidirectional current to the load during the entire input cycle. The result of full wave rectification is a DC output voltage that pulsates every half-cycle of the input. The rectified output is then passed through the filter capacitor to get a smooth DC Voltage. There are some limitations for the input channels of the XBee. The XBee only takes the input of no more than 1.2 V so the potential divider at the output signal of voltage transformer is used. This output signal is then fed to the analog input channel of the XBee end device. The acquired voltage signal is directly proportional to the input supply voltage. Experimental results from the voltage transformer showing input vs. output voltage are explained in chapter six of this thesis. The scaling of the signal is obtained from the input versus output voltage graph. The schematic circuit in altium is shown in figure 18.

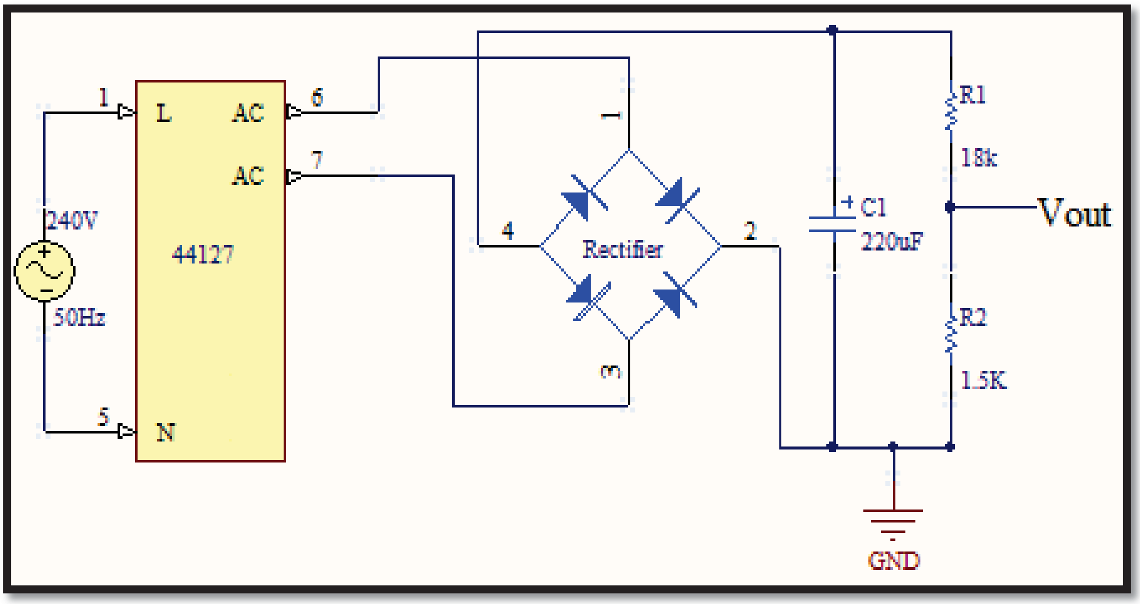


Figure 18: Circuit schematic for voltage measurement

4.4 Current Measurement

It is not possible to allow primary current to flow directly through an instrument for the measurement of high currents. Some of the methods follow the scheme of diverting a small current through resistive shunts, in which case there is no insulation between the high side and the measuring instrument. On the other hand, the current transformers are widely used for the measurement of alternating electric currents. The current transformer produces the reduced output voltage which is directly proportional to the input current. This output voltage can be measured using instruments like an oscilloscope. The current transformer is defined by its current ratio from primary to secondary [98].

Calibration of the current transformer is required to improve the accuracy of the output signal. It is difficult to choose a suitable current transformer with the correct sizing as the magnitude of the current in high inductive loads changes continuously. The current transformer used in this research is an ASM010 manufactured by Talema [99]. Talema provides a wide range of current transformers which are capable of measuring currents up to 100 amps. It is a low cost method of measuring AC current which is less than 100 amps. The main features of this sensor include full encapsulation for the PCB mounting and a compact size. The primary winding and the secondary windings are well insulated from each other. The primary current ratings range from 1 to 10 Amps (in this case) and operating temperature range from -40° C to +120°C. It transforms the line current, which is connected to the load, into output voltages that are suitable for the measurements at the output of the sensor with respect to the input current. The produced output voltage of the current transformer is proportional to the input current. The testing of current transformer, ASM010, has been done at the initial stages of the project to check the accuracy and the necessary calibration. Figures 19, 20 and 21 shows the initial stages of the ASM010 testing with some of the electrical appliances like Electric Room Heater, Electric Kettle and Toaster:

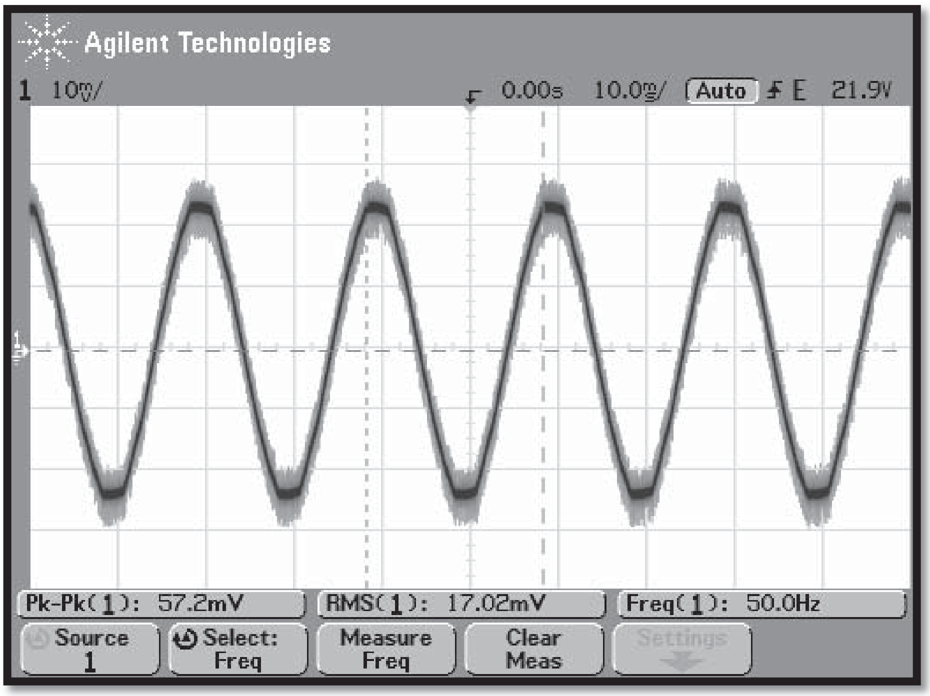


Figure 19: Current waveform of the electric heater

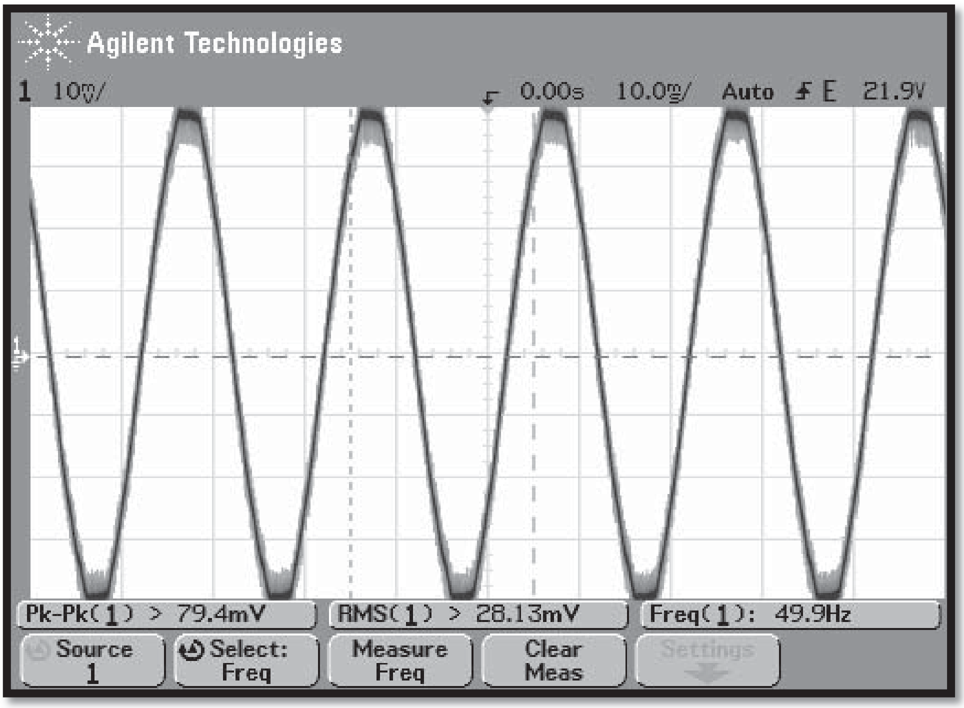


Figure 20: Current waveform of the electric kettle

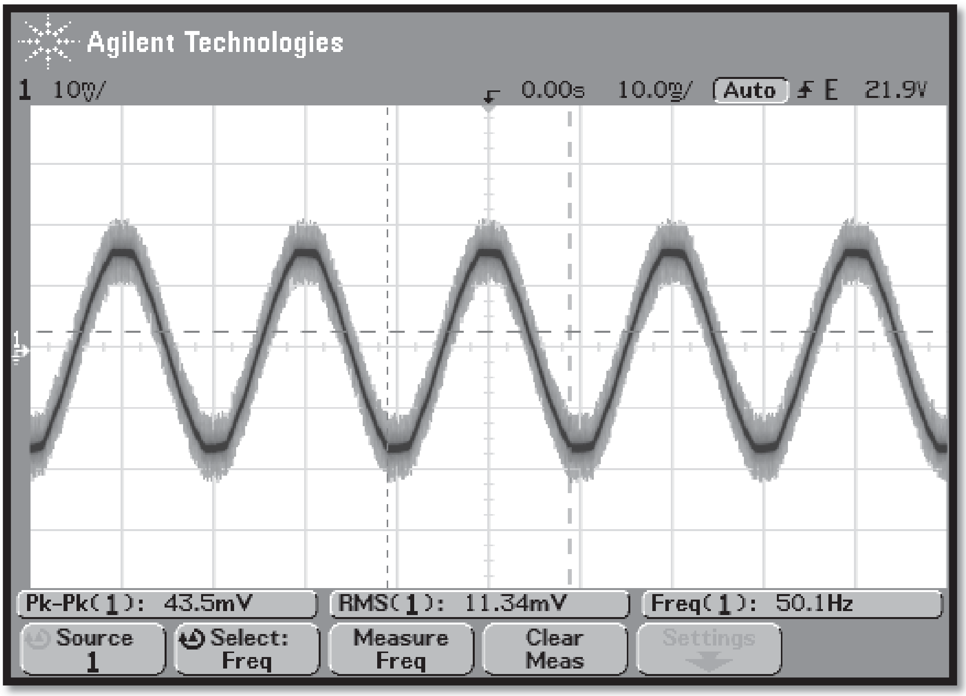


Figure 21: Current waveform of the toaster

A load resistor of 50 ohms is connected on the secondary terminals of the ASM010, so the voltage is measured across this burden resistor with minimal difference in the phase angle. The current transformer circuitry is shown in figure 22.

