AN ON-LINE PHOTOVOLTAIC MONITORING SYSTEM USING THE ZIGBEE BASED WIRELESS NETWORK

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ABSTRACT

The increase of global energy demand and depletion of fossil energy has brought tremendous growth in renewable energy particularly solar energy. For grid-connected photovoltaic system (PV), monitoring is considered as a crucial aspect to observe the stability and performance of the system. Various methods are used in monitoring system. The simplest method is to have data collection done in an offline manner, where data acquisition system is installed on the plant and the data are stored locally over a period of time before being manually extracted for processing. However, this restricts the effectiveness of the monitoring system, as the data are not collected in real time. For real time monitoring system, cables are commonly used to transmit data from sensors to the data acquisition system. Due to the cost and technical limitations of the data cable, the monitoring station needs to be located reasonably close to the monitored plant. Apart from being inconvenient, the use of data cable often adds capital and maintenance cost to the system. Simpler wireless connection was introduced with similar capabilities as wired monitoring system. This research proposed an online monitoring system for grid-connected photovoltaic system by integrating monitoring system with Zigbee embedded system. The system is developed using Java and C programming language. Analysis and calculation of raw data is done in real time. Parameters like temperature, irradiation, PV power output and grid inverter output are being monitored in order to study the efficiency and stability of the system. In addition to monitoring features, this system is also equipped with user friendly control function. Another advantage of this system is with availability of internet connection; the data is accessible from anywhere around the world. The system monitored 1.25 kW_p grid-connected photovoltaic system located at 3rd and 4th floor of the Wisma R&D, University of Malaya in Kuala Lumpur, Malaysia. The PV panels are mounted on the 3rd floor balcony of the Wisma R&D building, while the inverter is located on the monitoring laboratory on the 4th floor. The

base station, where the host PC is placed, is located at the other end of the 4^{th} floor. Wireless monitoring system for 1.25 kW_p grid-connected inverter with a simple web-based data acquisition system and its control has been developed. The system has provided an uncertainty of $\leq \pm 5\%$.

ABSTRAK

Peningkatan permintaan tenaga di dunia dan pengurangan tenaga fosil telah membawa kepada peningkatan dalam tenaga boleh diperbaharui terutamanya tenaga solar. Untuk sistem photovoltaik (PV) grid berkaitan, pemantauan dianggap sebagai aspek penting untuk memastikan kestabilan dan prestasi sistem. Pelbagai kaedah digunakan dalam sistem pemantauan. Kaedah yang paling mudah adalah dengan mengumpul data secara luar talian, di mana sistem perolehan data dipasang terus pada panel dan data disimpan dalam suatu jangka masa sebelum diekstrak secara manual untuk pemprosesan. Walau bagaimanapun, keberkesanan sistem pemantauan terhad kerana data tidak diambil dalam masa nyata. Untuk sistem pemantauan masa nyata, kabel selalu digunakan untuk menghantar data dari sensor ke sistem perolehan data. Oleh kerana kos dan batasan teknikal kabel data, stesen pemantauan perlu berada berhampiran dengan kawasan pemantauan. Selain mendatangkan kesulitan, penggunaan kabel data meningkatkan lagi modal dan kos penyelenggaraan kepada sistem. Sambungan tanpa wayar yang lebih ringkas telah diperkenalkan dengan keupayaan yang sama seperti sistem pemantauan berwayar. Kajian ini mencadangkan satu sistem pemantauan atas talian untuk sistem photovoltaik grid berkaitan dengan mengintegrasikan sistem pemantauan dengan sistem Zigbee terbenam. Sistem ini dibangunkan dengan menggunakan bahasa pengaturcaraan Java dan C. Analisis dan pengiraan data mentah dilakukan dalam masa nyata. Parameter seperti suhu, radiasi solar, output kuasa PV dan output penyongsang grid dipantau untuk mengkaji kecekapan dan kestabilan sistem. Selain ciri-ciri pemantauan, sistem ini juga dilengkapi dengan fungsi kawalan mesra pengguna. Satu lagi kelebihan sistem ini adalah dengan adanya sambungan internet, data boleh diakses dari mana-mana sahaja di seluruh dunia. Sistem ini memantau 1.25 kW_p sistem photovoltaik grid berkaitan yang terletak di

tingkat 3 dan 4 Wisma R&D, Universiti Malaya di Kuala Lumpur, Malaysia. Panel PV dipasang di balkoni tingkat 3 Wisma R&D, manakala penyongsang diletakkan di makmal pemantauan di tingkat 4. Kawalan utama iaitu PC diletakkan di hujung tingkat 4. Sistem pemantauan wayarles untuk 1.25 kW_p penyongsang grid berkaitan dengan sistem perolehan data mudah berasaskan web dan kawalannya telah dibina. Sistem ini telah menyediakan ketidaktentuan $\leq \pm$ 5%.

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LIST OF SYMBOLS AND ABBREVIATIONS

µc	:	Microcontroller
AC	:	Alternating current
ADC	:	Analog-to-digital Converter
AES	:	*Advanced Encryption Standard*
CDMA	:	Code Division Multiple Access
DAQ	:	Data Acquisition
DC	:	Direct current
DSP	:	Digital Signal Processing
E_{ac}	:	AC energy
ED	:	Energy detection
EEPROM	:	Electrically Erasable PROM
Elec.	:	Electrical
E_{pv}	:	PV energy
ESC	:	Enhanced self-configuration
ETSI	:	European Telecommunications Standards Institute
f	:	Frequency
FF	:	Fill factor
FFD	:	Full-function device
FP	:	Field Point
G	:	Solar Radiation
G_1	:	Irradiance on plane of PV array
GC	:	Grid-connected
G_o	:	Irradiance on horizontal plane
GPRS	:	General Packet Radio Service

GSM	:	Global system for mobile communications
GUI	:	Graphical user interface
GUM	:	Guide to the Expression of Uncertainty in Measurement
H	:	Hybrid
HMI	:	Human machine interface
H	:	Humidity
HSCHD	:	High-speed circuit switched data
I_{ac}	:	AC current, grid current
I_b	:	Battery current
iEDM	:	Intelligent Energy Distribution Management
I_l	:	Load current
I_{max}	:	Maximum current
I_{pv}	:	PV array current
I_{sc}	:	Short circuit current
L_{C}	:	Losses array capture
LP1	:	Logging Point 1
LP2	:	Logging Point 2
LQI	:	Link quality indication
MAC	:	Media storage control layer
MANET	:	Mobile ad hoc wireless sensor network
MCU	:	Microcontroller unit
Met.	:	Meteorological
MPPT	:	Maximum Power Point Tracking
NI	:	National Instrument
OS	:	Operating system
p	:	Barometric pressure

P	:	Active power
P_{ac}	:	AC power
PAN	:	Personal Area Network
PAR	:	Photosynthetically Active Radiation
P_b	:	Battery power
PC	:	Personal Computer
PCI	:	Peripheral component interconnect
PF	:	Power factor
PHP	:	Hypertext preprocessor
PHY	:	Physical layer
P_l	:	Load power
PLC	:	Programmable Logic Controller
P_{max}	:	maximum power
PPEs	:	Personal protective equipment
P_{pv}	:	PV power
ϕ_q	:	Soil heat flux
PV	:	Photovoltaic
PV-DG	:	Photovoltaic distributed generator
PVT	:	Photovoltaic-thermal
Q	:	Reactive power
RAM	:	Random Access memory
RF	:	Radio Frequency
RFD	:	Reduced-function device
RFID	:	Radio Frequency Identification Devices
S	:	Apparent power
SA	:	Stand-alone

SCADA	:	Supervisory Control and Data Acquisition
S_{Dir}	:	Wind direction
S_v	:	Wind velocity
S_w	:	Wind speed
SWC	:	Soil water content
T_a	:	Ambient temperature
T_m	:	Module temperature
T_s	:	Soil temperature
u_c	:	Total expanded uncertainty for current
u_e	:	Uncertainty for energy
u_i	:	Total expanded uncertainty for irradiation
u_p	:	Uncertainty for power
u_t	:	Total expanded uncertainty for temperature
u_v	:	Total expanded uncertainty for voltage
V_{ac}	:	AC voltage, grid voltage
VB	:	Microsoft Visual Basic
V_b	:	Battery voltage
VI	:	Virtual Instrumentation
V_l	:	Load voltage
V_{max}	:	Maximum voltage
V_{oc}	:	Open circuit voltage
V_{pv}	:	PV array voltage
W/G_c	:	Wind generator current
W/G_s	:	Wind generator rotational speed
W/G_v	:	Wind generator voltage
WS	:	Weather Station

WSN	:	Wireless Sensor Network
Z	:	Utility grid impedance
γ	:	Array yield
γ_r	:	Reference yield
η	:	Efficiency
η_{ave}	:	Average efficiency

LIST OF APPENDICES

CHAPTER 1: INTRODUCTION

1.1 Research Background

As the global energy demand increases with the growth of world population, countries all over the world are putting more and more emphasis on the development of renewable energy. Among the many sources of renewable energy, solar energy is considered as the most promising and reliable energy source (Tyagi, Rahim, Rahim, & Selvaraj, 2013). In this light, governments in many countries have provided various incentives to setup solar energy-based power plants, to complement the existing power plants which are running on fossil fuel. Photovoltaic (PV) technology is used to convert solar energy into electricity. PV contains cells which are built from layers of semiconductor material. It reacts to sunlight and produce electricity. Since year 2000, PV distribution has increased tremendously. In Europe, PV covers 2.6% of the electricity demand and 5.2% of the peak electricity demand. PV global market was expected to increase up to 48 GW by 2017 (Masson, Latour, Rekinger, Theologitis, & Papoutsi, 2013). Figure 1.1 shows the evolution of global annual PV market scenarios per region until 2017. Production of solar cells also increased worldwide (Laird, 2010). According to European Photovoltaic Industry Association report (2013), the highest PV market was in Germany with 7.6 GW of newly connected system while China is the leading country in Asia region with 5 GW followed by Italy, United States of America and Japan (Masson et al., 2013). As for PV cell and module production, China is the leading country (Jäger-Waldau, 2012). Figure 1.2 shows world PV cell and module production trend since 2000. However, European countries remain the world's leading region in terms of cumulative installed capacity, with more than 70 GW as of 2012 which represent 70% of world's capacity.

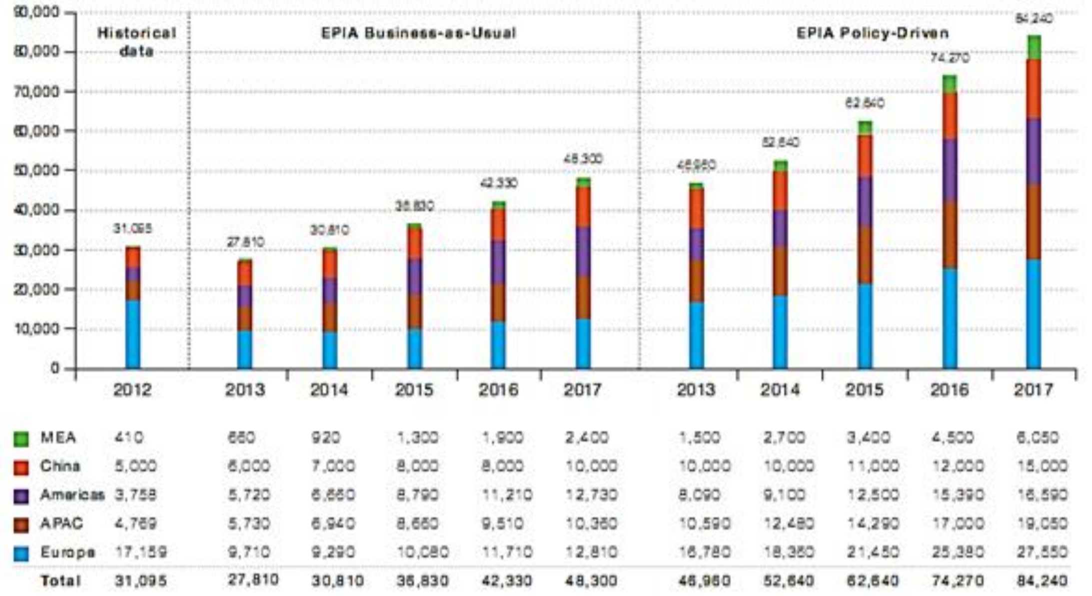


Figure 1.1: Evolution of global annual PV market scenarios per region until 2017 (MW) (Masson et al., 2013)

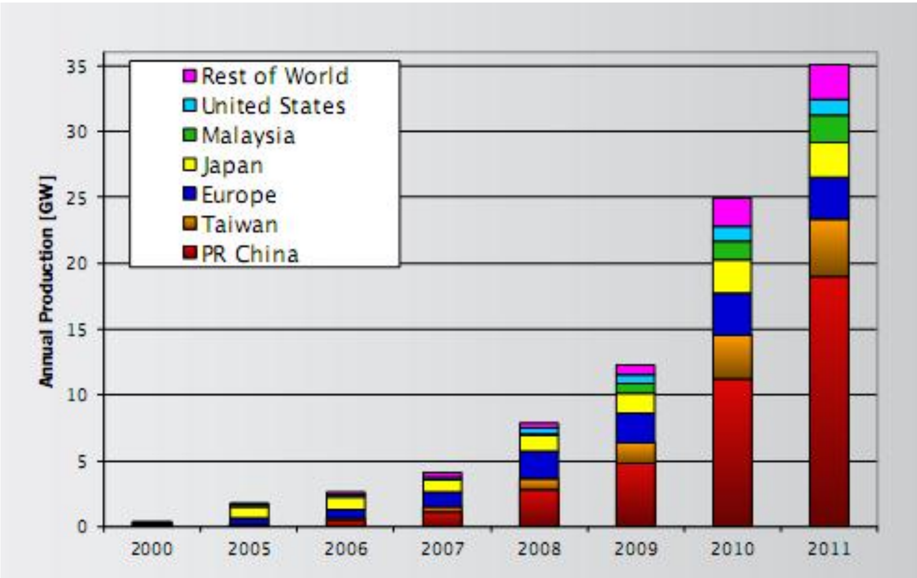


Figure 1.2: World PV cell/module production from 2000 to 2011 (Jäger-Waldau, 2012)

Monitoring process is a crucial aspect for many technical systems, including solar energy conversion system. Bartle (2007) defines monitoring as regular observation and recording activities in a project by collecting information on all aspects of the project. Monitoring is essential to observe the project progress. Monitoring also plays an important role in making decisions for project improvement thus facilitates the project planning and implementation. Implementation of monitoring provides valuable information for data analyzing, ensure the objectives gain, identifying problems and solution, and ensure that the system is operating properly. In order to ensure data is handled in systematic manner, user should implement monitoring function to their system.