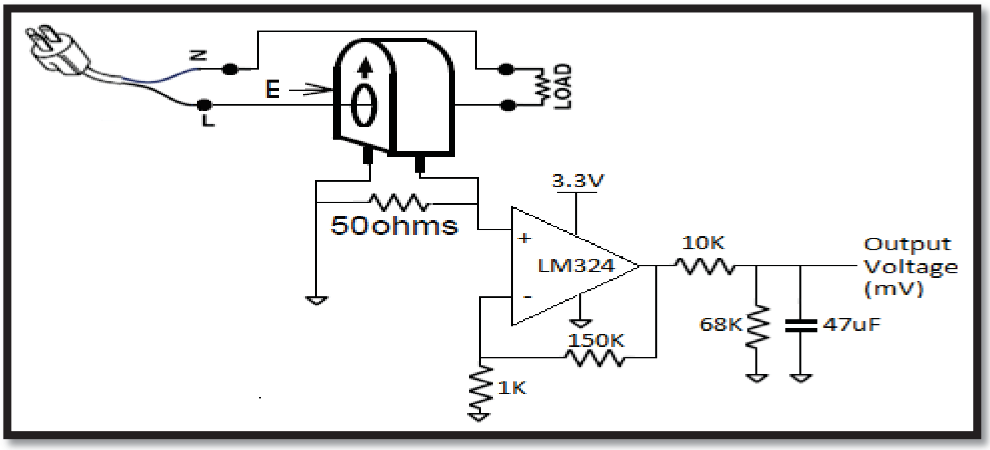


Figure 22: Current Transformer Circuitry

The circuit design layout for current measurement circuit in altium schematic file is shown in Figure 23. The line wire is connected to the load, which passes through the current transformer. When the main power supply is turned on, the current sensor will produce isolations which results in an output voltage at the secondary terminals of the current transformer. The output voltage is proportional to the derivative of the primary transient current and the number of turns on the primary side. The output of the current transformer is a very small signal which needs to be amplified. So the output of the current transformer is amplified by using an operational amplifier, LM324, along with the use of suitable gain resistors. The amplified signal is then fed to the analog input channel of the ZigBee module. The desired voltage settings are achieved by using burden resistor on the secondary side. The sensed output signal is directly proportional to the input current. Scaling is required to get the correct input current of the appliance. The number of turns can be increased on the primary side to increase the resolution of the measured signal. Experimental results are shown in chapter six of this thesis.

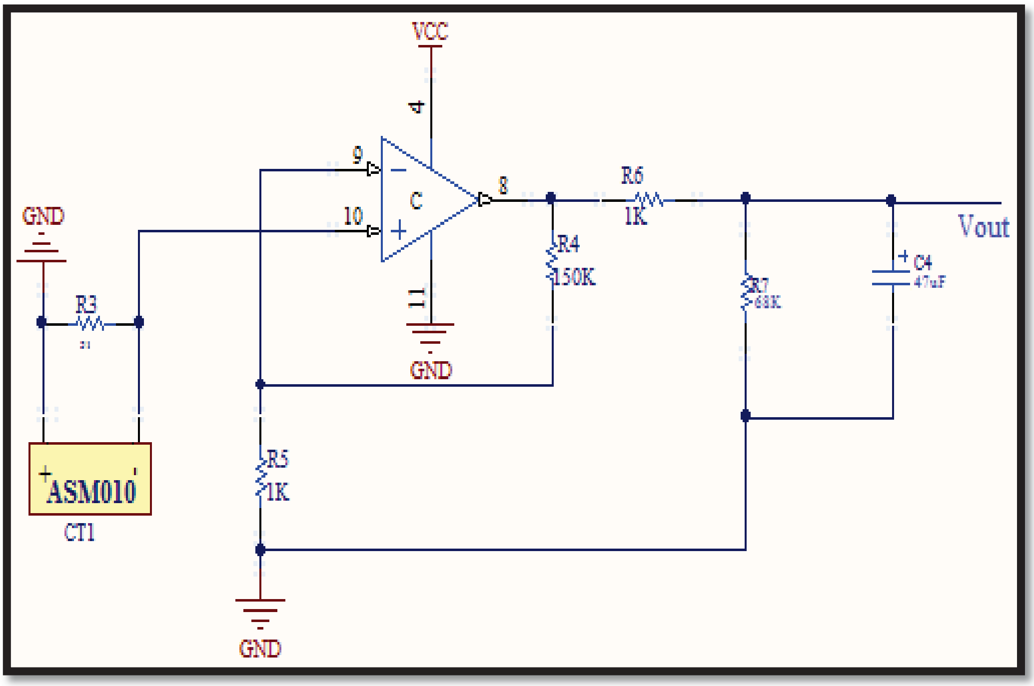


Figure 23: Circuit schematic for current measurement

4.5 Power factor

Power factor is the cosine of the phase angle of the voltage and current waveforms as shown in the Figure 24.

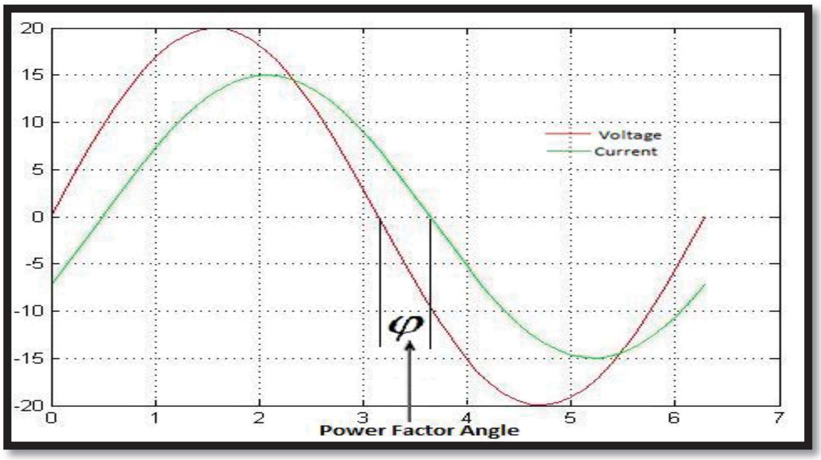


Figure 24: Representation of power factor

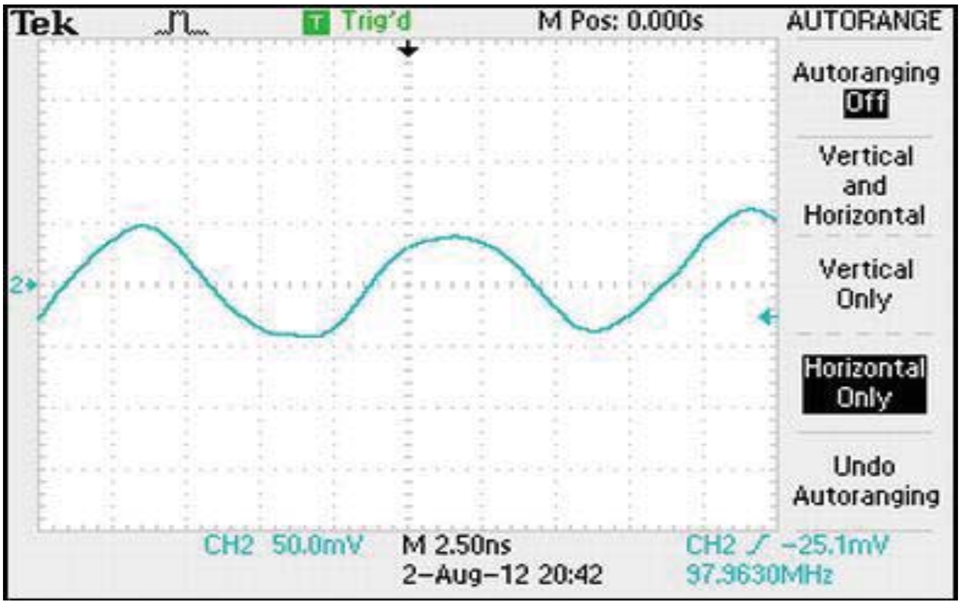
The term 'Cos θ' is called the power factor and is stated as

$$PF = \cos \theta$$

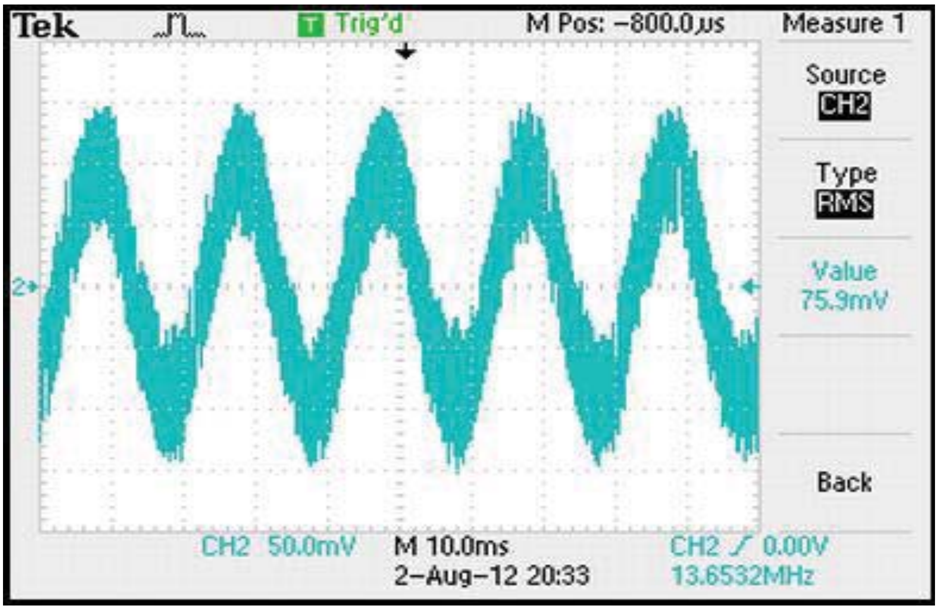
In order to calculate the power of a single phase AC circuit, the product of the volts and amps must be multiplied by the power factor. The method of measurement of the power factor is only applicable on the sinusoidal signals. Today's power supplies have built-in semiconductors, switching devices and power controlling systems causing non-sinusoidal waveforms. Today it is characteristic in most parts of the applications that the current and voltage are non-sinusoidal [100]. As the phase angle between the source voltage and the total current increases, the power factor decreases, indicating and increasingly reactive circuit. The smaller the power factor, the smaller the dissipation. The power factor can vary from 0 for a purely reactive circuit to 1 for a purely resistive circuit. In a RC circuit, the power factor is referred to as a leading power factor because the current leads the voltage.

Apparent power is the power that appears to be transferred between the source and the load, and it consists of two components: a true power component and a reactive power component. True power does all the work in all electrical and electronics system. The reactive power is simply shuttled back and forth between the source and the load [101].

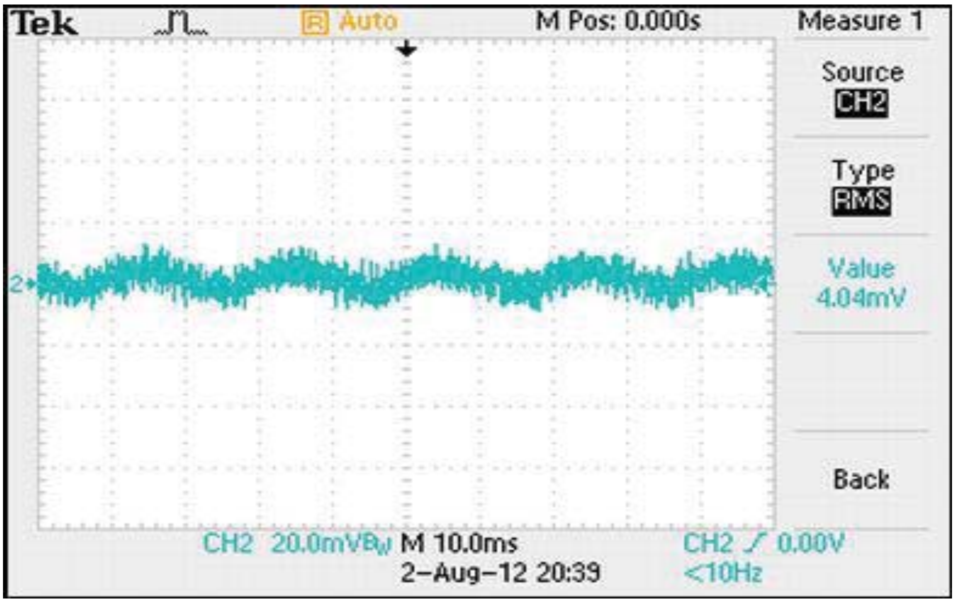
Power factor is 1 if the voltage and current are in-phase. The output signal of the current transformer completely depends on the nature of the connected appliance and whether the connected load is purely resistive, capacitive or is inductive. In most of the cases, the output waveforms are not purely sinusoidal as shown in the Graphs 2, 3 4 and 5. From the graphs, it is inferred that zero-crossing determination is difficult to measure for some of the appliances and elimination of noise is not trivial.



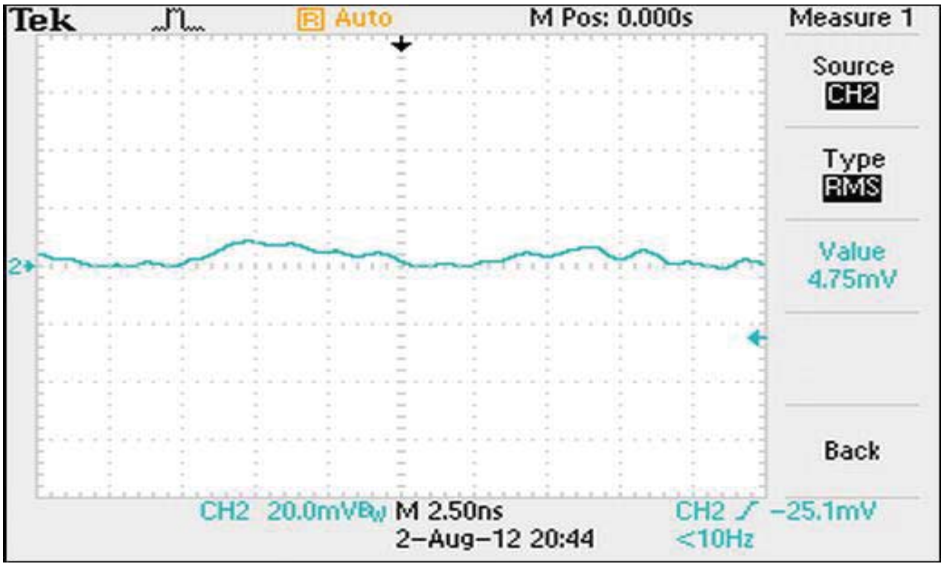
Graph 2: Output waveform of the current transformer for a 60 W electric bulb



Graph 3: Output waveform of the current transformer for a 100 W electric bulb



Graph 4: Output waveform of the current transformer for a 800 W room heater



Graph 5: Output waveform of the current transformer for an audio device

A technique of measuring the power factor by using the microcontroller, PIC16F877, is shown in [102]. In this proposed research, the power factor is not the key indicator as nowadays almost every electronic load contains power supplies, power controlling systems or semiconductors, and shape of the current is non-sinusoidal. Therefore no microcontroller is used in the developed system at the sensing end for processing of data. It is not important for this application to measure power with zero error. Hence, in the proposed work, a correction factor has been introduced instead of measuring the power factor to normalize the received power with respect to the actual power based on the scaling factors of the voltage and current measured. A correction factor is required for the power measurements of some loads only and this can be obtained by plotting a graph for calculated power against the actual power.

4.6 Calculation of power

Power is calculated in the computer system after receiving voltage outputs from the corresponding current and voltage sensors by the following equation:

$$P = (m_1 \times m_2 \times v_1 \times v_2) \times C_f \tag{1}$$

Where

P = Calculated power

m_1 = Scaling of the signal from voltage transformer to get the input Voltage

m_2 = Scaling of the signal from current transformer to get the input current

v_1 = Output voltage from the voltage circuit

v_2 = Output voltage from the current circuit

C_f = Correction factor

The scaling factors (m_1 and m_2) from both outputs are multiplied with the corresponding output signals to calculate the power. The correction factor is introduced to calculate the power accurately by the system. The correction factor is the ratio of reference power to the measured power.

The power is calculated using C-Sharp programming after receiving voltage outputs from the corresponding current and voltage sensors. Scaling factors from both outputs are multiplied with the corresponding output signals to calculated the power.

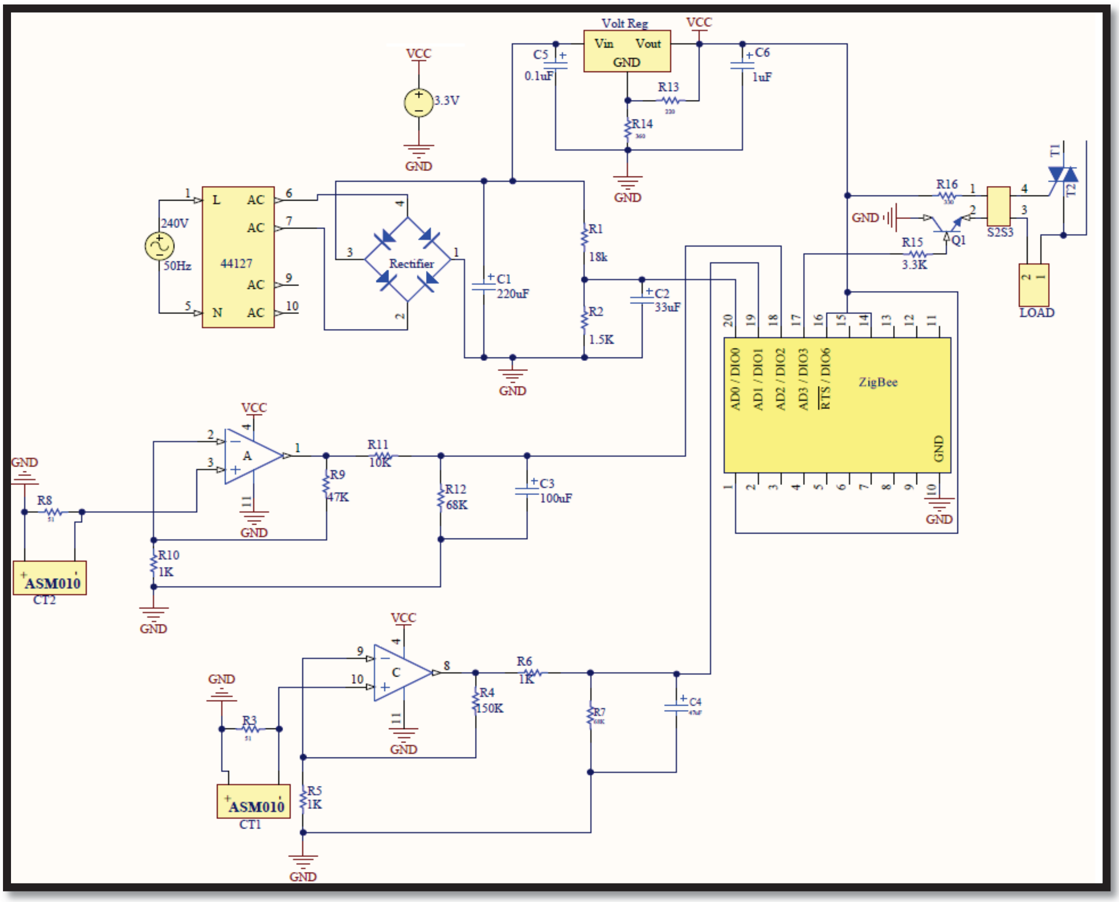


Figure 25: Circuit schematic of developed system

Figure 25 show the schematic of the prototype and Figure 26 represents the fabricated system with the integrated sensing circuit and the ZigBee module on printed circuit board (PCB). There are two current transformers used in the developed system. The reason for using two transformers in the same circuit is because the resolution of the output waveform for low load needs to be increased by increasing the number of turns on the primary channel of current transformer for the loads up to 100 W. The other current transformer is used for measurements of loads from 100 W to 2000 W with only one turn at the primary side. Both outputs from the current transformers are fed to the analog input channels of ZigBee.