In recent years, many solar energy conversion systems have included monitoring function as an integral part of the systems. Sugiura et al. (2003) implement monitoring program on residential PV systems in Japan. From the data obtained, factors that affected PV performance such as inverter loss, shading loss, inverter Maximum Power Point Tracking (MPPT) mismatch loss, array temperature rise loss and other loss were identified. Monitoring functions are applied not only to stand-alone PV system (Benghanem, 2010; Forero, Hernández, & Gordillo, 2006; Gagliarducci, Lampasi, & Podestà, 2007; Krauter, 2004; Park, Shen, Kim, & Rho, 2012; Ranhotigamage & Mukhopadhyay, 2011; Soler-Bientz, Ricalde-Cab, & Solis-Rodriguez, 2006), but also to grid-tied PV system (Anwari, Dom, & Rashid, 2011; Ayompe, Duffy, McCormack, & Conlon, 2011; Boonmee, Plangklang, & Watjanatepin, 2009; Carullo & Vallan, 2012; Drews et al., 2007; López, Mantiñan, & Molina, 2012; Pietruszko & Gradzki, 2003; Wittkopf, Valliappan, Liu, Ang, & Cheng, 2012), as well as hybrid PV system (Kalaitzakis, Koutroulis, & Vlachos, 2003; Koutroulis & Kalaitzakis, 2003; Papadakis, Koutroulis, & Kalaitzakis, 2005).

Conventional wired monitoring system provides reliable solution in data transmission but suffers from several limitations. Apart from the physical constraints during the laying of data cables, the use of these cables also increases installation and maintenance cost. Besides, for outdoor application such as PV systems, continuous exposure to sun beam and rains may reduce the lifespan of the system (Spertino & Corona, 2013). Therefore, wireless monitoring system is favored over conventional cable-based monitoring system. Web-based monitoring system (Benghanem, 2010; Kalaitzakis et al., 2003; Krauter, 2004; Papadakis et al., 2005) can be an attractive monitoring method, as it enables data to be distributed among remote users and users will have the convenience to view data from any device with internet connectivity.

In this research, a Zigbee-based wireless monitoring system is designed and built as a replacement to the conventional cable-based monitoring system for a grid-tied PV system. Various aspects of the system development, from the design to construction and testing, are explained in detailed afterwards. A simpler Zigbee network topology is implemented. Besides that, a PC-based application is designed and implemented in order to allow remote controlling of the system. In addition to the previous works done, web-based function is added which allows easy access of the data over the internet to provide timely evaluation on the system performance, as well as to provide counter measures if any failures detected.

1.2 Problem Statement

Nowadays, solar monitoring is important in photovoltaic system. It is important to measure the efficiency of the system and factors leading to malfunction in the system. Many problems and limitations occur when doing monitoring for solar system. Conventional cable-based monitoring system requires high cost in laying the cables for installations and incurs high maintenance over the years. Due to this, research concern arises in the area of method used to monitor performance of the system for either wired or wireless. Few researches applied wireless methods to monitor performance of photovoltaic system in unattended mode and from afar.

In this research, the development of a new data acquisition system has been proposed. The system is equipped with online features and is able to monitor and control the PV system from afar. Zigbee is chosen as the wireless medium for data transmission. Parameters like PV voltage; PV current; inverter voltage; inverter current; ambience temperature; panel temperature and irradiation are measured and recorded. For electrical sensors, calibration is done by using Fluke power quality meter, Fluke power quality analyzer and Fluke digital multimeter in order to determine the accuracy of the system proposed.

1.3 Objectives of the Study

This research is designed to cater the needs of monitoring grid connected photovoltaic system in order to monitor its performance and collecting data on environmental aspect. The purposes of this study are as follow:

- To design and implement a remote monitoring and controlling system for grid-connected photovoltaic system using Zigbee wireless sensor network.
- To build a web-based data system that can monitor data collected from the grid-connected photovoltaic system via online.

1.4 Scope of the Study

This research study intends to focus on the development of a new wireless data acquisition system in order to monitor the performance of grid-connected photovoltaic. The scope of study for the research includes:

- Design and implement a monitoring system that can be placed in remote area and controlled via Zigbee.
- Design an algorithm for wireless data processing system to store data in server.
- Develop a PC-based control application for the monitoring system via Zigbee.
- Develop a web-based application to view and monitor the system online.

1.5 Outline of the Report

Chapter 2 contains the literature review of the research. In this chapter, factors affecting efficiency of PV performance are discussed. Zigbee characteristics, features and technology are further explained here. Besides that, previous monitoring works which includes previous photovoltaic monitoring works done and previous Zigbee monitoring applications are also discussed in this chapter.

Chapter 3 explains the system architecture in this research. In this chapter, the overall system structures are discussed. Besides that, this chapter describes hardware and software methods used in order to implement the system.

Chapter 4 focuses on the results obtained from the system. Discussions on data obtained are further explained in this chapter. In this research, data obtained are displayed in web-based to enable other user to monitor the results. Furthermore, calculations on system uncertainty analysis are also described in this chapter.

Chapter 5 states the conclusion of the research. The advantages of wireless monitoring instead of wired monitoring are discussed in this chapter. In addition, future recommendations are also included in this chapter in order to enhance and improve any imperfection of this research.

CHAPTER 2: LITERATURE REVIEW

2.1 Chapter Overview

Grid-connected photovoltaic system has been widely utilized throughout the world as one of the alternatives to replace conventional energy. People have started to have awareness over capabilities of renewable energy to replace conventional energy. Monitoring becoming crucial aspects in order to ensure grid-connected photovoltaic system provide high performance and stability. Nowadays, many methods and devices used in monitoring either wired or wireless. Zigbee is chosen as wireless medium to monitor data in this research. In this chapter, factors affecting efficiency of PV performance is discussed. Zigbee characteristics and features as wireless transmission device have been investigated in section 2.3. Zigbee system technology is discussed in section 2.4 while previous monitoring works are discussed in section 2.5. Previous photovoltaic monitoring works and Zigbee monitoring applications are listed in section 2.5.1 and 2.5.2.

2.2 Factors Affecting Efficiency of PV Performance

Santos, Barrio, and Garcia (1986) proved that as the solar irradiance increases, the PV module efficiency also increases due to the high number of photons hitting the module. Many electron-hole pairs can be formed if the level of irradiance increase thus will produce more current. Yoo (2011) collected data on PV efficiency and solar irradiance. From his research, he found out that PV system efficiency directly proportional to the amount of solar irradiance received. Besides irradiance, there are also other factors that affected performance of PV system such as cell temperature and dust.

Losses occur in terms of array capture losses, system losses, cell temperature losses, soiling and degradation. Losses such as soiling and degradation are hard to estimate as they give small effects over large fluctuations in operating conditions (Ayompe et al., 2011). There are a few additional losses that can be observed under real operating conditions such as optical reflection losses; low irradiance levels; thermal losses; reduction of output current; wiring losses; decreasing conversion efficiency (Krauter SCW, 2006).

Shadowing of a single cell in a series string of solar cells leads to reverse bias of the shadowed cell. Reverse bias and consecutive microplasma breakdown have been physically described and modelled (Spirito & Albergamo, 1982; J W Bishop, 1989; J.W. Bishop, 1988). Bishop (1988) investigated shadowing effects on solar cells and found out that shadowing will reduce array efficiency and caused hot spot heating. Due to shadowing, cell encapsulation is damaged while array power output reduced. Kovach (1995) performed a thorough analysis of the reverse-biased solar cell and applied Bishop's model in order to draw conclusions on hot spot formation and yield reduction of PV arrays. For commercially available crystalline and amorphous cells, model parameters for both models were derived from measurements by Alonso and Chenlo (1998). Solar cell I–U characteristics in reverse bias show more variation than in forward bias. Kovach (1995) also found that under shadowing conditions a poor PV array lay-out can lead to large energy losses and those even small shadows can appreciably affect the energy yield.

Increasing module temperature will lead to decrease in efficiencies in PV module (Yamaguchi et al., 2003). An effective way of improving efficiency and reducing the rate of thermal degradation of a PV module is by reducing the operating temperature of its surface. This can be achieved by cooling the module and reducing the heat stored inside the PV cells during operation. As an example, solar-water pumping system can be given. Such a system consists of a PV module cooled by water, a water pump, and a water storage tank. Cooling of the PV module is achieved by introducing water trickling configuration on the upper surface of the module (Endecon Engineering, 2001).

Based on European Photovoltaic Technology Platform (2011) report, dust was identified as one of the factors affecting PV efficiency. The occurrence of dust may block the coming irradiance onto PV modules. Goossens & Van Kerschaever (1999) investigated the effect of wind velocity and air borne dust concentration on the PV cell performance caused by dust accumulation on such cells. From the investigation, they found out that as dust density increase, PV power output will drop. Jiang, Lu, and Sun (2011) tested the effect of air borne dust on three types of PV modules which are (1) monocrystalline (2) polycrystalline and (3) amorphous silicon. The experiments were conducted in a lab, using a solar sun simulator and dust generator. They concluded that air borne dust will reduce the short circuit current and thus affect the efficiency of the PV module and the efficiency drop linearly with the dust deposition density. The results of this study also indicated that dust pollution has a significant impact on PV module output. With dust deposition density increasing from 0 to 22 g/m^2, the corresponding reduction of PV output efficiency grew from 0% to 26%. The reduction of efficiency has a linear relationship with the dust deposition density, and the difference caused by cell types was not obvious.

2.3 Zigbee Characteristics and Features

Zigbee is a low power and transmission rate wireless communication technology. It was developed based on IEEE 802.15.4 stack model. It was set by IEEE 802.15.4 and Zigbee Alliance organizations. Development of the physical layer (PHY), media storage control layer (MAC), and the data link layer is led by IEEE, while the ZigBee Alliance is responsible for determining logic networks, data transmission encryption mechanisms, application interface specifications, and communication specifications between system products. ZigBee agreement structure diagram is revealed in Figure 2.1 (Lin, Liu, & Fang, 2007; Labiod, Afifi, & Santis, 2007).

Zigbee device was built to support sensor networking-based applications which utilized radio frequency. Zigbee devices are designed for simple and lightweight wireless networks. Zigbee's transmission ranges are up to 100 m indoor and 1.5 km outdoor (line-of-sight). Zigbee is a low power device which operates at 2.4 GHz frequency. Initial version of Zigbee devices has transmission rate of 20 to 250 kbps; supports different topologies such as star and mesh; addressing based on short 16 bits or normal MAC (64 bits) address; support simple access and slotted allocation with guarantees; support acknowledge data transfer and optional beacon structure; energy detection (ED); link quality indication (LQI); and multilevel security (Labiod, Afifi, & Santis, 2007).

The MAC level of ZigBee utilizes a talk-when-ready collision prevention mechanism: data is transmitted immediately when there is need, and each transmitted data packet is confirmed to be received by receiver and is responded to with a confirmation message; if a confirmation message is not received in response, then a collision has occurred and the data packet is transmitted again. This method greatly increases the reliability of the system's data transmission.

In addition, a ZigBee network can include a maximum of 255 nodes, making it highly expandable (Lin et al., 2007; Sung & Hsu, 2011).

Zigbee devices support three network topologies which are centralized star, cluster-tree-based and mesh network as shown in Figure 2.2 (Hsu, 2010). Zigbee devices have two types of capabilities which are reduced-function device (RFD) and full-function device (FFD). RFD circuits are less complex compared to FFD and less memory.

Normally, RFD functions as a slave or regular node which has no master-slave communication while FFD may functions as master (coordinator) and a Personal Area Network (PAN) coordinator with controller functions (Lin, Liu, & Fang, 2007; Labiod, Afifi, & Santis, 2007).

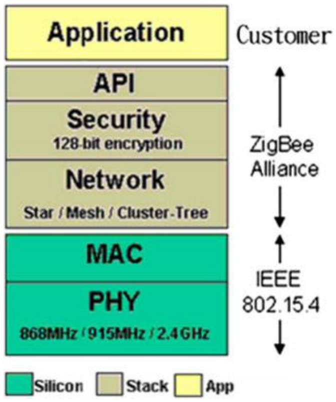


Figure 2.1: Zigbee agreement structure diagram (Lin et al., 2007; Labiod, Afifi, & Santis, 2007; Sung & Hsu, 2011)

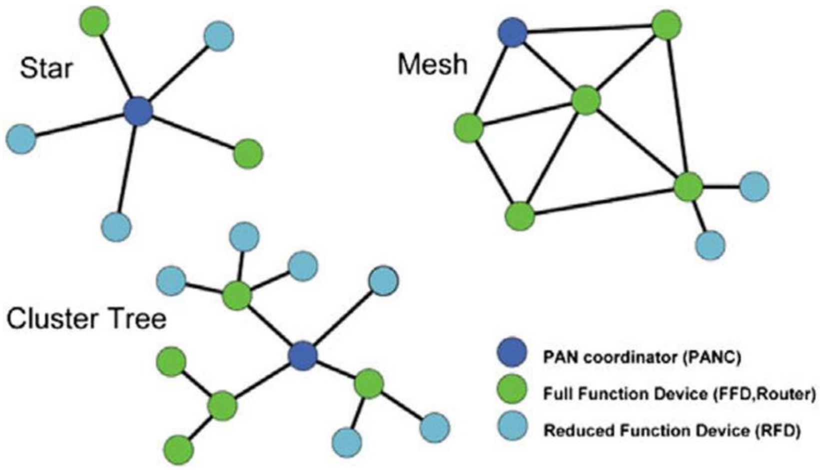


Figure 2.2: Topology of Zigbee wireless networks (Hsu, 2010)

2.4 Zigbee System Technology

Early research of wireless sensor networks mainly focusing on military applications. In the beginning of 2000-2002, companies such as Ember, Dust, Sensicast and others begun to find prospects of sensor network topology (Wheeler & Corporation, 2007). Other parties started to build industry standard body called Zigbee and initiated 802.15.4 group within IEEE. As described in previous section, Zigbee is a standard released by IEEE 802.15.4 and Zigbee Alliance organization. Their main objective was to standardize PHY and MAC for low-cost, low-power and robust performance (Wheeler & Corporation, 2007). Philips and Motorola are also included in Zigbee member companies (Wheeler & Corporation, 2007).

In 2003, standard of 2.4 GHz, 900 MHz and 868 MHz unlicensed bands were confirmed (Wheeler & Corporation, 2007). At 2.4GHz band, the 802.15.4 standard operated at 250 kb/s while for 900 MHz and 868 MHz, the standard operated at 40 kb/s and 20 kb/s (Wheeler & Corporation, 2007).

The first released of Zigbee was in December 2004 which was stated as version 1.0 (Egan, 2005). Zigbee Alliance specified six applications spaces for Zigbee which are (1) consumer electronics; (2) PC and peripherals; (3) residential/light commercial control; (4) industrial control; (5) building automation; and (6) personal healthcare (Egan, 2005). The main concerns from users are robustness and security. Zigbee introduced mesh networking to increase robustness and cater security needs by applying 128-bit *Advanced Encryption Standard (*AES) (Egan, 2005).

Several years of research brought to a new revision and the introduction of Zigbee Pro (Wheeler & Corporation, 2007). The new stack (Zigbee Pro) was the upgraded version of Zigbee 1.0. Various changes were made to improve robustness and scalability of the Zigbee standard. One of the changes made was addressing (Wheeler & Corporation, 2007). Zigbee 1.0 supports tree structure addressing which would run out of address in large scale deployments (Wheeler & Corporation, 2007). Zigbee Pro introduced random address assignments which consist of 16-bit address space (Wheeler & Corporation, 2007). Hence, collision problems are not common. Other additional feature includes conflict resolution mechanism which detected addresses conflicts based on unique IEEE MAC addresses (Wheeler & Corporation, 2007).

Zigbee 1.0 used single routing algorithm which required both memory and network overhead and Zigbee only have 4-8 kb of Random Access Memory (RAM) to reduce cost (Wheeler & Corporation, 2007). Enhancement made to Zigbee Pro algorithm was two routing algorithm in the same network which helps in keeping storage and network overhead to minimal (Wheeler & Corporation, 2007). Besides that, Zigbee Pro supports point-to-point connection and many-to-one connection (Wheeler & Corporation, 2007). Figure 2.3 shows tree addressing and stochastic addressing diagram.

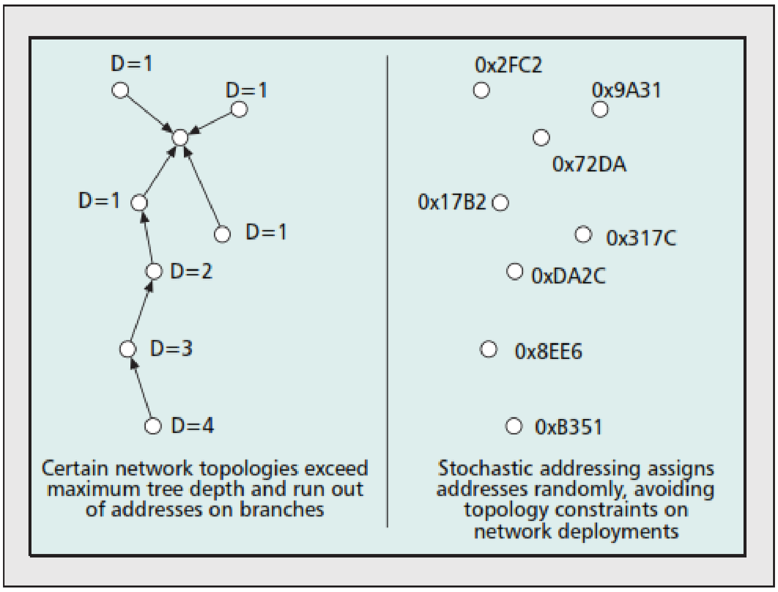


Figure 2.3: Tree addressing and stochastic addressing (Wheeler & Corporation, 2007)

Zigbee 1.0 has asymmetric links problem due to manufacturing variances in radio (Wheeler & Corporation, 2007). Transmission path normally constructed in reverse directions thus creating routing path that may be functional in destination to source direction but not in forward direction (Wheeler & Corporation, 2007). Zigbee Pro adds asymmetrical links detection and constructs path in forward direction instead of reverse direction and each device exchanged link reliability information (Wheeler & Corporation, 2007). During route discovery, links was weight based on the reliability in the direction link based on the information obtained (Wheeler & Corporation, 2007).

Zigbee's closest competitor is Bluetooth. Both Zigbee and Bluetooth came from family of IEEE802 standard. Table 2.1 listed out the differences between Bluetooth and Zigbee (Sikora, 2006). Bluetooth was established on 1997 while Zigbee was established on 2001. Both Zigbee and Bluetooth operate at the same frequency which is 2.4 GHz, but provide different routing system, algorithms and security. Zigbee supports large network capacity and multiple wireless nodes as it has tree, neighbor and table-based routing algorithms compared to Bluetooth which only supports point-to-point communication.

Table 2.1: Difference between Bluetooth and Zigbee (Sikora, 2006)

Characteristics	Bluetooth	Zigbee
Since	1997	2001
Standard	IEEE802.15.1	IEEE802.15.4
Frequency	2.4 GHz	2.4 GHz
System	Master-slave	CSMA/CA
Routing algorithms	Point-to-point	Tree, neighbor and table-based
Security	Cryptographic	Tiered
Target Applications	Consumer and communication applications	Residential home control, commercial building control, industrial plant management

2.5 Previous Monitoring Works

Traditional monitoring was done using wired connection. Some define this method as on-site monitoring. Previous literature review shown that for monitoring, data acquisition system was wired directly to Personal Computer (PC) to store and display data. Koutroulis & Kalaitzakis (2003) used microcontroller to collect data and transmitted data were sent to PC using RS232 serial connection. Aste, Chiesa, and Verri (2008) monitored performance of a photovoltaic-thermal (PVT) air collector. A computer-based real time monitoring system has been connected by cable to measure the thermal and electrical performance of the system.

European Telecommunications Standards Institute (ETSI) has built European standard for cellular communications which was known as Global system for mobile communications (GSM) (Mouly & Pautet, 1992). GSM is renowned for its capability to encode voice and convert to digital stream before transmitting in network. According to Rapeli (1995), GSM have been implemented in over 100 countries and considered most important service in voice telephony. By using circuit-switched data channels, GSM able to provide data services with maximum bit rate of 14.4 kbit/s. High-speed circuit switched data (HSCHD) was introduced to serve for higher bit rates. However, it is still insufficient for bursty data application such as web browsing. General Packet Radio Service (GPRS) improved GSM standard by introducing packet switched techniques to mobile subscriber. Unlike GSM, GPRS provides higher bit rates for bursty data transmissions. GPRS used several time slots which resulting in bit rate about 170 kbit/ s and able to support bursty data applications (Ghribi & Logrippo, 2000).

Radio communication has the possibility of sending and receiving a huge amount of information with reduced costs of the transmission, and it is also a good alternative in the case of the lack of telephone lines. Its main disadvantage is the difficulty in obtaining permission for the transmission frequency and the high price of its installation (Rosiek & Batlles, 2008). (Benghanem, 2009b) used Radio Frequency (RF) circuit to transmit data to remote server for storage and processing with distance more than 200 m.

Bluetooth is widely used for data transmission. Bluetooth is a universal short-range low-power radio protocol operating in the unlicensed industrial, automotive, scientific, and medical frequency band. Bluetooth technology was designed primarily to support simple wireless networking of personal consumer devices and peripherals. The advantages of Bluetooth is wireless signals transmitted with Bluetooth cover only short distances, typically up to 10 m for Bluetooth class 2 and 100 m for Bluetooth class 1. It allows both data and voice connections (Hua, Lin, Xu, Li, & Ouyang, 2009).

Ethernet is also one of the most widely used communication protocol. Naeem, Anani, Ponciano, and Shahid (2011) presented remote condition monitoring system using embedded web server. The advantages of Ethernet are it provides reliability, speed and good immunity to noise and electromagnetic interference. The drawback of using Ethernet was the control unit must be connected to Local Area Network using cable. Thus, it was not suitable for remote photovoltaic station. Besides that, Ethernet use TCP/IP protocol which was complex to configure.

The satellite also known as one of the medium used for communication. Satellite has a great spatial and temporal coverage and it is very useful in places without access to telephone lines. However, satellite is a very expensive method. Its main disadvantage is the high cost of its installation (Rosiek & Batlles, 2008).

WiFi and WiMax are one of wireless communication techniques used these days. Although WiFi and WiMax offered higher transmission speed, their coverage is limited to 200 m. WiMax has more advantages compared to WiFi as it can covers area in 50 km order (Rosiek & Batlles, 2008). Cao, Chen, Zhang, and Sun (2008) used wireless sensor network (WSN) as communication medium for micro-environmental monitoring system.

Zigbee characteristics which utilized low power and cost makes it fits for the data transmission medium for communication. Zigbee's transmission ranges are up to 100 m indoor and 1.5 km outdoor (line-of-sight). Initial version of Zigbee devices has transmission rate of 20 to 250 kbps which is higher than GSM and GPRS (Labiod, Afifi, & Santis, 2007). Besides that, Zigbee consumes far less power than Bluetooth resulting in lower transmission rate compared to Bluetooth. Zigbee capable of range expansion due to mesh topology supports (Sung & Hsu, 2011). Fields of application for ZigBee include family automation, family security, overall medical care in hospitals, and industrial automation. ZigBee can be used in conjunction with products such as home appliances, consumer electronics, PC peripherals, and sensors, providing functions such as home appliance sensing, wireless PC peripheral control, and home appliance remote control (Lin & Liu, 1997).

2.5.1 Previous Photovoltaic Monitoring Works

With the aim of building an effective yet low cost monitoring system, numerous previous works on solar energy monitoring system have been reviewed. Table 2.2 listed all important characteristics based on the reviewed works. Earlier, both wired and wireless systems are used for transmitting data.

RS232 (Anwari et al., 2011; Forero et al., 2006; Mukaro & Carelse, 1999; Soler-Bientz et al., 2006) cable and RS485 cable (Ayompe et al., 2011) are normally used in data transmissions for pc-based monitoring system. However, continuous sun beam and rain exposure on cable may reduce the lifespan of the system. Besides that, the use of cable often add maintenance cost to the system (Spertino & Corona, 2013). Due to this, wired systems are less favorable compared to wireless system for PV monitoring system.

Various data transmission technology was utilized for wireless monitoring system, i.e. the use of satellite (Krauter, 2004), GSM (Gagliarducci et al., 2007; Rosiek & Batlles, 2008), Zigbee (López et al., 2012; Ranhotigamage & Mukhopadhyay, 2011) and other general RF devices (Benghanem, 2009b, 2010; Kalaitzakis et al., 2003; Papadakis et al., 2005),. Satellite took the longest time when transmitting data which is around 8 to 12 minutes (Krauter, 2004) compared to other wireless technology. Among all wireless technology, GSM is the most reliable in data transmission. However, GSM has higher operating cost as the user needs to pay the services for every data transmitted. Based on the reviewed literature, RF is frequently chosen as wireless data transfer mechanism. Within all RF devices, Zigbee is known for its low cost and secure communication features. One of its features is allocation of special time slot which makes Zigbee able to avoid data collision. Besides that, Zigbee is capable of supporting large network capacity which is up to 65536 nodes which makes it highly expandable compared to Bluetooth and Wifi which is only up to 7 and 32 nodes (Lin et al., 2007; Sung & Hsu, 2011). Therefore, Zigbee is chosen over other RF devices for its low cost; secure communication; robustness; and upgradable network capacity features.

As seen from the surveyed literature, microcontroller or Data Acquisition (DAQ) card and units are used as the main brain of PV monitoring system. Microcontroller is one of the low cost solutions. Besides sensor's precision, using processors with high Analog-to-Digital Converter (ADC) resolution also enhance the accuracy of measurement. 8-bit ADC (Mukaro & Carelse, 1999), 10-bit ADC (Anwari et al., 2011;

Benghanem, 2009a, 2009b; Krauter, 2004; Rosiek & Batlles, 2008) and 12-bit ADC microcontroller provides low-cost solution (Koutroulis & Kalaitzakis, 2003) compared to DAQ card or units (Ayompe et al., 2011; Carullo & Vallan, 2012; Forero et al., 2006; Gagliarducci et al., 2007; Kalaitzakis et al., 2003; Koutroulis & Kalaitzakis, 2003; López et al., 2012; Papadakis et al., 2005; Park et al., 2012; Pietruszko & Gradzki, 2003; Soler-Bientz et al., 2006). Microcontroller is chosen in this research, as it provides a low cost solution besides providing high ADC resolution.

According to IEC61724 standard, sampling intervals depend on parameters recorded. Sampling intervals for parameters which vary directly with irradiance shall be set to 1 minute or less (Anwari et al., 2011; Forero et al., 2006; Kalaitzakis et al., 2003; Koutroulis & Kalaitzakis, 2003; Mukaro & Carelse, 1999; Papadakis et al., 2005; Ranhotigamage & Mukhopadhyay, 2011; Rosiek & Batlles, 2008; Soler-Bientz et al., 2006). For parameter with larger time constants, i.e. temperature, sampling interval between 1 to 5 minutes is acceptable. In this research, sampling interval is set to 1-minute which is applicable to all parameters and complies with IEC61724 standard.

Various types of management software were used and reported in Table 2.2. For programming microcontroller, Turbo C++ (Mukaro & Carelse, 1999) and MPLAB (Anwari et al., 2011) software were used while for language, Assembly (Mukaro & Carelse, 1999) and C (López et al., 2012) were normally used. SCADA systems implemented Autobase (Park et al., 2012) which was used to control PLC. For numeric calculation and analysis, MATLAB (Benghanem, 2009a; Wittkopf et al., 2012) was the best choice of software. System design software such as LabVIEW (Anwari et al., 2011; Benghanem, 2009b, 2010; Carullo & Vallan, 2012; Forero et al., 2006; Gagliarducci et al., 2007; Koutroulis & Kalaitzakis, 2003; López et al., 2012; Soler-Bientz et al., 2006) served various comprehensive tools for measurement and control application. Java

(Kalaitzakis et al., 2003), Microsoft Visual Basic (VB) and SQL server (Papadakis et al., 2005) provides software design and interface for web-based implementations. In this research, C language is considered the best choice for programming microcontroller as C is not complicated compared to MPLAB, Turbo C++ and Assembly while Autobase is only applicable to monitor and control PLC system. MATLAB was good for calculation and prototyping but hard to deploy on server. Although LabVIEW contains various tools for measurement and control, its Virtual Instrumentation (VI) is complicated and hard to interface. In terms of web-based implementation, Java is considered the best choice over VB and SQL server (.NET platform). Java is crossed-platform software which can run in all operating system (OS) compared to .NET which can only run on Windows. Besides, Java platform is more secured compared to .NET.

From Table 2.2, measured parameters were categorized to Met. (Meteorological) and Elec. (Electrical) parameter. Weather station only collects data on meteorological parameters such as solar radiation and temperature (Benghanem, 2009b, 2010; Mukaro & Carelse, 1999; Rosiek & Batlles, 2008). Parameters recorded for stand-alone PV systems (Benghanem, 2010; Forero et al., 2006; Gagliarducci et al., 2007; Krauter, 2004; Park et al., 2012; Ranhotigamage & Mukhopadhyay, 2011; Soler-Bientz et al., 2006) and grid-connected PV systems (Anwari et al., 2011; Ayompe et al., 2011; Boonmee et al., 2009; Carullo & Vallan, 2012; Drews et al., 2007; López et al., 2012; Pietruszko & Gradzki, 2003; Wittkopf et al., 2012) were similar except for parameters related to battery and load which only applied to stand-alone system and parameters related to utility/grid which only applied to grid-connected system. For hybrid renewable energy systems (Kalaitzakis et al., 2003; Koutroulis & Kalaitzakis, 2003; Papadakis et al., 2005), parameters for both PV and wind system were collected. As seen from Table 2.2, grid-connected PV system required both meteorological and electrical parameters.