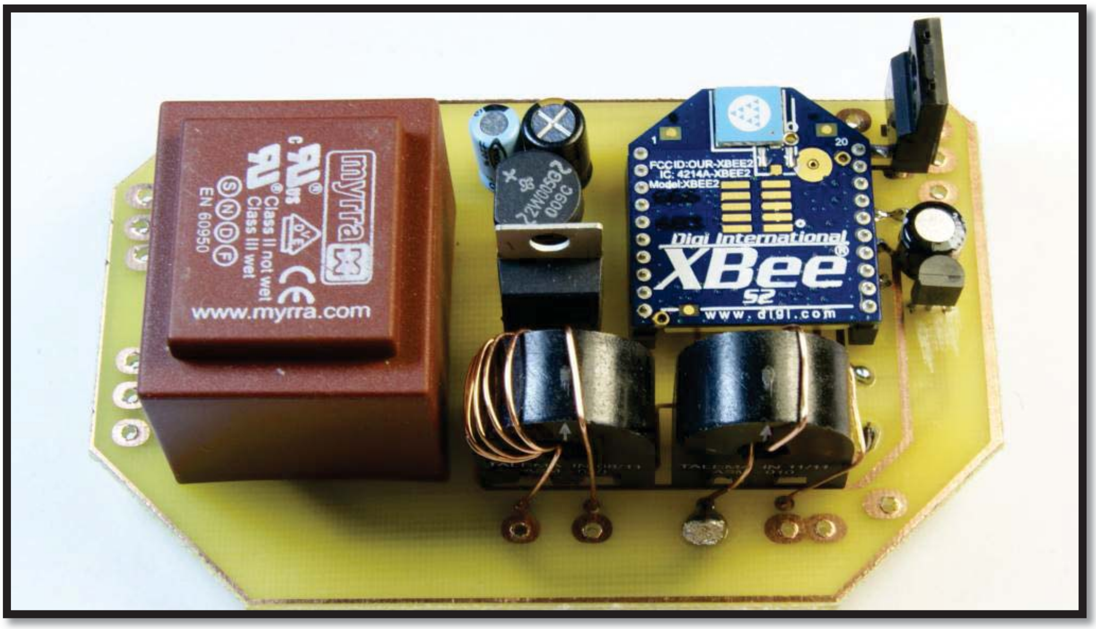


Figure 26: Fabricated PCB for smart power monitoring unit

4.7 Function and power requirement of ZigBee Module

Both the ZigBee module and the operational amplifier require a 3.3 V DC power supply for their operation. For this requirement, a voltage regulator, LM317, is used. The voltage regulator is connected to the rectified output of voltage transformer to give a precise voltage output of 3.3V. The XBee takes all three signals from the current and voltage transformer and send those signals wirelessly to the XBee coordinator. The configuration of XBee coordinator and the XBee end devices are shown in the chapter 3. Once the configuration is complete and all the XBee modules within a set are in the same network, communication can be started. The end devices are connected to the appliances and the XBee coordinator is connected to the computer system. End devices take the voltage and current signals from the connected appliances and send them to the coordinator. The coordinator receives the information and sends it to the computer system via a USB cable. The computer stores all the information in the computer database for further processing. Controlling the XBee via its digital channel is discussed in the next chapter.

4.8 Conclusion

The main objective of this research is to develop a control mechanism for the optimization of power consumption in a household in such a way that costs are minimized for the users, and grid stability is improved. We refer to a flexible job as a task with a load profile that the user requires to be finished within a deadline. Given a number of flexible jobs, a price signal, an optional local micro-generation profile and an imposed load shape, the local scheduler will schedule the flexible jobs such that the cost is minimized, and imposed load shape is respected. The algorithm will be evaluated in terms of its computational and timing characteristics.

Chapter 5

Controlling of the appliances

In this chapter, the Mechanism used to control the power consumption within an average household during this research is presented. Variety of control mechanisms provided on the sensing unit is discussed briefly.

5.1 Introduction

ZigBee wireless communication technology has been used in the control application of the electrical appliances in the proposed research after realising the wireless link between the end devices connected to the electrical appliances located everywhere in a house and the control unit. An algorithm was developed to generate a digital signal from the XBee coordinator which is then received by all XBee end devices within the network and further action can be taken by the end devices. The user can control most of the electrical appliances from a centralized controller via a computer system's GUI simply by clicking the ON or OFF button provided by the software. The entire monitoring and control of a home electrical appliance is digitally based on the computer to which the XBee coordinator is connected. C# (C Sharp) programming has been chosen as the control interface between the user and the system. C Sharp provides simple and neat programming to communicate with the rest of the component block.

5.2 Components used for controlling

In the solution, power consumption within a household is minimized by controlling various appliances used in the household for certain period of time. The components used for controlling are an optical photo coupler switch, S2S3, and a BT138-800E triac. The decision to use these components was made after analyzing different types of control applications such as the use of relay circuits.

5.2.1 Triac BT138

The BT138 triac is used in the system for the switching ON or OFF of the electrical appliance. The BT138 is a Planar Passivated sensitive gate four quadrant triac and is very reliable for use in general purpose bidirectional switching and phasor control applications [103].

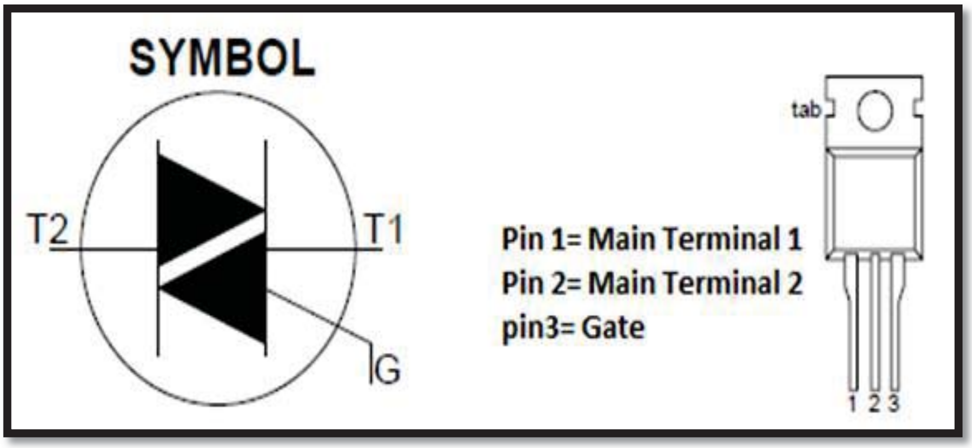
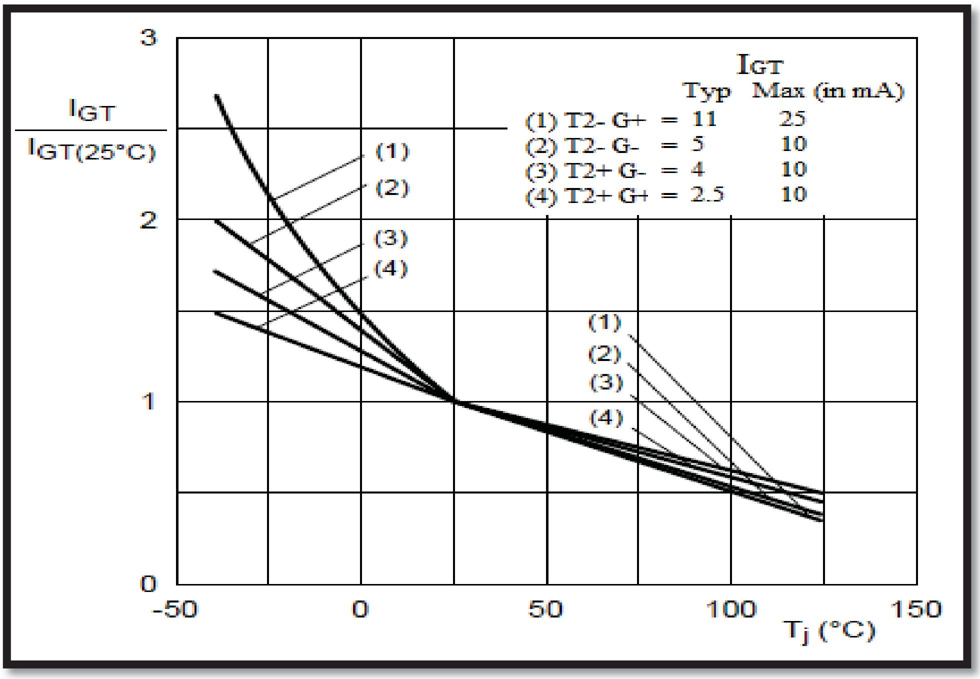


Figure 27: Pictorial view and Symbol of Triac BT138

This particular "series E" is intended for use in low power gate trigger circuits. The triggering is direct from low power drivers and logic ICs. It has the capability of blocking high voltage. The appropriate design in the sensor control unit is provided to minimize any risk. The BT138-800E has been tested in the control application of the proposed research on the breadboard. It is very reliable for the use in control current values of up to 12 amps. The pictorial view and symbol of BT138-800E is as shown in the Figure 27.

5.2.2 Characteristics of BT138

The Gate Trigger Current (I_{GT}) is the gate current required to switch the device from a blocked state to the unblocked state i.e. from OFF to ON. The triac will go to the OFF state when the current drops to zero. To operate the triac again, a triggering current is required which should be above the holding threshold. The Holding Current (I_H) is the minimum current which must pass through the device in order for it to remain in the 'ON' state [104]. I_{GT} of the BT138-800E is typically 2.5 mA and the holding current I_H is typically 6.0 to 30 mA [103]. Graph 6 shows the gate trigger current characteristics of the BT138-800E with respect to the junction temperature showing the values of different gate trigger currents.



Graph 6: Gate Trigger Current as a function of Junction Temperature

5.2.3 Phototriac Coupler Switch S2S3

S2S3 is a very small four pin optical photo coupler coupled by an infrared emitting diode (IRED). This photo coupler is used for the triggering of the BT138-800E as the applications of the S2S3 are intended for use in triggering the triacs used to control AC loads. The SOP package of the S2S3 provides 3.75 kV of isolation from the input to the output with superior noise immunity [105]. The symbolic representation and the picture of S2S3 opto photo coupler is as shown in figure 28.

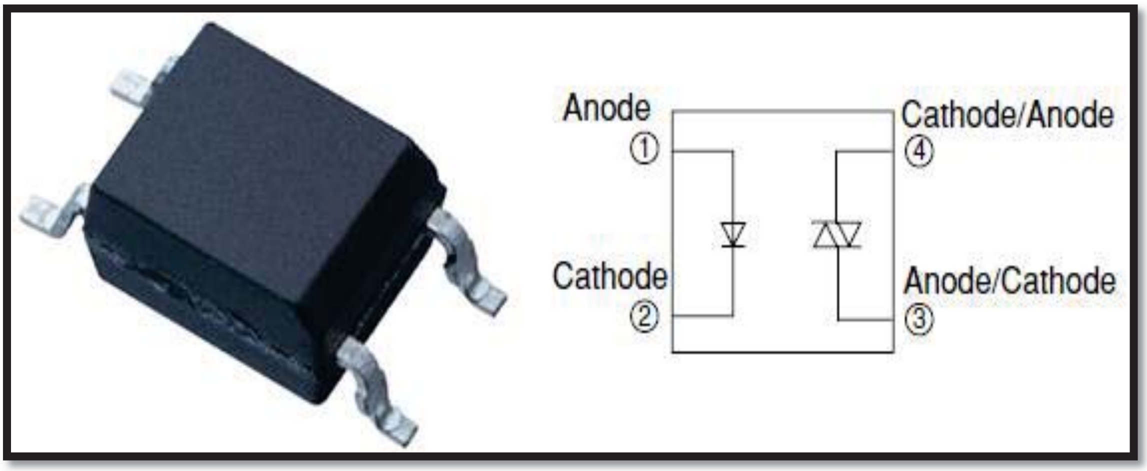


Figure 28: Pictorial view of S2S3 Phototriac coupler and its Symbol

The S2S3 goes to the OFF state when the triggering current is less than or equal to 0.1 mA. A snubber circuit is included to reduce excessive noise or sudden changes. This component requires a very gentle and quick hand soldering technique as it should be soldered within two to three seconds to avoid the overheating of the component. Figure 29 shows the method of using the S2S3 photo coupler switch to drive the high power triac.