Monitoring is important to monitor PV system performance and provide fast failure detection. Renewable energy systems are usually installed on geographically isolated areas. It is costly to install monitoring system on-site and troublesome for users to collect data. Therefore, in this research, a web-based system is built to overcome this problem. Web-based system enabled data to be distributed among remote users which made it easily accessible from all devices with internet connectivity. Besides that, web-based system allowed the data to be displayed in an attractive manner. Based on Table 2.2, few works implemented web-based monitoring system to their research projects (Kalaitzakis et al., 2003; Krauter, 2004; Papadakis et al., 2005; Park et al., 2012).

Table 2.2: Summarize of previous monitoring works

Work done by	Data transfer mechanism	PV system type	Controller	Parameters		Samp. interval	Monitoring method	Software/ language
				Met.	Elec.			
Mukaro & Carelse, 1999	Wired: RS232	WS	ST62E20	G	none	1m	PC	Turbo C++, ASSEMBLY
Pietruszko & Gradzki, 2003	Wired	GC ($1kW_p$)	DAQ unit	G_o, G_1, T_a, T_m, S_v	V_{pv}, V_{ac}, I_{pv}, I_{ac}, P_{ac}, E_{ac}, Z, f	5m	PC	None
Koutroulis & Kalaitzakis, 2003	Wired: PCI bus	H: PV and wind	PCI-6024E	T_a, G, H, SWC, T_s, ϕ_q, S_{Dir}, W/G_s, S_v, p	V_{pv}, I_{pv}, V_b, I_b, W/G_v, W/G_c	1m	PC	LabVIEW
Kalaitzakis, Koutroulis, & Vlachos, 2003	Wire-less: RF	H: PV and wind	DAQ unit	S_w, S_{Dir}, T_a, H, p, G, T_s, ϕ_q, SWC	V_{pv}, I_{pv}, W/G_v, W/G_c, W/G_s, V_b, I_b	1m	Web	Using java applet interface
Krauter, 2004	Wire-less: Satellite	SA ($5kW_p$)	µc	G	P_{pv}, V_b, P_b, P_{ac}	15m	Web	None
Papadakis, Koutroulis, & Kalaitzakis, 2005	Wire-less: RF	H: PV and wind	PCI DAQ card	T_a, H, p, G, S_w, S_{Dir}, T_s, ϕ_q, SWC	W/G_v, W/G_c, W/G_s, V_{pv}, I_{pv}, V_b, I_b	1m	Web	VB, SQL server 2000
Forero, Hernández, & Gordillo, 2006	Wired: RS232	SA	FP DAQ board	T_a, G	V_{pv}, I_{pv}, E_{pv}, P_{pv}, V_{oc}, I_{sc}, FF, η, P_{max}	<30s	PC	LabVIEW
Soler-Bientz, Ricalde-Cab, & Solis-Rodriguez, 2006	Wired: RS232	SA	FP	T_m, T_a, G	V_{pv}, I_{pv}, P_{pv}, V_b, I_b	1m	PC	LabVIEW
Gagliarducci, Lampasi, & Podestà, 2007	Wire-less: GSM	SA	FP DAQ	G	P_{pv}, E_{pv}, DC P_l, AC P_l, V_{pv}, η_{ave}, γ, γ_r, L_C	1m	PC	LabVIEW
Drews et al., 2007	Wired	GC ($5kW_p$)	-	G, T_a	P_{pv}	1hr	PC	None

'Table 2.2: Summarize of previous monitoring works, continued'

Work done by	Data transfer mechanism	PV system type	Controller	Parameters		Samp. interval	Monitoring method	Software/ language
				Met.	Elec.			
Rosiek & Batlles, 2008	Wire-less: GSM/ GPRS	WS	ATmega 16	*PAR*, G, H, T_a	None	10s	PC	None
Boonmee, Plangklang, & Watjanatepin, 2009	Wired	GC ($5kW_p$)	DAQ card	G	V_{pv}, I_{pv}, P_{pv}, V_{ac}, I_{ac}, P_{ac}, E_{ac}	-	PC	None
Benghanem, 2009b	Wire-less: RF	WS	PIC 16F877	H, T_a, p, G, S_w, S_{Dir}	None	1hr	PC	LabVIEW
Benghanem, 2009a	Wire-less	SA	PIC 16F877	T_a, G	V_{pv}, I_{pv}	-	PC	Matlab
Benghanem, 2010	Wire-less: TX5002, RX5002	WS	PIC 16F887	Rainfall, S_w, S_{Dir}, T_a, H, p, G	None	1m	Web	LabVIEW
Ayompe, Duffy, McCormack, & Conlon, 2011	Wired (RS485)	GC (1.72 kW_p)	DAQ unit	T_m, T_a, G, S_w,	E_{pv}, E_{ac}	5m	PC	None
Anwari, Dom, & Rashid, 2011	Wired: RS232	GC ($700W_p$)	PIC 16F877a	T_a, G	V_{pv}, I_{pv}	1s	PC	MPLAB, LabVIEW
Ranhotigamage & Mukhopadhyay, 2011	Wire-less: Zigbee	SA	µc	G, T_a	V_{oc}, I_{sc}, P_{max}, V_{max}, I_{max}	1s/ less	PC	None
Boonmee, Plangklang, & Watjanatepin, 2009	Wired	GC ($5kW_p$)	DAQ card	G	V_{pv}, I_{pv}, P_{pv}, V_{ac}, I_{ac}, P_{ac}, E_{ac}	-	PC	None
Wittkopf, Valliappan, Liu, Ang, & Cheng, 2012	Wired	GC (142.5 kW_p)	-	G, T_m, T_a, S_v, S_{Dir},	V_{ac}, I_{ac}, E_{ac}	5m	PC	Matlab
Carullo & Vallan, 2012	Wired	GC	NI DAQ card	T_a, H, T_m, G_o, G_1	V_{pv}, I_{pv}, V_{ac}, I_{ac}, P_{pv}, P_{ac}, E_{pv}, E_{ac}	1m	PC	LabVIEW

'Table 2.2: Summarize of previous monitoring works, continued'

Work done by	Data transfer mechanism	PV system type	Controller	Parameters		Samp. interval	Monitoring method	Software/ language
				Met.	Elec.			
Park, Shen, Kim, & Rho, 2012	Wire/ wire-less: Ethernet	SA (50kW)	HMI, PLC	None	V_{pv}, I_{pv}, P_{pv}, V_l, I_l, P_l, f, PF	-	PC	Autobase
López, Mantiñan, & Molina, 2012	Wire-less: Zigbee	GC (1.28 kW_p)	DSP	S_w, G, T_a, T_m	V_{ac}, I_{ac}, P, Q, S, V_{pv}, I_{pv}, P_{pv}	-	PC	C, LabVIEW

2.5.2 Previous Zigbee Monitoring Applications

Wide range of Zigbee applications extended to home energy management system. Han, Lee, Park, Standby and Outlet (2009) proposed remote-controllable and energy-saving room architecture. By using Zigbee as the controller with enhance infrared code functionality, user are able to control power outlets and other home appliances. The results proved that power consumption was reduced after implementing the system. In 2011, Han, Choi, and Lee (2011) extended their research by reducing standby power consumption by turning off a home device and the power outlet simultaneously through the ZigBee hub. This method eliminates the waiting time of a typical automatic power cut-off outlet. Hwang, Choi, and Kang (2010) built an enhanced self-configuration (ESC) scheme to improve robustness of conventional Zigbee-based home automation system. The proposed system helps in solving node failure or frequent link breakages problem. Nowadays, technology growth increases development of smart home. Han and Lim (2010) integrated Zigbee sensor networks with home to build a new smart home energy management system. Hence, produce more intelligent and automatic home. The main objective of the system is to manage energy more efficiently while conserving the environment.

In order to improve electrical safety in building, a monitoring protection system based on Zigbee has been developed and installed (Huang, Chang, Chen, & Kuo, 2011). The system consists of traditional remote control functions, and branch circuit protection strategy to prevent overloading or overheating of outlets. Leccese (2013) designed remote control system that able to enhance management and efficiency of street lighting systems based on Zigbee wireless device. He utilized Zigbee point to point communication to obtain street lamps state and to take actions in case of failure. Chae, Yoo, Kim, and Cho (2012) developed a WSN system to monitor bridge suspension. They integrate Zigbee with Code Division Multiple Access (CDMA) to ensure wide range coverage for monitoring.

In manufacturing environment, Lu (2011) introduced a plug-and-play data gathering system based on Zigbee network. The system includes system simulator, instrument definition module and network monitor module. The system was built to enable users to plug-and-play in production system and automatically capturing production data. In order to enhance safety quality in factories, Sung and Hsu (2011) proposed a remote monitoring system based on Zigbee embedded system. It was built for unified monitoring with the real-time processing capabilities. The control interface was developed using LabView.

In construction industry, safety of the workers is important. Barro-Torres, Fernández-Caramés, Pérez-Iglesias, and Escudero (2012) developed a device to monitor the use of personal protective equipment (PPEs) by the workers. This device was developed by combining Zigbee mesh network topology with Radio Frequency Identification Devices (RFID) technologies. The device was sewn to workers clothing and send monitoring data to central unit for supervision. Zigbee not only applies to factories needs but also applicable to car industry.

Automation industry also utilized Zigbee as communication medium. Tsai, Tonguz, Saraydar, Talty, and Ames (2007) built an inta-car WSN based on Zigbee. Experiments done shown that Zigbee network has high potential in intra-car WSN implementation. Practical problems such as engine noise, interference and location of sensors may affect packet error rate but this problem is solvable. North American are concerns about the safety and security of their railroad industry. However, train arrangement's requires sensors to be placed in long linear network topology. The main concern is WSN addressing. In order to overcome this problem, Shrestha et al. (2013) proposed a heterogenous multihop network approach by integrating Wifi and Zigbee. Results obtained shown that delay and packet losses are reduced when integrating Wifi and Zigbee.

In agriculture, monitoring systems capable of measuring animal behavioral parameters utilizing Zigbee communication network has been designed. Nadimi, Jørgensen, Blanes-Vidal, and Christensen (2012) build a 2.4 GHz ZigBee-based mobile ad hoc wireless sensor network (MANET) to monitor sheep head movements. Two relay nodes were applied to the monitoring system in order to improve network connectivity. Multi-hop communication and handshaking protocol lead to high efficiency of network communication and low energy consumption. Morais et al. (2008) introduced a wireless acquisition device for remote sensing applications in precision viticulture. The main concern is device power management system and connectivity failures. Proposed system proved that due to Zigbee low power consumption, Zigbee could be power up from batteries that were charged from energy harvested in solar energy and kinetic energy sources. Author's design nodes solved connectivity problem.

In the field of environmental monitoring, Junxiang and Jingtao (2011) have built a WSN based on Zigbee protocol. By combining WSN and CDMA, data were sent directly to database server on control center and hence made the data accessible in real time. Mirabella and Brischetto (2011) investigates wired/wireless network in monitoring farm made up of several greenhouses. They integrated Zigbee with Controller Area Network and proposed a suitable multiprotocol network to hide differences between two protocols. This made all devices belong to a single network and easy to control.

In Queensland, Australia, WSN-based framework to monitor marine environment have been implemented by Alippi, Camplani, Galperti and Roveri (2011). The proposed system was built to monitor underwater luminosity and temperature and corraline barrier’s status. Data obtained also gives quantitative indication related to cyclone formations in tropical areas. Each WSN device equipped with adaptive solar-energy-harvesting mechanisms and tandem batteries to prolong battery lifetime.

Besides that, Zigbee are also beneficial to health and medical sector. Malhi, Mukhopadhyay, Schnepper, Haefke and Ewald (2012) built non-invasive wearable monitoring device to monitor physiological parameters such as skin temperature, heart rate and body impact. This device utilized Zigbee as communication medium. Data obtained from monitoring device were sent to receiver unit using Zigbee. The device helps in monitoring elderly patients who needs constant lookout. Besides that, this device also easily adapted to monitor athletes and infants. Furthermore, it was equipped with panic button to notify user in case of emergency.

The deployment of Zigbee in monitoring applications also extended to renewable energy systems. Batista, Melício, Matias, and Catalão (2013) installed Zigbee system to photovoltaic and wind energy systems. They have proven proficiency of the ZigBee devices for monitoring real-time data in distributed renewable generation and smart metering systems, making them valuable, flexible and robust assets within a smart grid. Hong, Kang, and Park (2012) built Intelligent Energy Distribution Management (iEDM) to monitor environment variables and manage solar power. The proposed system utilized Zigbee as communication medium and proved that energy efficiency increased compared to normal utility interactive systems. López, Mantiñan, and Molina (2012) employed Zigbee to build low power consumption and cost-effective photovoltaic distributed generator (PV-DG) wireless remote monitoring and control system. Few tests were done to test the system capabilities and results obtained shown that Zigbee network able to monitor and control PV-DG system. This proved that it have high potentials to be extended to other energy sources. Hsu (2010) introduced a transmitting interface which was built based on Zigbee and Bluetooth to monitor wind-power electricity generator. A low cost monitoring system was introduced by Ranhotigamage and Mukhopadhyay (2011) to monitor performance of solar panel mounted on the roof of houses. The system was built using wireless sensors and Zigbee communication and capable of detecting defected solar panels that required maintenance. Katsioulis, Karapidakis, Hadjinicolaou, and Tsikalakis (2011) developed a monitoring system based on Zigbee device to monitor voltage and current output of six rooftop PV modules. Rashidi, Moallem, and Vodjani (2011) built a monitoring system to identify output voltage and current from each PV module in strings. In this research project, Zigbee was used as the data transfer mechanism (Rashidi et al., 2011). In (Li, Liao, Cai, & Pan, 2010), hierarchical Zigbee network structure has been proposed to further increased robustness of Zigbee-based network in monitoring PV array. There are several products of Zigbee-based PV monitoring system that has been commercialized, such as IntellyGreen PV from 4-noks (4-noks, 2013). However, the displayed are updates every 15 minutes while this research displayed updates every minute. In this research, the simplest Zigbee network topology is used which is point-to-point network topology instead of star topology (Ockenden, 2012).