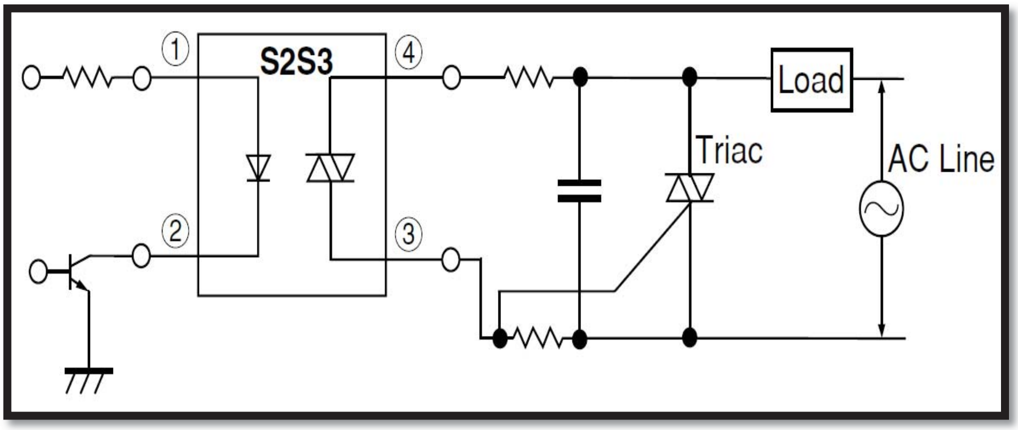
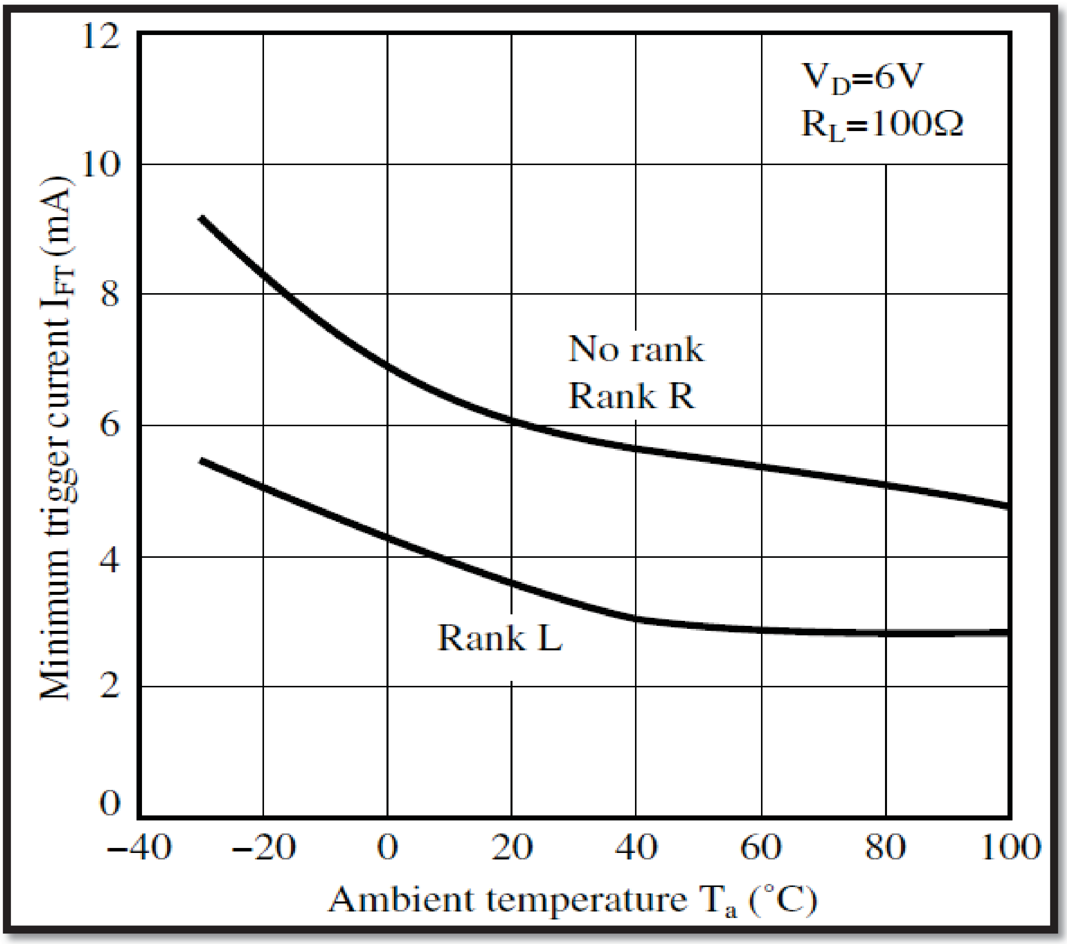


Figure 29: Standard Circuitry of S2S3 with Triac

5.2.4 Characteristics of the S2S3

The Input Forward Voltage (V_F) for the S2S3 is 1.2 to 1.4 V and the Holding Current (I_H) is 0.1 to 3.5 mA. The turn ON time for the S2S3 is less than 100 µs. Graph 7 shows the transfer characteristics of the S2S3 showing the minimum trigger current with respect to the ambient temperature.



Graph 7: Minimum trigger Current vs. Ambient Temperature

In the developed circuit an NPN transistor, BC-337, with the base resistance of 3.3K ohms is used to trigger the S2S3 switch. The base voltage is approximately 0.6 V for the BC-337. A small amount of supply current flowing from the base is enough to trigger the S2S3 switch which in turn triggers the BT138-800E triac.

5.3 PCB File showing control components in the developed circuit

Figure 30 shows the final PCB print for the project prototype. The PCB print shows the footprints of the components used for the controlling of the electrical appliances i.e. S2S3 and Triac BT138-800E.

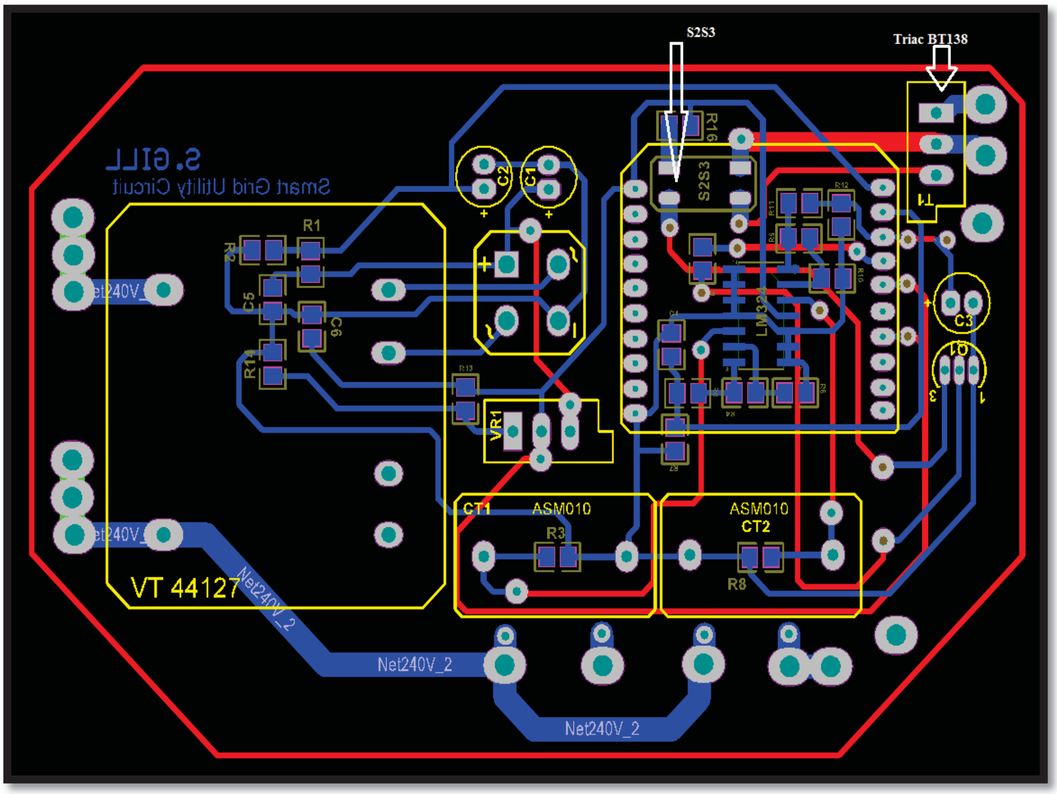


Figure 30: PCB File showing S2S3 and BT138 assembly

5.4 Different Control Algorithms

The designed system is flexible in that, depending on the needs of the user, the devices can be controlled in the following ways:

- Automatic Control: Based on the electricity tariff conditions, the appliance can be regulated with the help of Smart software. This enables the user to have increased cost saving by automatically switching off the appliances during the electricity peak hours without any direct user interaction. The electricity tariff is procured from the website of the electricity supply company and is updated at regular intervals.

- ❖ Manual control: An on/off switch is provided to directly intervene with the device. This feature enables the user to have more flexibility by having manual control on the appliance usage without following automatic control. With the help of the GUI software developed for monitoring and controlling, the user can control the device for its appropriate use. This feature has the higher priority to bypass the automatic control.
- ❖ Remote control: The Smart monitoring and control software has the added feature of flexibility of access. The user is able to access the software remotely through the Internet (website) via a secure Internet web connection. The user can monitor the state of all appliances and adjust control as is necessary, thus avoiding any case of leaving appliances turned on while away from the house.

5.5 Role of ZigBee

The ZigBee operates in two different modes, FFD (Full Function Device) and RFD (Reduced Function Device). The ZigBee coordinator always operates in FFD which means it always listens to the end devices. End devices operate in RFD mode which means when the connected appliances are not in use, the connected XBee module goes into sleep mode until the next command is sent by the XBee coordinator. The XBee module plays an important role in controlling electrical appliances. When the user selects an ON signal from the system GUI, the coordinator sends a digital high signal on the seventeenth channel, which is a digital I/O pin, of XBee. When pin 17 on the XBee end device is on digital high, it sends an ON command to the triac which then turns the connected electrical appliance ON. The appliance will remain in the ON state until the coordinator sends a digital low signal on pin 17 of the XBee chip. The sending of signal can be done manually (by selecting ON or OFF from the system GUI) or it can be done by following a tariff plan in which case the controlling will happen automatically.

5.6 Purpose of Manual Switch

Manual switching is provided on the system hardware, as seen in Figure 31. This manual switch is connected in parallel to the triac circuitry. The purpose of the manual switch is entirely based on the user requirement.