CHAPTER 3: RESEARCH METHODOLOGY

3.1 Overview

This chapter explains the design considerations of overall system architecture. Methodology used to design the hardware and software implementations are discussed in this chapter. Hardware implementations describe installation of sensors and its measurement circuit while software implementations describe software design of every important aspect such as system control and data transmission. Position of every sensors used and range between points are discussed in this chapter. The implementations of PIC microcontroller as the main brain of the data acquisition system are also covered.

3.2 System Architecture

The system is installed in a 1.25 kW_p grid-connected photovoltaic system located at 3^{rd} and 4^{th} floor of the Wisma R&D, a 21-floors building owned by University of Malaya in Kuala Lumpur, Malaysia. Figure 3.1 shows the overall system structure of the monitoring system, which are separated into three main parts, i.e. the main base, logging point 1 (LP1) and logging point 2 (LP2). Figure 3.2 shows the overall setup of the system. The PV panels are mounted on the 3^{rd} floor balcony of the Wisma R&D building, while the inverter is located on the monitoring laboratory on the 4^{th} floor. The main base, where the host PC is placed, is located at the other end of the 4^{th} floor. Due to the fact that the various parts of the system are at separate locations, wireless-based monitoring system is preferred over cable-based system. Figure 3.3 shows LP2 view from main base control room at level 4.

As shown in Figure 3.1, the main base consists of a PC for control and one XBee for data transmission. On the other hand, each logging point (LP1 and LP2) contains several sensors for parameter measurement, one microcontroller for control, an Electrically Erasable PROM (EEPROM) for data storage and an XBee device for data transmission. Furthermore, LP1 is equipped with a real-time clock chip to provide clock function.

In this system, PIC18F4553 from Microchip is used as the microcontroller chip on the logging points. PIC18F4553 is chosen because of its low cost and high resolution (12-bits) analog-to-digital converter, which allows cheap but high accuracy measurements. A total of seven sensors are used for obtaining seven electrical and atmospheric parameter data. The electrical parameter sensors are placed at LP1 (indoor, 4th floor), and consist of

a) A voltage sensor for measuring PV panel output voltage
b) A current sensor for measuring PV panel output current
c) A voltage sensor for measuring grid-connected inverter output voltage
d) A current sensor for measuring grid-connected inverter output current

The atmospheric parameter sensors are placed at LP2 (outdoor, 3rd floor) which include

a) A temperature sensor for measuring ambient temperature
b) A temperature sensor for measuring PV panel temperature
c) An irradiance sensor for measuring solar irradiance

All sensors and their circuits are interfaced with the respective microcontroller, and the measurement is sampled at one minute interval which complies to IEC61724 standard. All data are first stored in EEPROM before being transmitted through XBee device. This is to ensure that a backup copy of the data is available even if some data is loss during transmission.

Data transmission is done using XBee devices. Each point consists of one XBee device and uses the Zigbee protocol for data transmission. The topology used is point-to-point communication which is the simplest topology among other Zigbee topologies.

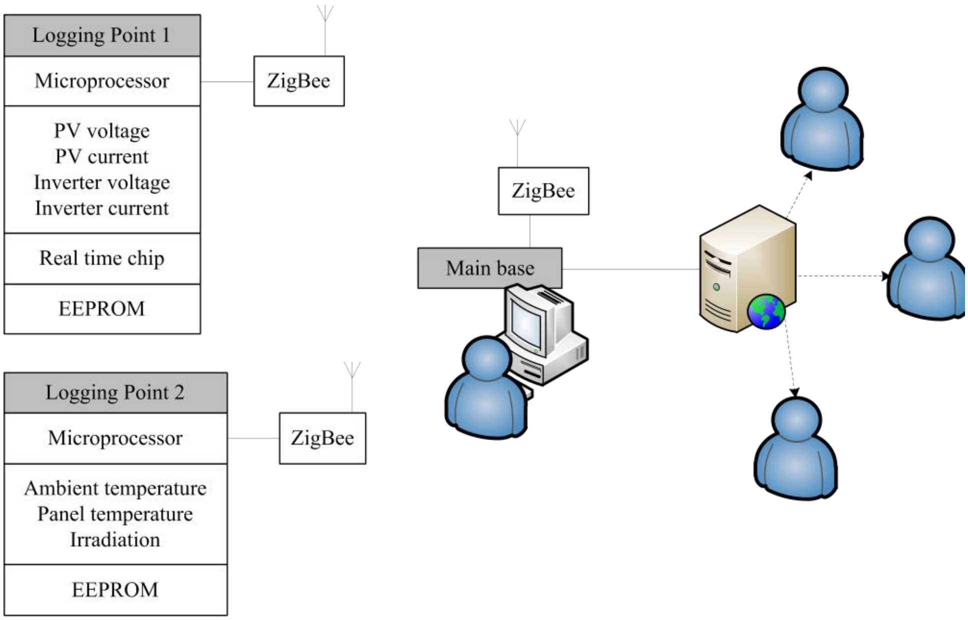


Figure 3.1: System structure of monitoring system

All data is transmitted to main base and processed by a computer. At the main base, the XBee device, which is directly connected to the PC via USB, acts as a transceiver to facilitate data exchange between PC, LP1 and LP2. A control system is developed and implemented on the main base computer using Netbeans software, with the program written in Java programming language. A single frame Graphical User Interface (GUI) with 5 buttons is created. Since the data received via XBee device is in string format, they are processed and saved into CSV format. A website is built using HTML and Hypertext Preprocessor (PHP) languages for online monitoring of the system. More details on software implementation are discussed in Section 3.4.

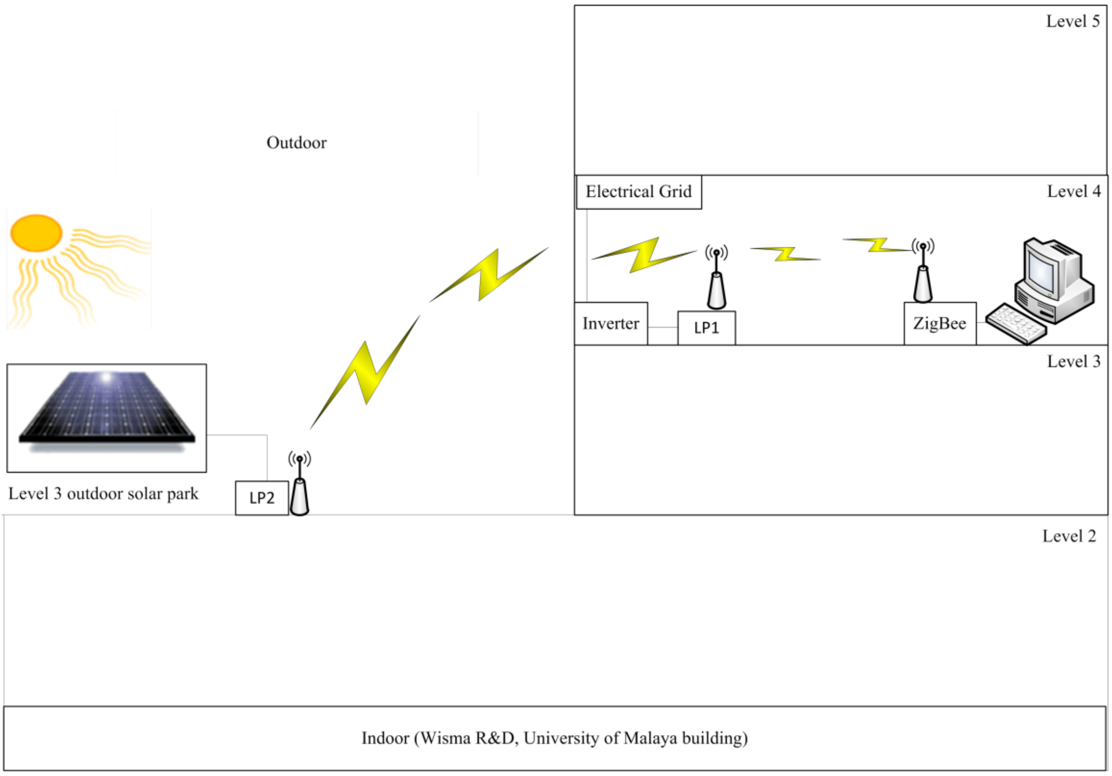


Figure 3.2: Overall architecture of the grid-connected photovoltaic system

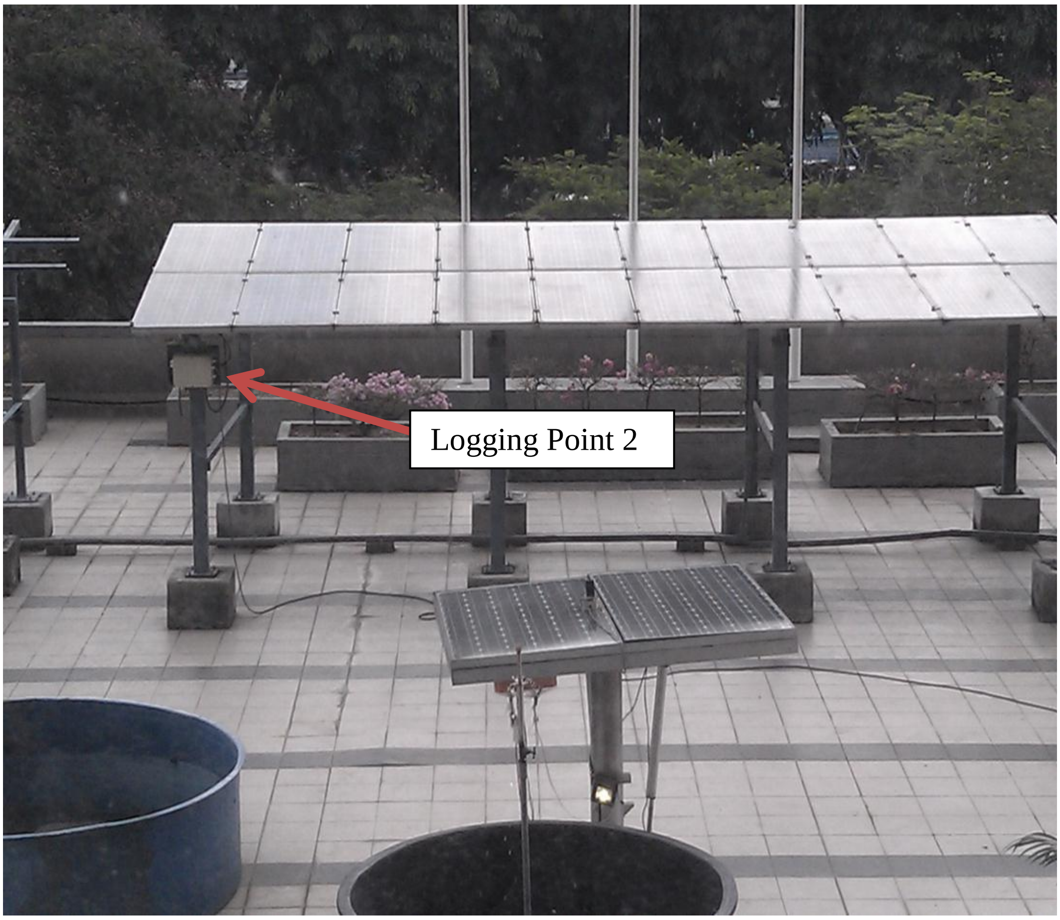


Figure 3.3: LP2 view from main base control room at level 4

3.3 Hardware Design

3.3.1 Sensor Components

(a) ***PV voltage and inverter voltage sensing***

The output voltage from PV module and inverter is measured using Voltage Transducer LV25-P from LEM, which is capable of measuring direct current (DC), alternating current (AC) or pulsed voltages. Figure 3.4 shows the connection for PV voltage transducer sensor circuit (DC) while Figure 3.5 shows inverter voltage transducer sensor circuit (AC). LV25-P is suitable for measuring nominal voltage which ranges from 10 to 500 V for either DC or AC mode. The voltage transducer is supplied with bipolar voltage supply of ±15 V. External resistor, R_1 is selected and implemented in series with the transducer primary circuit to ensure that the current is proportional to the measured voltage. Galvanic isolation between the primary circuit and the secondary circuit steps down the input voltage before being inserted to electronic circuit. The voltage transducer has two circuits; primary and secondary, which are electrically isolated from one another. Voltage measured across the primary circuit produces current in secondary circuit, where its magnitude is proportional to the measured voltage. Since the ADC circuit of the Microcontroller Unit (MCU) is voltage-fed, a resistor R_1 is needed to convert this current to the corresponding voltage signal. R_1 is calculated using the formula:

$$R_1 = V_{PN} / I_P$$

Where V_{PN} is the voltage to be measured, and primary current, I_P =10 mA.

For PV voltage, the maximum input voltage is set to 500 V. Thus, 50 kΩ resistor is used as R_1. Similar to PV voltage, maximum voltage to be measured from inverter is 500 V. R_1 for the inverter voltage sensor is also set to 50 kΩ. The advantages of using the voltage transducer are provision of excellent accuracy, good linearity, low thermal drift, high bandwidth, high immunity to external interference and low disturbance in common mode. Sensor circuits for AC or DC voltage measurement are different. DC measurement circuit is shown in Figure 3.6 while AC measurement circuit is shown in Figure 3.7. AC measurement circuit is more complex compared to DC measurement circuit. This is because additional circuits are needed to provide an offset voltage at the output of the AC measurement circuit, to ensure that the signal fed to the ADC pin on the microcontroller is within the range of 0 V to +5 V. Voltage over or less than the range may damage the microcontroller.

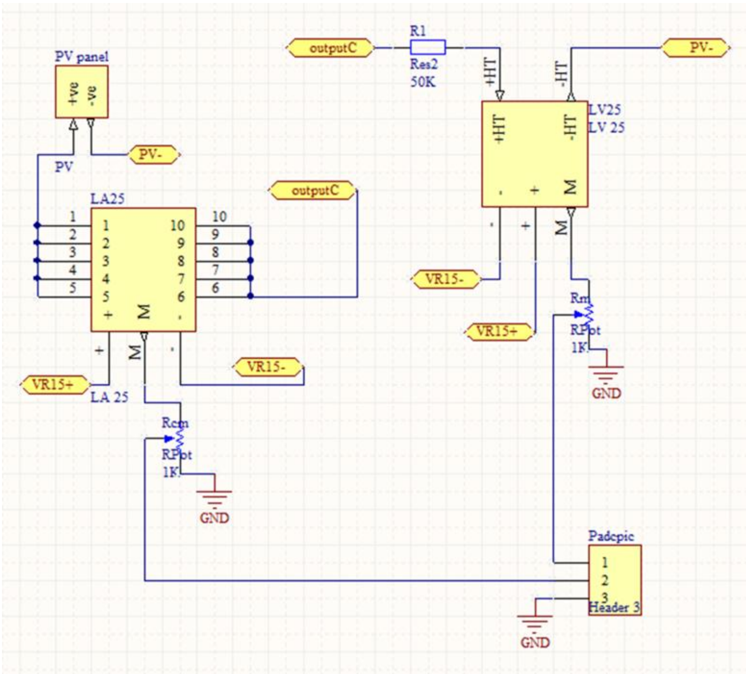


Figure 3.4: PV voltage and current transducer sensor’s circuit (DC)

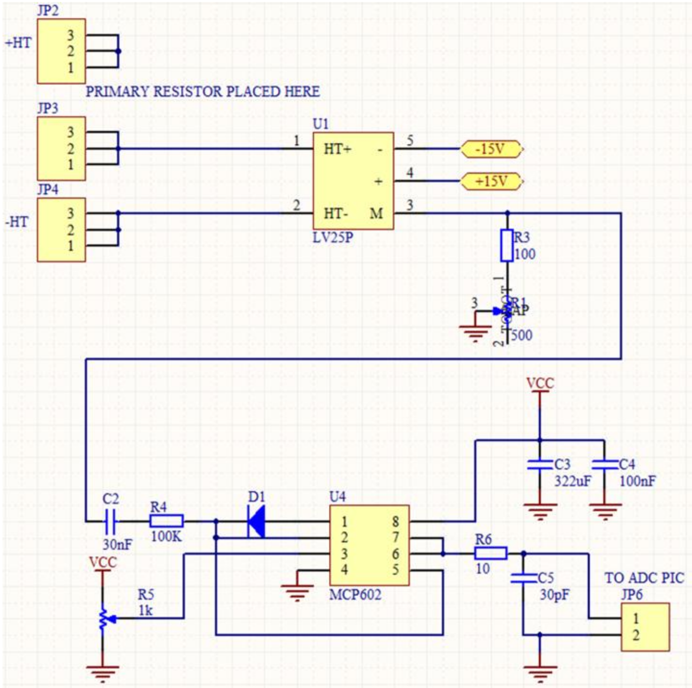


Figure 3.5: Inverter voltage transducer sensor circuit (AC)

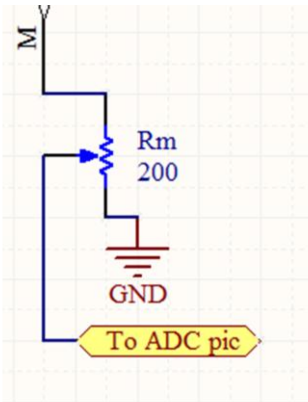


Figure 3.6: Measurement circuit for dc input from inverter

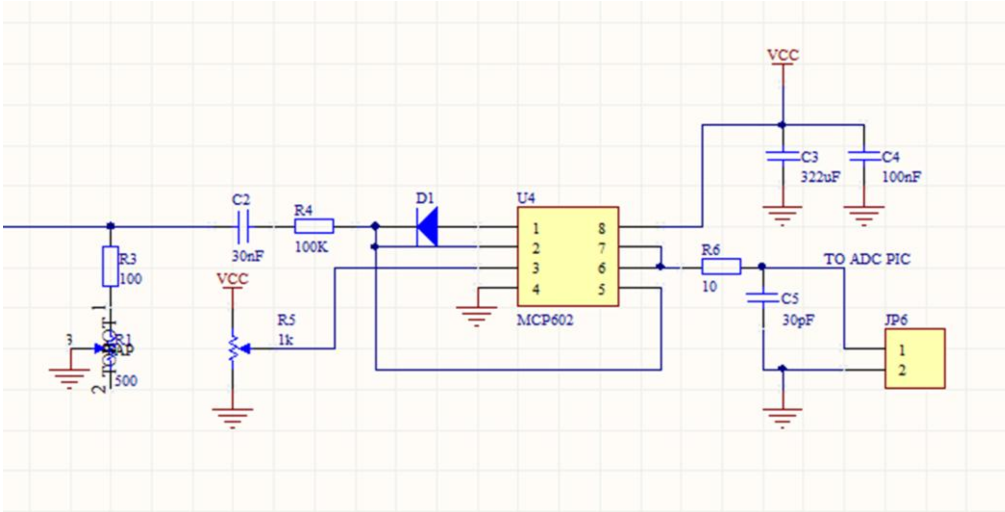


Figure 3.7: Measurement circuit for ac input from inverter

(b) ***PV current and inverter current sensing***

In this system, LA25-NP is used as the current transducer. LA25-NP is capable of measuring DC, AC and pulsed current. Unlike voltage sensors, current transducer needs to be implemented in series with the measured circuit. Figure 3.4 shows the current sensing circuit for PV current (DC) while Figure 3.8 shows the inverter current sensing circuit (AC). The current transducer can measure up to 36 A direct current and 26 A for RMS current. It also needs supply voltage range from +12 V to +15 V for positive terminal and -12 V to -15 V for negative terminal in order to operate. The current transducer is supplied with bipolar voltage supply of ±15 V. LA25-NP allows different connection of its pins to achieve different sensing current level. LA25-NP has various applicable connections depending on the current range. In this research, the first connection is used which enable the system to sustain maximum primary current, I_P up to 36 A while the nominal primary current, I_{PN} is 25 A (LEM, 2011). The advantages of the selected current transducer are excellent accuracy, good linearity, low temperature drift, optimized response time, wide frequency bandwidth, no insertion losses, high immunity to external interferences and current overload capability. Circuits for AC and

DC current measurement are similar to those of the AC and DC voltage measurement. Measurement circuits are connected to pin M of the current transducer. For AC measurement, the input needs to be shifted up to eliminate negative value before being fed to ADC pin of microcontroller similar to the voltage measurement.

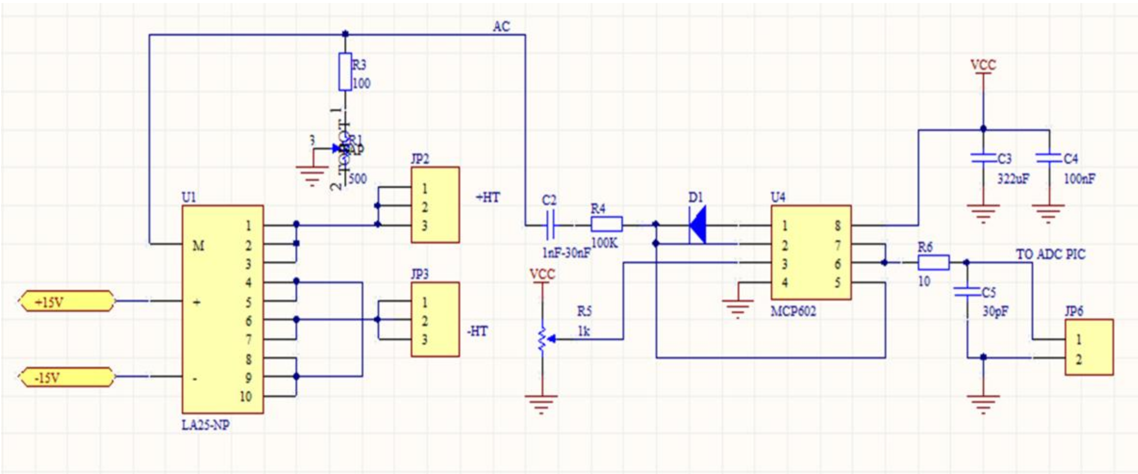


Figure 3.8: Inverter's current transducer sensor circuit (AC)

(c) ***Temperature sensing***

Two units of LM35DZ Precision Centigrade Temperature Sensor are used to measure the ambience and panel temperature (Vasileios Katsioulis, 2011). The sensor has a measuring range from -55 ˚C to +150 ˚C. The sensor output voltage is proportional to degree Celsius temperature. Thus, it has an advantage over linear temperature sensors calibrated in Kelvin. The sensor output will change by 10 mV for each degree Celsius change in temperature. Temperature sensor is installed on the back surface of the panel to measure panel surface temperature. For measuring ambience temperature, temperature sensor is placed at the side of the panel which is located in open air and in solar radiance shields as stated in IEC61724. Figure 3.9 shows the locations of temperature sensors installed on PV while Figure 3.10 shows the full-range centigrade temperature sensor circuit. In Figure 3.10, *Ta* and *Ts* denote the sensor outputs from the ambience temperature sensor and panel temperature sensor respectively. *Tout* is the connection to ADC pin of the microcontroller. The temperature sensor circuits are powered up from 5 V supply output from DC-DC converter placed after 12 V DC power supply.

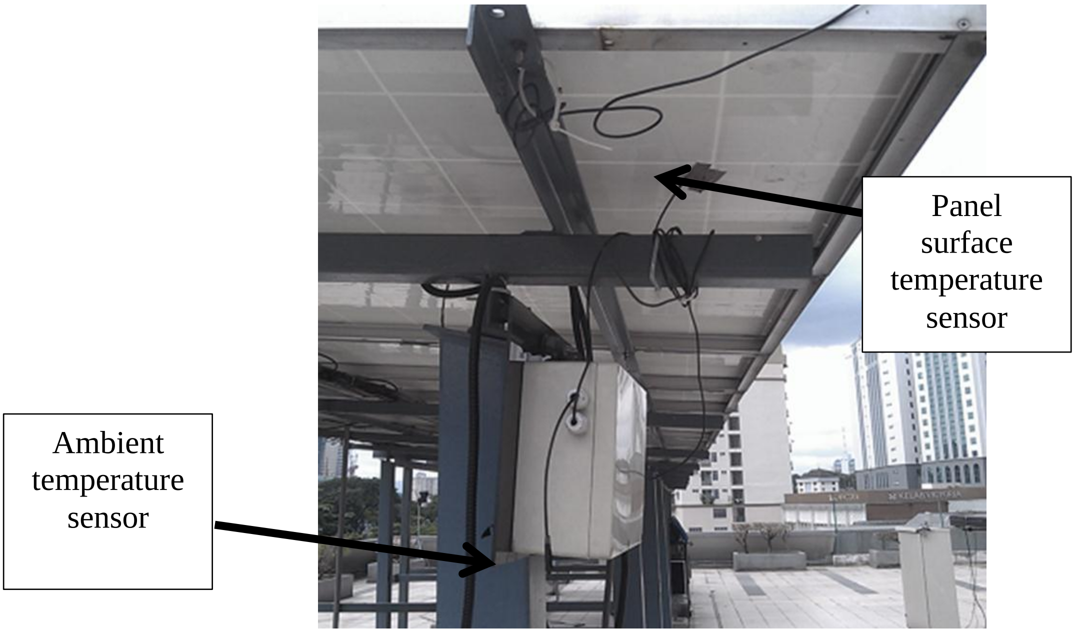


Figure 3.9: Location of temperature sensors

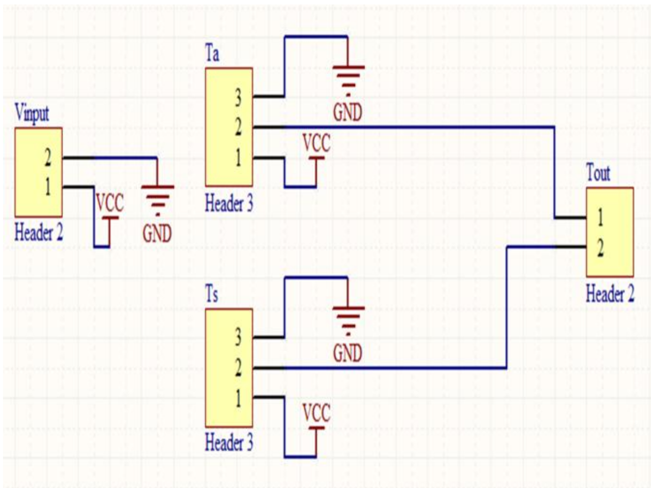


Figure 3.10: Temperature sensor circuit

(d) ***Solar irradiation sensing***

To collect data of solar radiation, a pyranometer (Li-200, model number: PY76096) from Li-Cor is placed at the edge of the panel frame, to measure solar radiation emitted from sunlight. The selected pyranometer has a measuring range from 0 W/m^2 to 2000 W/m^2, with the output given in the form of a proportional voltage, ranging from 0 V to 5 V. The voltage is provided as the input to microcontroller ADC pin.

3.3.2 Logging Point 1

LP1 is placed indoor to measure voltage and current from PV module and inverter. PIC18F4553 is used because it is equipped with 12-bit ADC which provides higher accuracy in measurement. PIC18F4553 comes with 12 ADC channels. Figure 3.11 shows the LP1 circuit. In this research, ADC pins RA0, RA1, RE0 and RE1 are used. Pins RA0 and RA1 are connected to voltage and current circuit to measure PV output while pins RE0 and RE1 are connected to voltage and current circuit to measure inverter output. 20 MHz crystal is chosen for clock. Besides that, LP1 is also connected to other sub circuits such as real time clock, EEPROM and XBee development board. Pins RB2 and RB3 are chosen as real time clock SDA and SCL pins while pins RC4 and RC5 are used as EEPROM SCL and SDA pins. RC6 and RC7 pins are connected to XBee and used as transmit and receive pins.