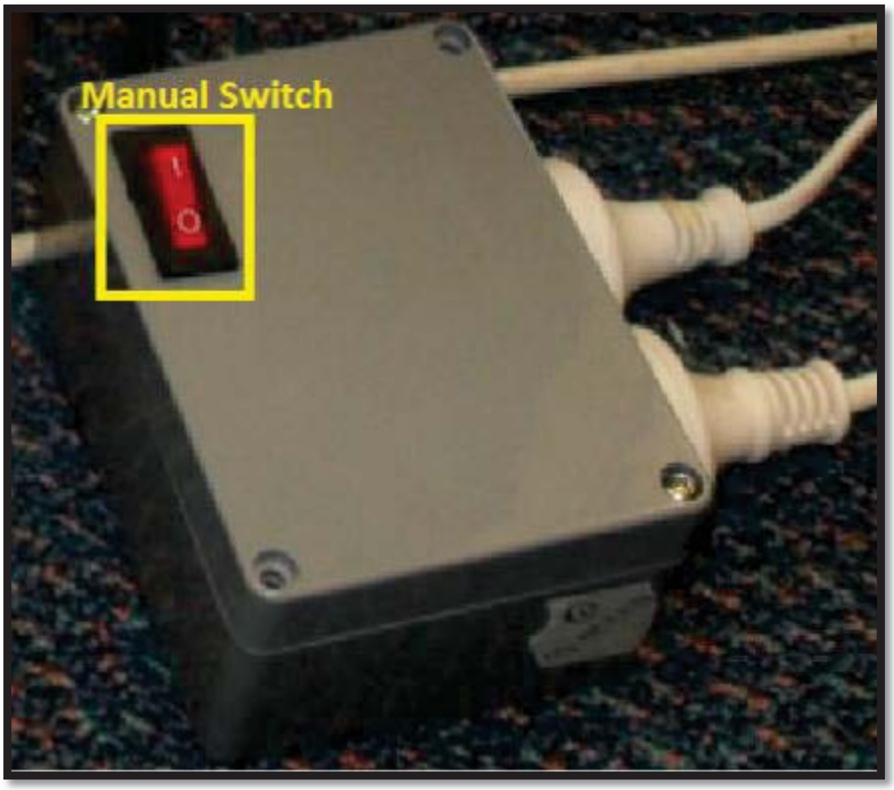


Figure 31: Hardware Unit showing the Manual Switch

If, for any reason, the user decides to turn their appliance ON at any time, it can be done by switching the manual switch ON. This essentially overrides the unit and there will be no control of the power consumption until that switch is turned OFF again. When the switch is turned OFF, the system goes into the original state where it starts following the tariff plan and the control over power consumption will start following the tariff rates again. An electricity tariff has been set to run various appliances at peak and off peak tariff rates.

5.7 Conclusion

In conclusion, the average household user can decide when to turn ON or OFF an electrical appliance using the proposed method through a centralized controller. The load is connected to the BT138 triac through the system. Depending on the user requirements, the appliances can be monitored or controlled in different ways as mentioned in the previous section. More research is being done to allow the user to monitor and control the consumption of power in a household from anywhere in the world through the Internet. The present system can only monitor and control home communication devices, but research is ongoing in to the support for multimedia content and on the security policy on users' authority for each device. The latter being the priority.

Chapter 6

Experimental Results and Analysis

The parameters obtained from the XBee Coordinator after receiving the data from Current Sensor and Voltage Sensor through XBee End Devices is plotted and scaling required for the signal outputs is shown in this chapter. Introduction of the Power Correction Factor to get the actual values of power is also explained and the corresponding results are verified with results obtained from a traditional parameter measuring device.

6.1 Introduction

In the previous chapter the design of the Smart power monitoring unit, using wireless sensor networks, has been explained. In this chapter, the data obtained from the circuit and its analysis is presented. The results from both sensors are plotted and a correction factor for calculating the power will be introduced. The data is collected by the Smart coordinator unit which saves all the information in the computer system's software, or database, after monitoring the consumption of power of the individual appliances by the end device connected to it in the household. The number of sensors used to collect data is kept at a minimum. This, combined with intelligent data analysis reduces the overall cost of the sensing unit, which makes it more affordable to anyone using that system. More sensors can be added to the system but cost will increase accordingly. Increasing the number of sensors will lead to overflow of data which may be hard to manage. In the proposed sensing unit, the parameters which will be entered in the data coordinator software include voltage, current and the calculated power. These parameters will be stored in the database and analysed.

6.2 Connection of electrical sensing unit to the appliances

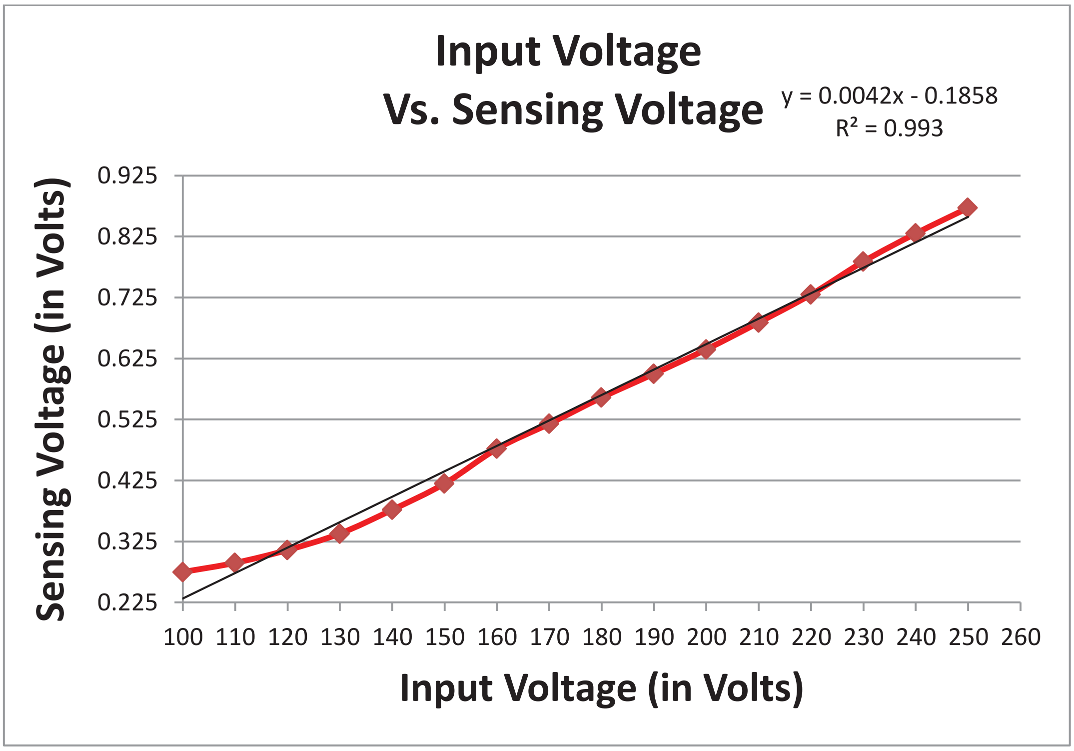
Figure 32 shows the electrical appliances in an average household connected to the Sensing unit installed. Sensing unit hardware is designed in such a way that the user can connect two appliances at the same time to each sensing unit. Electrical parameters from both appliances connected to same sensing unit can be monitored instantaneously through the system's graphical user interface (GUI). The user can also detect the time frame that a particular appliance is ON.

Figure 32: Connected electrical devices to the sensing unit

The electrical sensors are integrated with the ZigBee modules to collect the household electrical appliance data at the centralized coordinator.

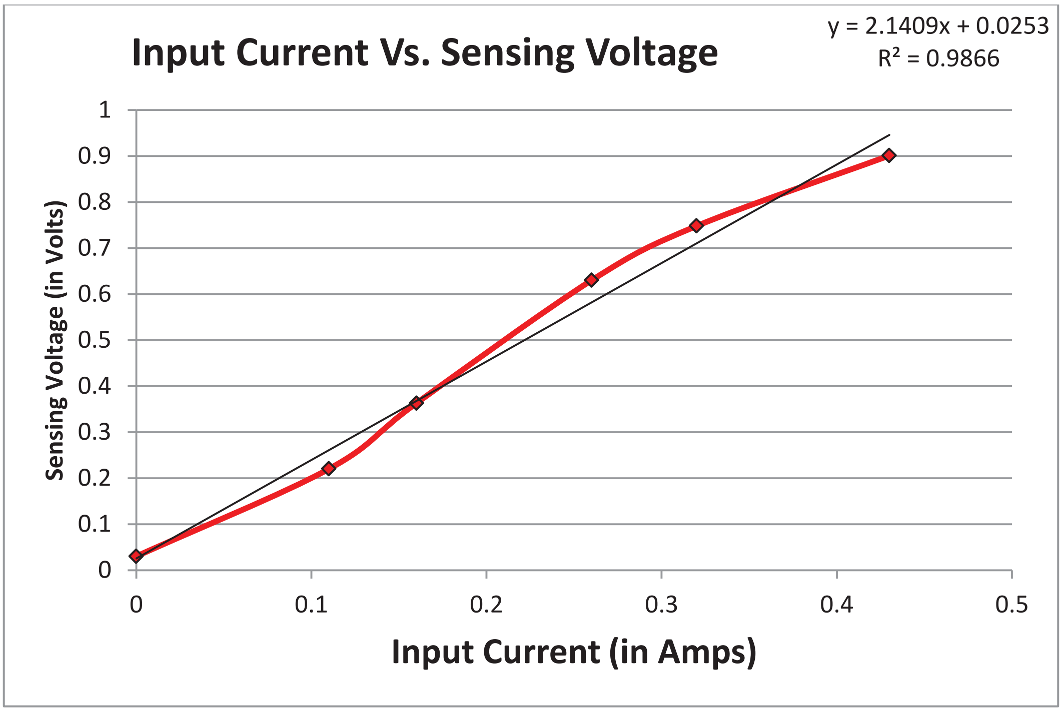
6.3 Data Reception

This section shows the type of data received at the system's GUI. Graph 8 below shows the output characteristics of the voltage transformer 44127. From the graph, it is very clear that the output of the transformer is directly proportional to the input voltage. The output signal of voltage transformer is fed to the analog channel of the XBee end device on pin number 20 of XBee chip.



Graph 8: output waveform of voltage transformer

As the system is designed for the measurement of current of two different types of loads i.e. Low Load and high Load, the data obtained from the low load electrical appliance is plotted as shown in Graph 9. From the data obtained from the graph, it is concluded that apart from measuring power factor, scaling of the signal is required get the actual current values of the connected appliance.

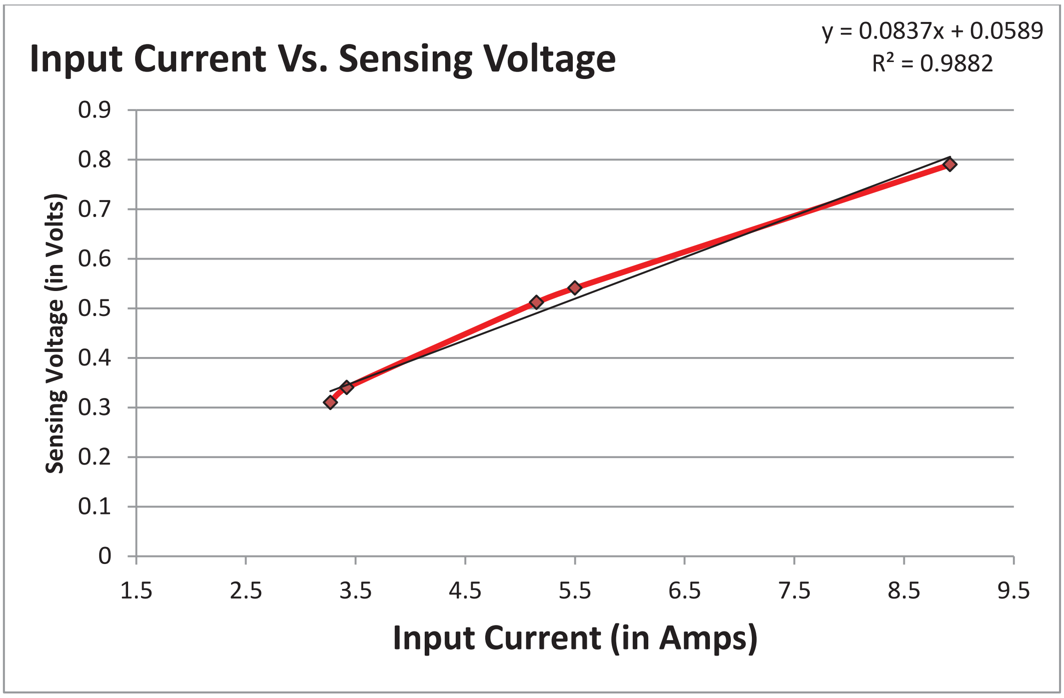


Graph 9: output waveform of current transformer-1 for Low Loads

Graph 10 shows the results obtained from the high load current. Most of the parameters are linear. However, the scaling of the signal is also introduced for high load current to get the actual values. The scaling factor is defined as the ratio of the actual value to the received value.

$$\text{Scaling Factor} = \frac{\text{Actual Value}}{\text{Received Value}}$$

The scaling factor is very important as otherwise the XBee coordinator will receive faulty values and it will be difficult to differentiate the activity of the two different devices, and determine which one is ON.



Graph 10: output waveform of Current Transformer-2 for High Loads

Table 3 shows some test results that were done in the initial stages of the XBee testing. The test results shows the actual voltage values received at the XBee output. The results obtained are relevant to the actual values. The hexadecimal values are received on either pin 18 and 19 of the XBee coordinator chip, depending on the load connected.

Table 3: XBee test results for current output signal

Voltage Signal (ASM010 Output)	XBee Output (Hexadecimal Values)	Decimal Value	Current Value = (decimal Value x 1.2)/1023
1.1 V	03BB	955	1.12
1 V	032A	810	0.950
0.9 V	02EB	747	0.88
0.8 V	02A1	673	0.79
0.7 V	0245	581	0.69
0.6 V	01E2	482	0.58

The hexadecimal values are then converted into the decimal values and then the output value can be retrieved from the XBee data frame by the following formula:

$$\text{Output Current} = \frac{\text{Decimal value X 1.2}}{1023}$$

6.4 Correction factor

The correction factor is the ratio of the actual, or reference power, to the calculated power. As can be seen from the data provided, there is a variation between the actual power measured by some traditional device and the calculated power. The correction factor is required for the power measurement for some loads. This correction factor can be obtained by plotting a graph for calculated power against the reference power. The prototype has been tested and the results gained for certain home electrical appliances. Table 4 below shows the percentage error for all measured parameters with the corresponding references. From the very low percentage error of power, it can be decided that power can be calculated without considering power factor and without introducing the microcontroller. The error percentage is minimal for most of the loads. It is observed that the correction factor value for a high load is different from a low load. The obtained value for the correction factor is multiplied by the calculated power through the C# (C sharp) program and the final value can be seen on the developed GUI on the computer system.

Table 4: Percentage error of received voltage, current and measured power

Appliance	Ref. Load (W)	V ref (V)	I. Ref (amps)	Mea. Vol (V)	%Error-Voltage	Mea. Cur (amps)	%Error-Current	Cal. Power (W)	%Error-Power
Bulb	25	229	0.11	229	0	0.11	0.00	25.19	0.76
Bulb	36	229	0.16	230	0.44	0.17	6.25	39.1	8.61
Bulb	59	229	0.26	229	0	0.27	3.85	61.83	4.80
Bulb	73	229	0.32	229	0	0.32	0.00	73.28	0.38
Bulb	98	228	0.43	229	0.44	0.42	2.33	96.18	1.86
Heater	401	226	1.73	225	0.44	1.82	5.20	409.5	2.12
Heater	755	223	3.41	222	0.44	3.45	5.86	781.91	3.56
Heater	1155	224	5.15	223	0.44	5.16	6.43	1145.23	0.85
Toaster	811	226	3.49	226	0	3.56	1.17	808.97	0.25
Toaster	665	234	2.90	235	0.43	2.73	2.01	658.72	0.94
Heater	733	236	3.11	237	0.42	2.91	0.19	703.1	4.08
Heater	1217	235	5.19	236	0.43	5.05	2.70	1192	2.05
Heater	1902	233	8.17	234	0.43	7.83	4.16	1869	1.74
Kettle	1995	233	8.72	233	0	8.18	6.20	1917.2	3.90

6.5 ZigBee Data Format

The ZigBee coordinator receives data in the hexadecimal format. To retrieve the data from that hexadecimal information, it is essential to understand each and every bit of that data frame. Figure 33 shows a screenshot of X-CTU terminal and figure 34 shows an individual data frame.

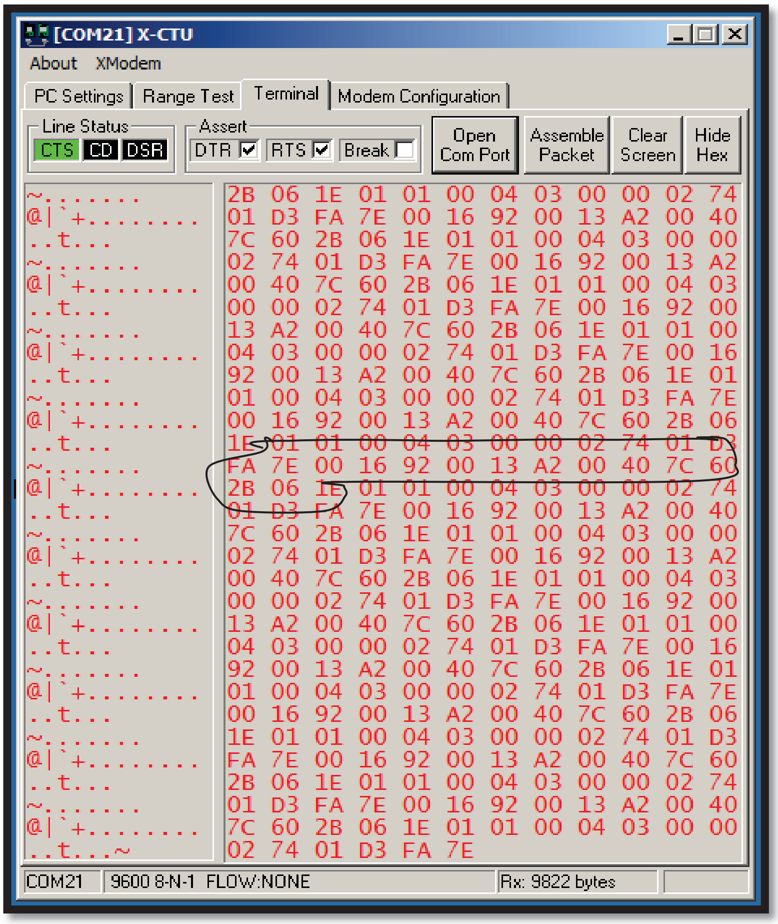


Figure 33: X-CTU terminal Displaying Sensor Hex Values

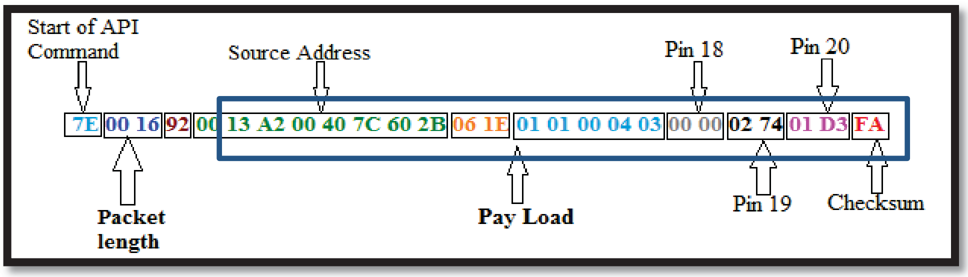


Figure 34: XBee Coordinator Data Format

A brief description of the packet structure is given below [106]:

- Start of the API command: As the data contains information in the form of packets, every packet begins with 0x7E. Everything before it is discounted.
- Command Length: The next two bytes after the start of API contain the length of the rest of the packet, without the checksum.
- Command Body- All the data bytes without the Checksum contains specific API

command information.

- ❖ Checksum: The sum of all the bytes after the command length, including the checksum should be 0xFF. The checksum can be calculated by adding all the bytes after command length and keeping only the least significant 8 bits and subtract it from 0xFF [106].

6.6 Displaying of the data

The monitored electrical parameters will be displayed on the GUI window. The appropriate actions, such as turning devices ON or OFF, are taken from the GUI running on the computer.

The processing of the voltage readings are processed using C# programming. Figure 6 shows the prototype being tested. The room heater and the light bulb are both connected to the sensing unit and the relevant parameters can be seen on the display as shown in Figure 35. The screenshot of the developed GUI with the status of each electrical appliance is shown in Figure 36. The user can select the individual appliance to check the incoming voltage, current and the power consumed for that particular device. The system is based on the tariff plan provided by the service provider, which means the electrical appliances can be turned ON or OFF automatically through the programming depending on the average usage. Manual control of the electrical appliances is also provided on the GUI so that the user can select any appliance to turn ON or OFF at any time regardless of the tariff information.