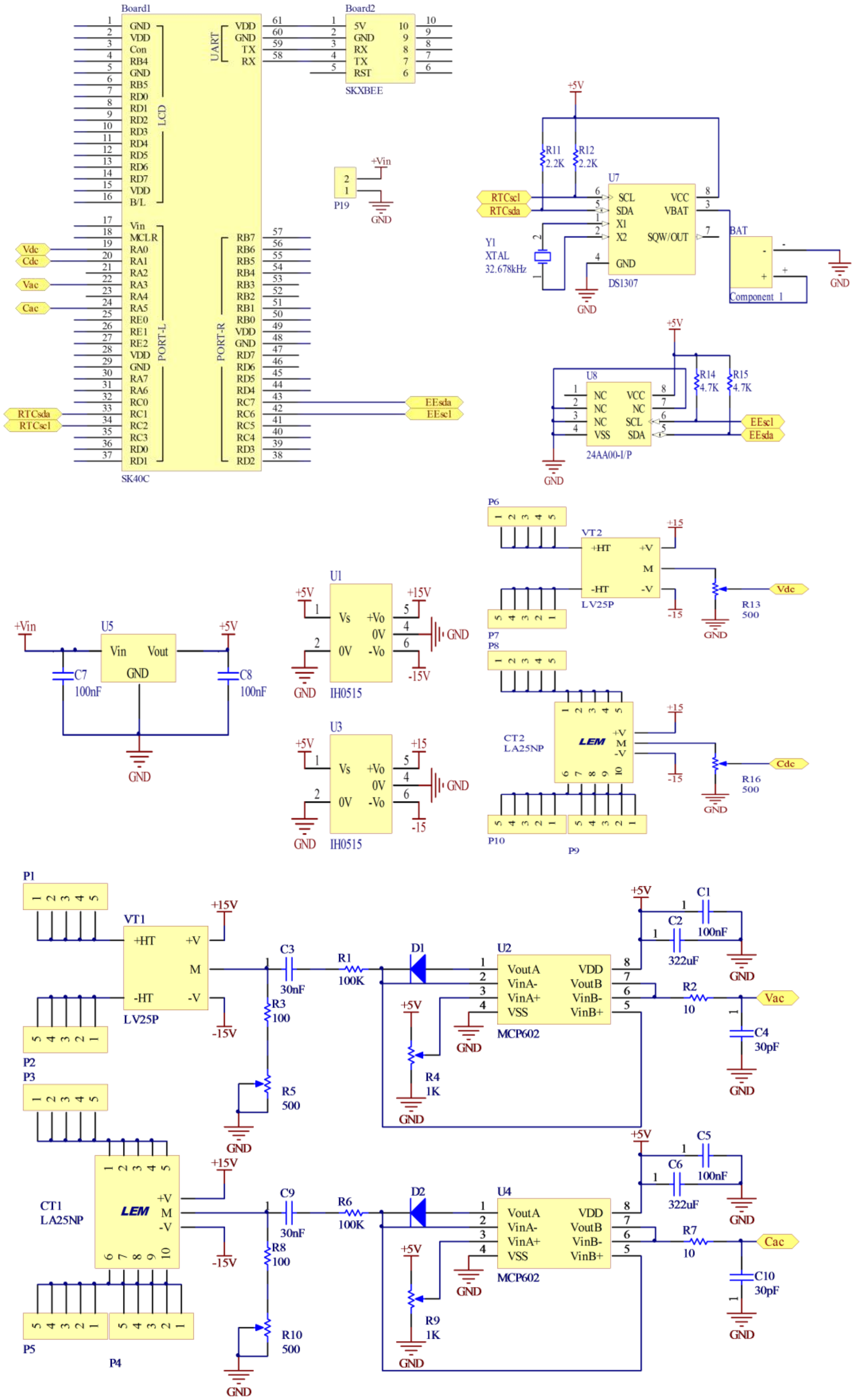


Figure 3.11: Logging point 1 circuit

3.3.3 Logging Point 2

LP2 is placed outdoor to measure ambience temperature, panel temperature and solar radiation. Similar to LP1, PIC18F4553 is used because it is equipped with 12-bit ADC which produces highly accurate data. Figure 3.12 shows the LP2 circuit. LP2 utilizes ADC pin RA5, RE0 and RE1 which are used to measure irradiation, ambience temperature and panel temperature respectively. Like LP1, 20 MHz crystal is chosen for the clock. LP2 is also connected to EEPROM circuit and XBee development board. Unlike LP1, pins RB2 and RB3 are used as EEPROM SDA and SCL pins. RC6 and RC7 are used as transmit and receive pins. LP2 used the same configuration as LP1 in LED display circuit and crystal connection.

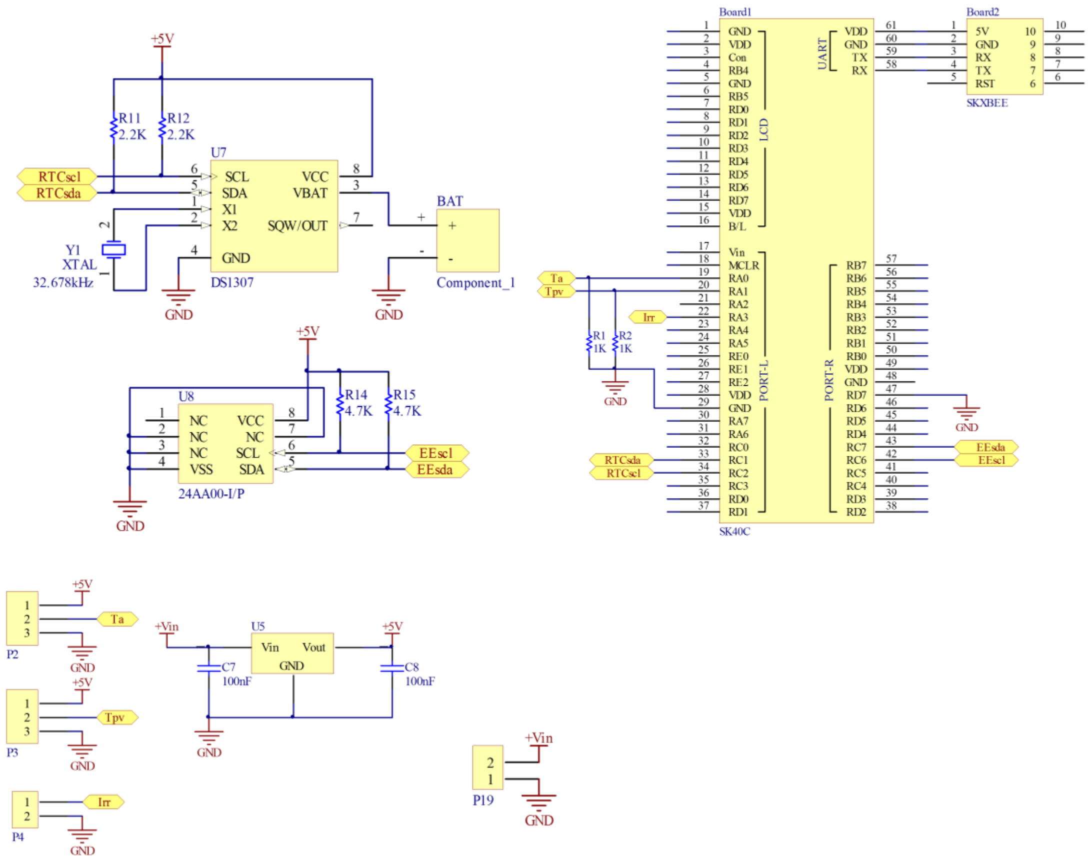


Figure 3.12: Logging point 2 circuit

3.3.4 Data Transmission

For data transmission, SKXBee board from Cytron is used as shown in Figure 3.13 (Technologies, 2013). SKXBee is a compact, easy and reliable platform which offers UART serial communication to XBee module. It is designed and ready for microcontroller interface. It may act as serial port replacement and supports various types of Zigbee devices such as XBee Series 1, Series 2, XBee Pro Series 1 and Cytron's BlueBee. It is also equipped with USB Plug and Play features.

SKXBEE board from Cytron comes with an XBee-PRO Series 1 from Digi International as shown in Figure 3.13 (Technologies, 2013). XBee-PRO transmission ranges are up to 100 m for indoor and 1500 m for outdoor compared to XBee where its transmission ranges are up to 30 m only for indoor and 100 m only for outdoor. Specifications of XBee-Pro are listed in Table C.8 (Appendix C). Figure 3.14 shows the connection made from microcontroller to SKXBee. Receive pin (Rx) of SKXBee needs to be connected to pin RC6 (Tx) which is the transmit pin of microcontroller while transmit pin (Tx) of SKXBee needs to be connected to pin RC7 (Rx) of microcontroller.

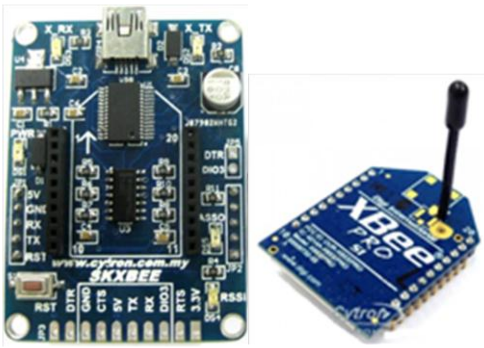


Figure 3.13: SKXBee development board from Cytron (Technologies, 2013)

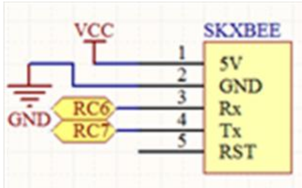


Figure 3.14: SKXBee to microcontroller connection

3.3.5 24LC1026 EEPROM

In this research, 24LC1026 EEPROM from Microchip is chosen as data storage device. This device is a 1024 kbit two-wire serial interface. Thus, only two pins need to be connected to microcontroller, which are pins SDA and SCL. It requires 2.5 V to 5.5 V supply power and maximum of 400 kHz clock frequency. It supports both byte write and page write capability of up to 128 bytes of data. Chip select pins (A1 and A2) need to be connected to either GND or Vcc to enable the control feature by microcontroller. Figure 3.15 shows the connection in EEPROM data storage circuit.

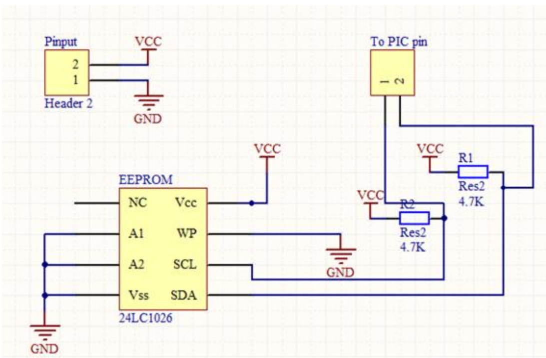


Figure 3.15: EEPROM data storage circuit

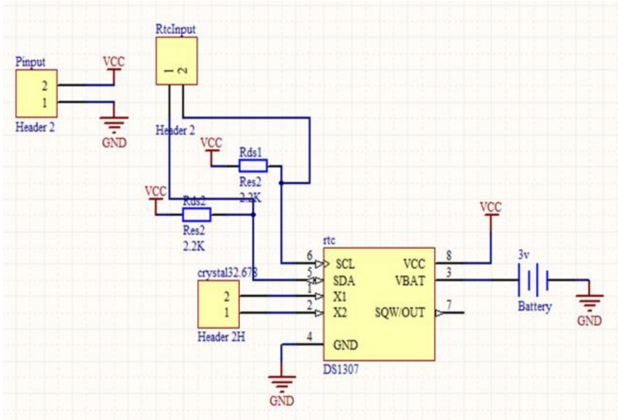


Figure 3.16: Real time clock circuit

3.3.6 Real Time Clock

Real time clock implementation is done by using DS1307 chip from Dallas Semiconductor. It has the capability to count seconds, minutes, hours and so on. This chip also uses two-wire serial interface. Hence, its implementation is easy. Data are transferred serially via the two-wire, bidirectional bus. This chip needs +5 V input to power up. From Figure 3.16, it is shown that 3 V battery is connected to pin 3 of DS1307. The chip is equipped with power sense circuit that detects power failures and automatically switches to supply power from battery. 32.768 kHz crystal is needed for crystal connection at pin X1 and X2.

3.4 Software Design

3.4.1 System Control

System control is developed using Netbeans software. In Netbeans, Java language is used. Graphical User Interface (GUI) is created using the Netbeans. As shown in Figure 3.17, GUI with five buttons is designed. Each buttons have different functions. Table 3.1 summarizes the list of buttons created in GUI and its functions. Flowchart for button ‘Initialize’ is depicted in Figure 3.18.

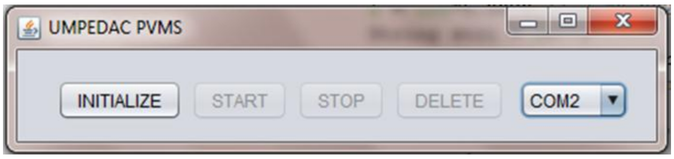


Figure 3.17: GUI in main base control system

Table 3.1: List of GUI buttons and functions

Buttons	Functions
Initialize	• Send initialize system command to LP1 • Create CSV file in main control system
Start	• Start data analysis and save it in CSV file
Stop	• Send stop monitoring command to LP1
Delete	• Delete file
COM	• Choose which communication port to communicate

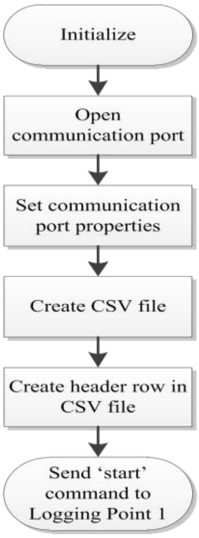


Figure 3.18: Flowchart for button 'Initialize'

When button ‘Initialize’ is clicked, communication port is opened and its properties such as baud rate, parity bit, total bits send are set. Drop down list in GUI will determine which port will be opened when the button ‘Initialize’ is clicked. After that, CSV file is created and saved to specific folder. The file naming is done based on the date set in main control PC. In the first row of the CSV file, header for column A to L will be created along with the creation of CSV file. Then, start command is sent to LP1 to initiate monitoring process.

Flowchart for button ‘Start’ is presented in Figure 3.19. After clicking on the button ‘Start’, ‘raw.txt’ and ‘rawsave.txt’ files are created. All data received from port are saved in these files. ‘raw.txt’ file is used when system retrieves the data before saving them to CSV file while ‘rawsave.txt’ file is archive files used for saving all raw data. More discussions on this process are explained in data processing section.

The function of button ‘Stop’ is to send command to LP1 to stop monitoring while button ‘Delete’ functions are to delete and clear ‘raw.txt’ file from database. Flowchart for these two button processes are shown in Figure 3.20 and Figure 3.21.