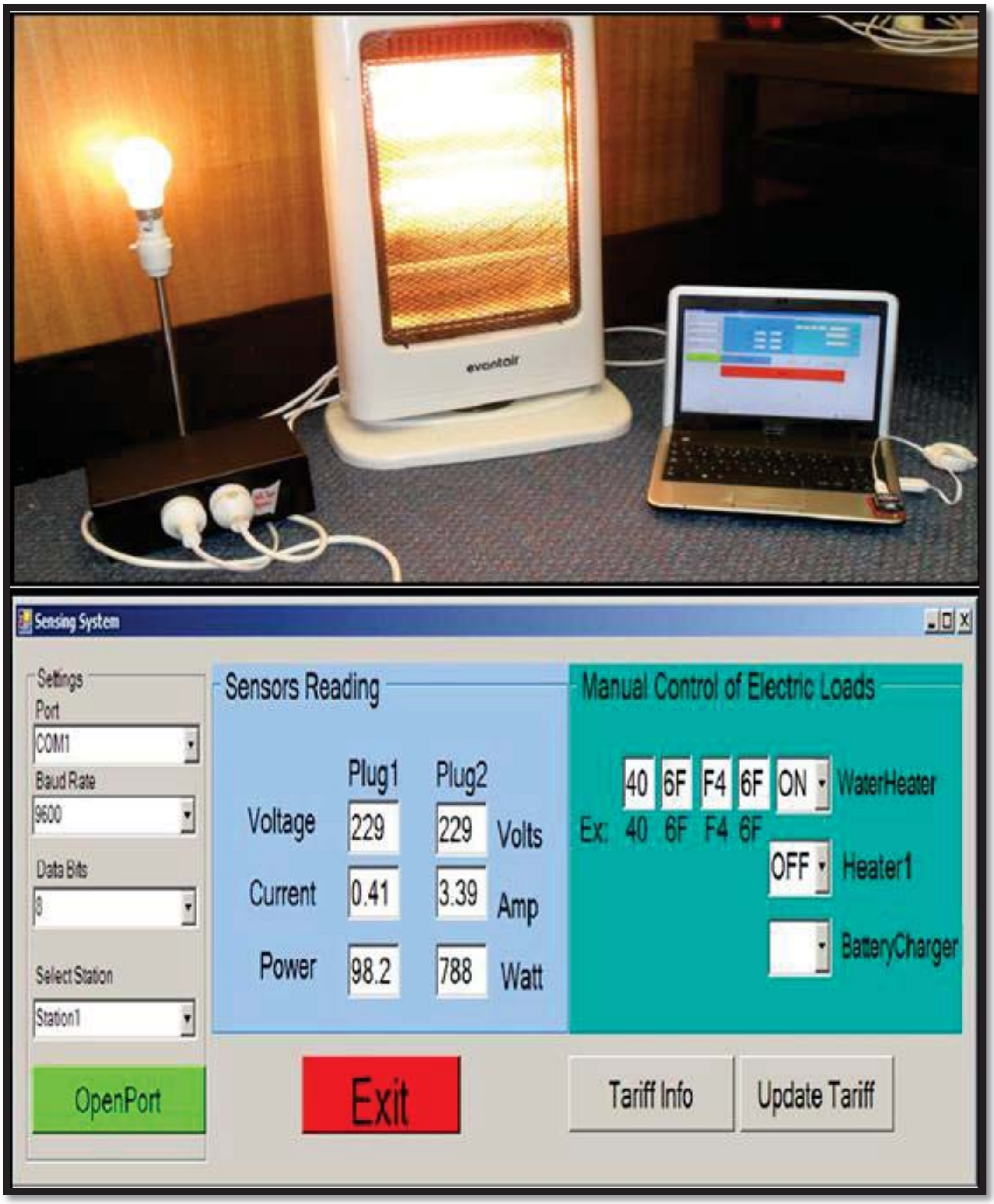


Figure 35: Prototype of the Smart power monitoring system and Graphical User Interface

Multiple devices can be monitored on the same GUI. The figure given below shows majority of appliances used within a household and the control of electrical loads.

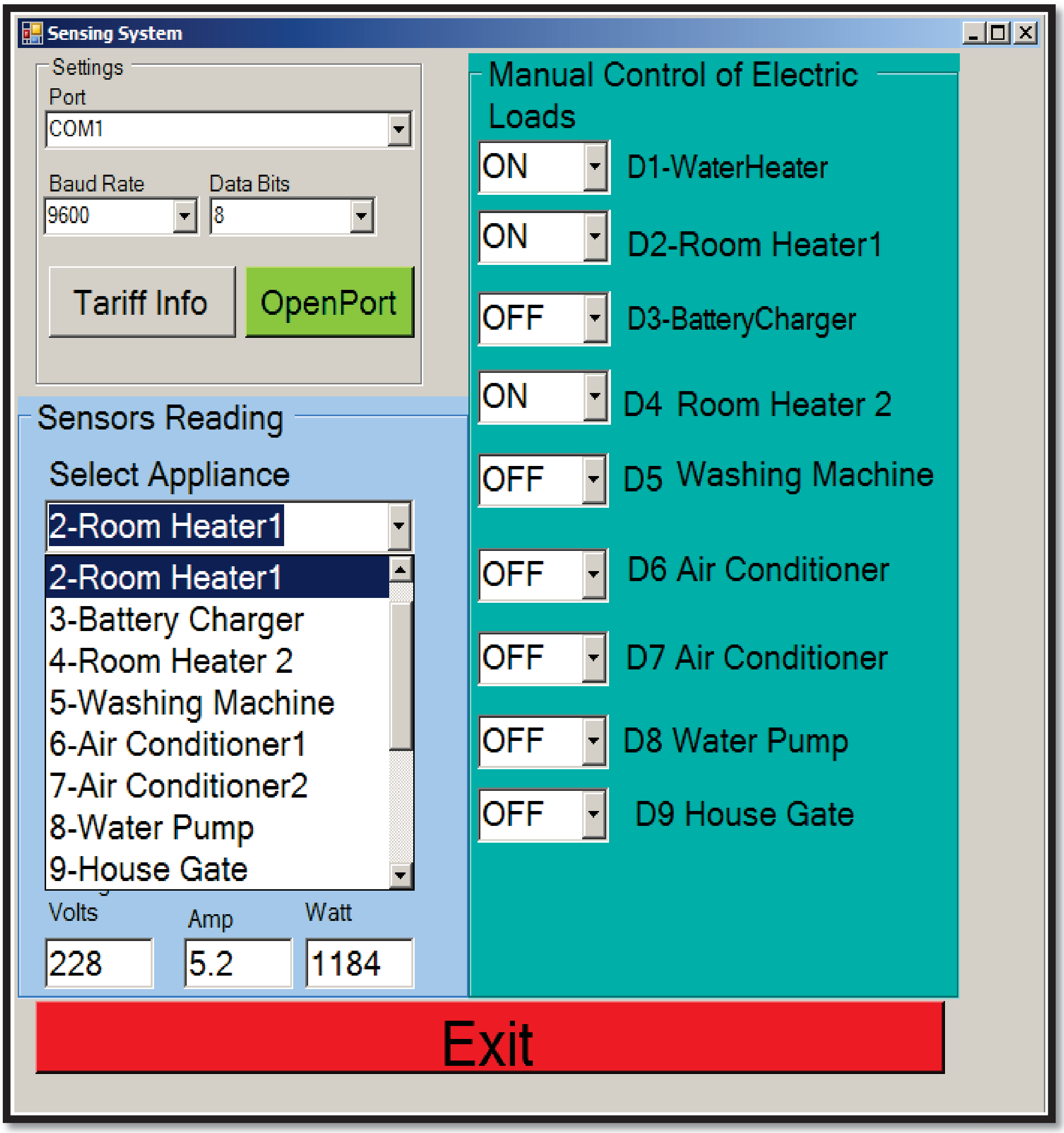


Figure 36: Screenshot of Developed GUI

6.7 Conclusion

The operation of Smart Power Monitoring Unit for different electrical appliances and their respective results are reported. Several tests have been done in different houses during the research and results are shown and analysed. The correction factor is introduced accordingly to get the desired parameters in the program. Each parameter is measured and the power is calculated and evaluated with a traditional electrical parameter measuring device.

Chapter 7

Conclusion and Future works

This Chapter considers the outcome of the research, and draws conclusions about the success of the research based upon achievement of the key research objectives, and appropriately addressing the problem domain. Finally, the possibilities of future work extending from this research are proposed.

7.1 Research objectives

The work in this thesis includes the fundamental studies to develop an in- house sensing system based on wireless sensor networks and determine the areas of daily peak hours of electricity usage levels. The operating principle and the experimental results from sensors are reported in this work and come with a solution by which an individual can lower their consumption and better utilize already limited resources during the peak hours by implementing various control techniques. The proposed power monitoring and controlling unit shows that simple and smart sensors can be easily used by a non-specialist user, in the household, to recognize the power consumption level. Control can be easily done by using the proposed technique within the tariff plans provided by the electrical companies. The system is becoming more popular as the electricity bills increase day by day. More intelligent features can be added to the existing protocol to make it more efficient in recognizing the daily activity and usage of an appliance by the user. The system was tested in different homes and can be installed in residential environments without any complexity. The sensing unit is well encapsulated so that the components used in the system are almost invisible and the user can use it without any difficulty. Moreover, the proposed sensing unit presents an alternate to the other sensors available on the market today, most of which use microcontrollers for the conversion of received data bits. The developed system is designed for the continuous monitoring of power consumption from the various appliances connected to the unit and stores the data into the computer database for further processing. Storing the data frames can be changed by altering the sampling rate in the ZigBee end device. Experimental results received from the sending units were encouraging.

7.2 Research Outcome

The sensor networks are programmed with various user interfaces suitable for users of varying ability as well as for expert users, such that the system can be maintained easily and interacted with very simply. This study also aims to assess the consumer’s response towards perceptions of Smart Grid technologies, their advantages and disadvantages, possible concerns and overall perceived utility.

7.3 Future Works

At present the system is independently tested with different loads of domestic appliances. In the later stage the system will be integrated with co-systems like Smart home behavior recognition systems to determine the wellness of the inhabitant in terms of energy consumption. The stored data bits can be used to monitor the activity pattern of the inhabitant on a regular basis and therefore future behavior of that inhabitant can be predicted.

The work conducted in this thesis has focused on the development of a Smart power monitoring and controlling based on the wireless sensor networks. Various design intricacies, hardware and software level analysis and experimental tests have been done to achieve the research objectives. The developed unit can be easily implemented in the real time scenario. Furthermore, additional areas have also opened for the investigation in the future. In the conclusion of this thesis, several areas are suggested for future research on the topic:

1. The Sensing Unit Hardware size can be reduced.
2. The sensors used in this research need to be further calibrated to improve the results, although complexity of the sensing unit could be increased.
3. The sensing unit should be further expanded by installing more sensors to monitor environmental factors like temperature and humidity.
4. This thesis can be used as a good reference source for further integrating or developing similar projects using ZigBee modules.
5. System capability can be further improved in terms of data storage.
6. Integration with the relevant projects like home monitoring for elder care can be done.
7. Development of a protective casing for the current transformer's primary winding to avoid any health hazard can be done.
8. Further investigation of power consumption and control using intelligent systems.
9. Performance can be improved in some areas.
10. BT138-800E triac is limited for use under 12 amps of current in electrical appliances, so further research is needed in the area of higher loads above 12

amps.

11. Coordination with other projects based on Smart metering systems.
12. A fuse circuit can be introduced to save the sensor unit under fault conditions like overload.

Control over power consumption is an important contributor to world economies. Despite the size of the industry, there has been only limited development into modern technology regarding power consumption. Some tasks require the use of sensors that are capable of monitoring the power factor to limit the variation in the electrical system.

Chapter 8 : References

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Chapter 9 Publications

A. Proceeding and Conference Paper

S. P. S. Gill, N. K. Suryadevara and S. C. Mukhopadhyay, "Smart Power monitoring system using wireless sensor networks," in the proceedings of Sixth *International Conference on Sensing Technology*, ISBN 978-1-4673-2245-4, Kolkata, India, Dec. 18-21, 2012, pp. 444-449.

B. Seminar/Presentation

S. P. S. Gill, N. K. Suryadevara and S. C. Mukhopadhyay, "Smart Power monitoring system using wireless sensor networks," in the proceedings of Sixth *International Conference on Sensing Technology*, Presentation on the 19th Dec. 2012, CDAC, Kolkata, India.