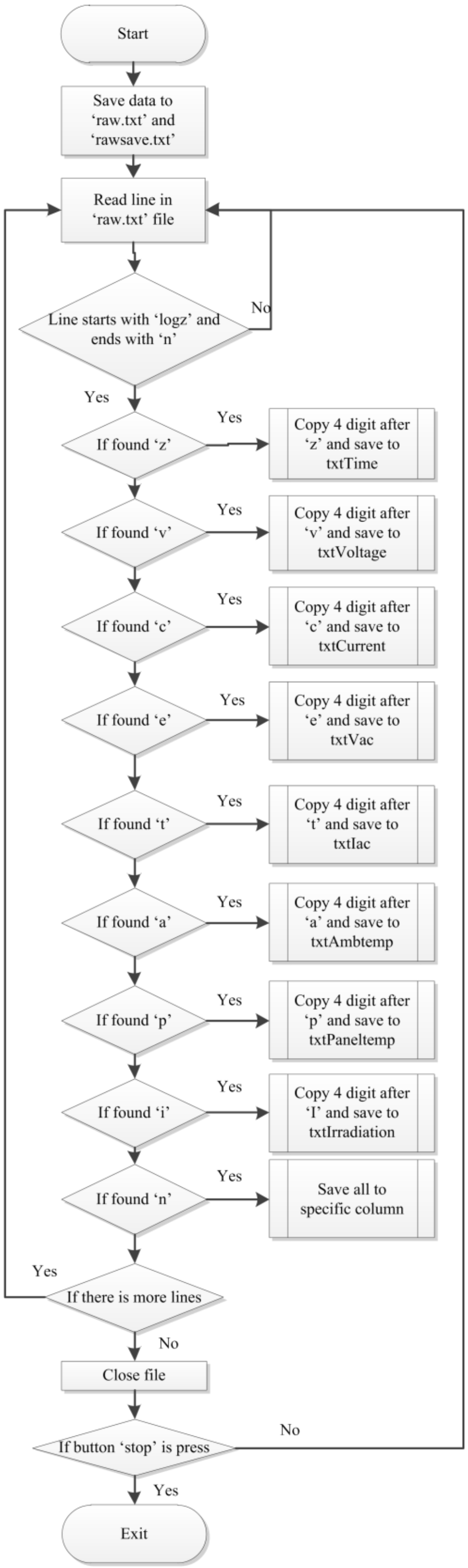


Figure 3.19: Flowchart for button 'Start'

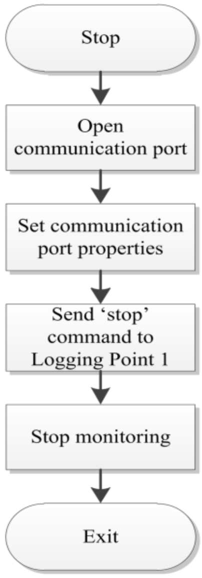


Figure 3.20: Flowchart for button 'Stop'

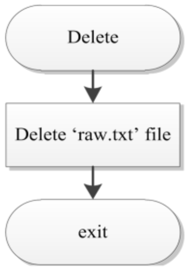


Figure 3.21: Flowchart for button 'Delete'

LP1 and LP2 codes are developed using C programming. Flowcharts for LP1 process is shown in Figure 3.22. Firstly, LCD display, DS1307 chip and EEPROM are initialized. Next, it will wait till ‘Start’ command is received from main base. Afterwards, monitoring process will start by getting date and time information from DS1307. Then, microcontroller will start reading ADC value from pins RA0, RA1, RE0 and RE1 in sequence. Then, data are sent along with its assigned start bit to LP2. ADC value is saved in EEPROM for backup purpose in case of data loss during transmission. Before the process ends, microcontroller will check whether any ‘Stop’ command is received. If no ‘Stop’ command received, monitoring process will continue.

LP2 codes are much simpler compared to LP1 as it only consists of temperature sensor, irradiance sensor, and EEPROM. From Figure 3.23, the process starts with initialization of LCD display and EEPROM. Then, microcontroller will wait for any received data. If the data received starts with ‘logz’ which is the start bit assigned in LP1, all data received in port are saved to String1. After that, monitoring process will start. ADC value from ambient sensor, panel temperature sensor, and irradiance sensor are transmitted to main base along with String1 which contains the data received from LP1. Data measured from ADC value are saved in EEPROM for backup. Zigbee remained idle and turned on when the next cycles of data are ready to be sent.

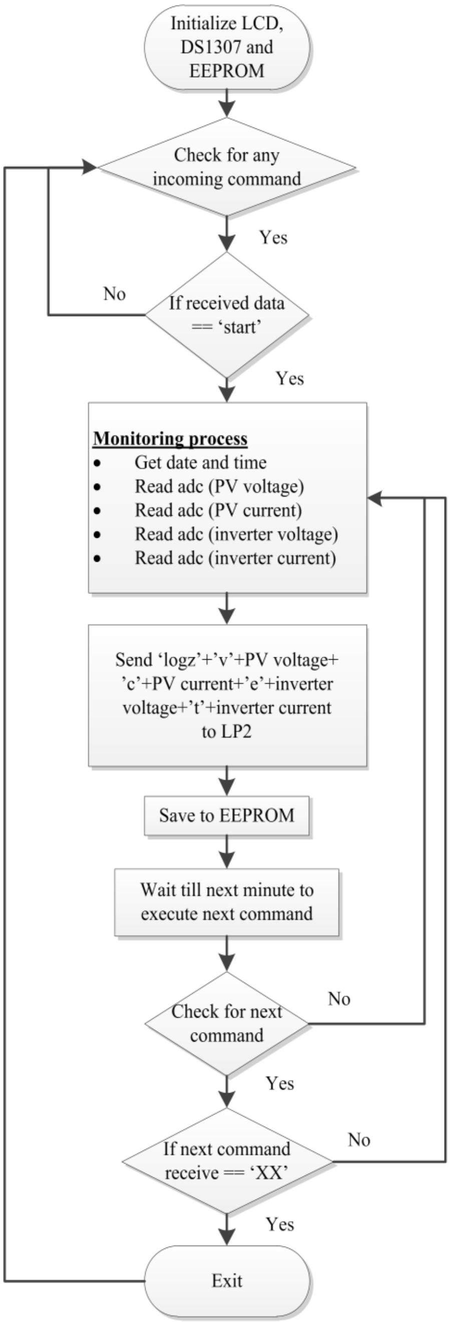


Figure 3.22: Flowchart for LP1

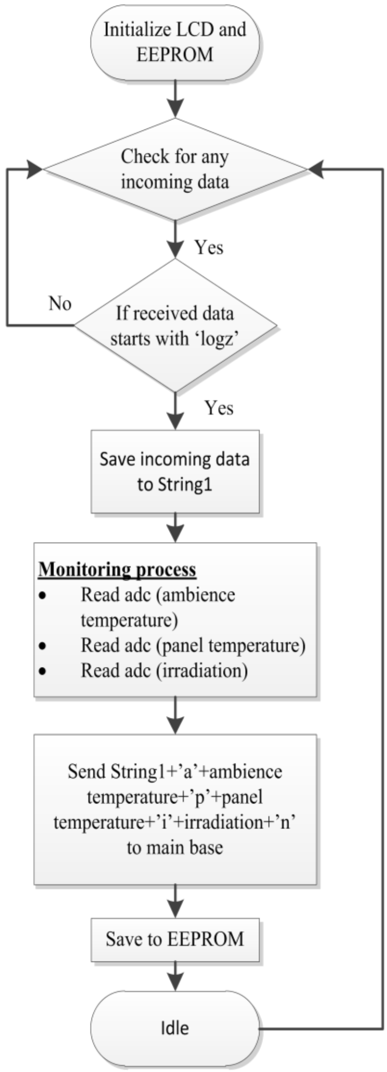


Figure 3.23: Flowchart for LP2

3.4.2 Data Transmission

Data transmission between LP1, LP2 and main base are done using XBee-PRO by applying Zigbee protocols. Data is designed in point-to-point network topology which is the simplest in Zigbee topology network. Initialization message is sent from main base to LP1. LP1 will send collected data from voltage and current transducer to LP2. Then, the combined data from LP1 and LP2 will be sent back to main base from LP2 to be processed and stored. In order to ensure wireless connection between the three points is established, few settings need to be applied to each XBee-Pro device before running the system. Figure 3.24 shows the procedures done to create wireless link between devices while Figure 3.25 shows the direction for transmission of all points.

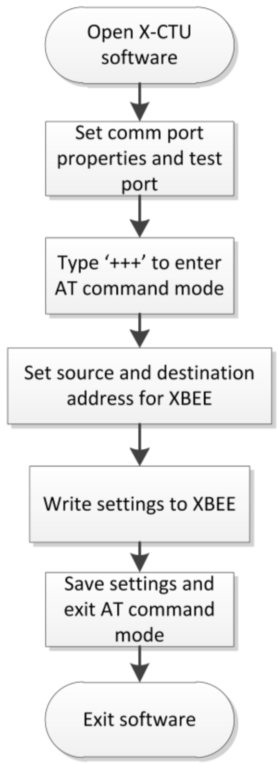


Figure 3.24: Flowchart of XBee-PRO settings

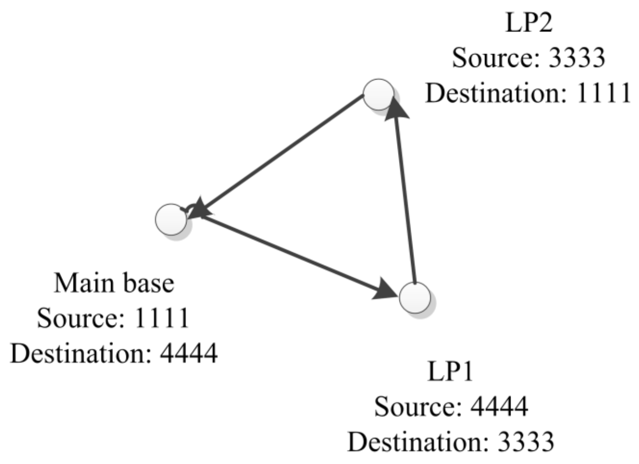


Figure 3.25: Direction of transmission with source and destination address for main base, LP1 and LP2

The main concern is settings the source and destination address of each wireless node. From Figure 3.25, it can be seen that source address for LP1 wireless device must be equal to main base's destination address to establish wireless link between the points. Similarly, source address of LP2 must match with destination address of LP1 and these also apply to wireless link between LP2 and main base.

3.4.3 Displaying Data Online

Added value feature which enable user to monitor data online has been added to the system. Web pages interface are designed by using Adobe Dreamweaver software in HTML while table and graph display are designed by using PHP. The designed web pages consists of a table displaying real time data on power generated and energy yield from PV module, energy output from inverter and cumulative power generated from PV module and graph of daily monitored data. Figure 3.26 shows the flowchart for table display process while Figure 3.27 shows the flowchart for graph display process. When a user browses the webpage, 'tableright.php' is run to display the table with data on power generated and energy yield from PV module, energy output from inverter and cumulative power generated from PV module. First, date and time information from main PC will be collected and used to check the existence of CSV file. If no file exists, alert message will echo. If the file exists, the file is then opened and the total column in each row is counted. Then, arrays will be populated. Data that corresponds to the particular time obtained before will be extracted from column 0. If data is available, it will echo on page according to column assigned. If no data exists at that particular time, alert message of ‘data not available’ is displayed.

Graph display is created by integrating PHP code and library from pChart. Based on Figure 3.27, when button ‘Submit’ is clicked, day, month and year variable chosen by the user will be parsed to ‘action.php’ file. Then, it will check whether the file exists or not. If no file exists, alert message will echo on screen. If file existed, variable are parsed to ‘graphnew.php’ file. Data from CSV are imported and graph properties are set before scale and legend are created. After all procedures are done, graph will be rendered and displayed online.

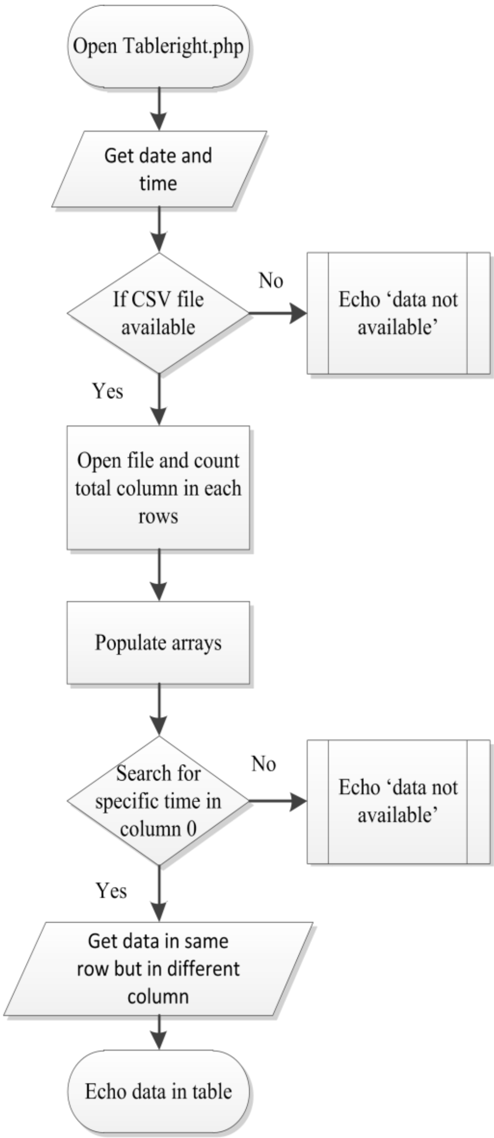


Figure 3.26: Flowchart of table display

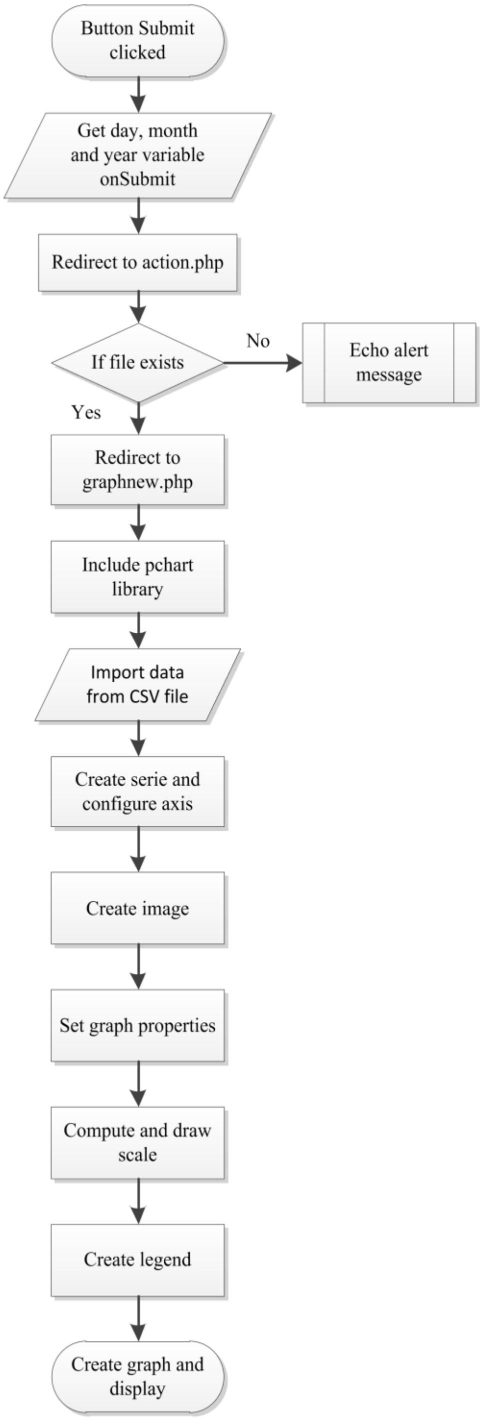


Figure 3.27: Flowchart of graph display

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Results of System Control

Figure 4.1 shows the result of system control after implementation of the monitoring system. It can be seen that when the button 'Initialize' is clicked, output form displays 'Message Sent' which indicates that start monitoring command is sent to LP1. After button 'Start' is clicked, 'Requesting data from port' is displayed on output form which indicates that the connection to communication port has been established and the system is ready to receive data. Output form also displays the total bytes of raw data received in port and the raw data is saved to text file before the system allocates the received string to specific column. 'Time's up!' string in output form indicates that 1-minute cycle is completed and next cycle will begin. The whole process is repeated until button 'Stop' is clicked.

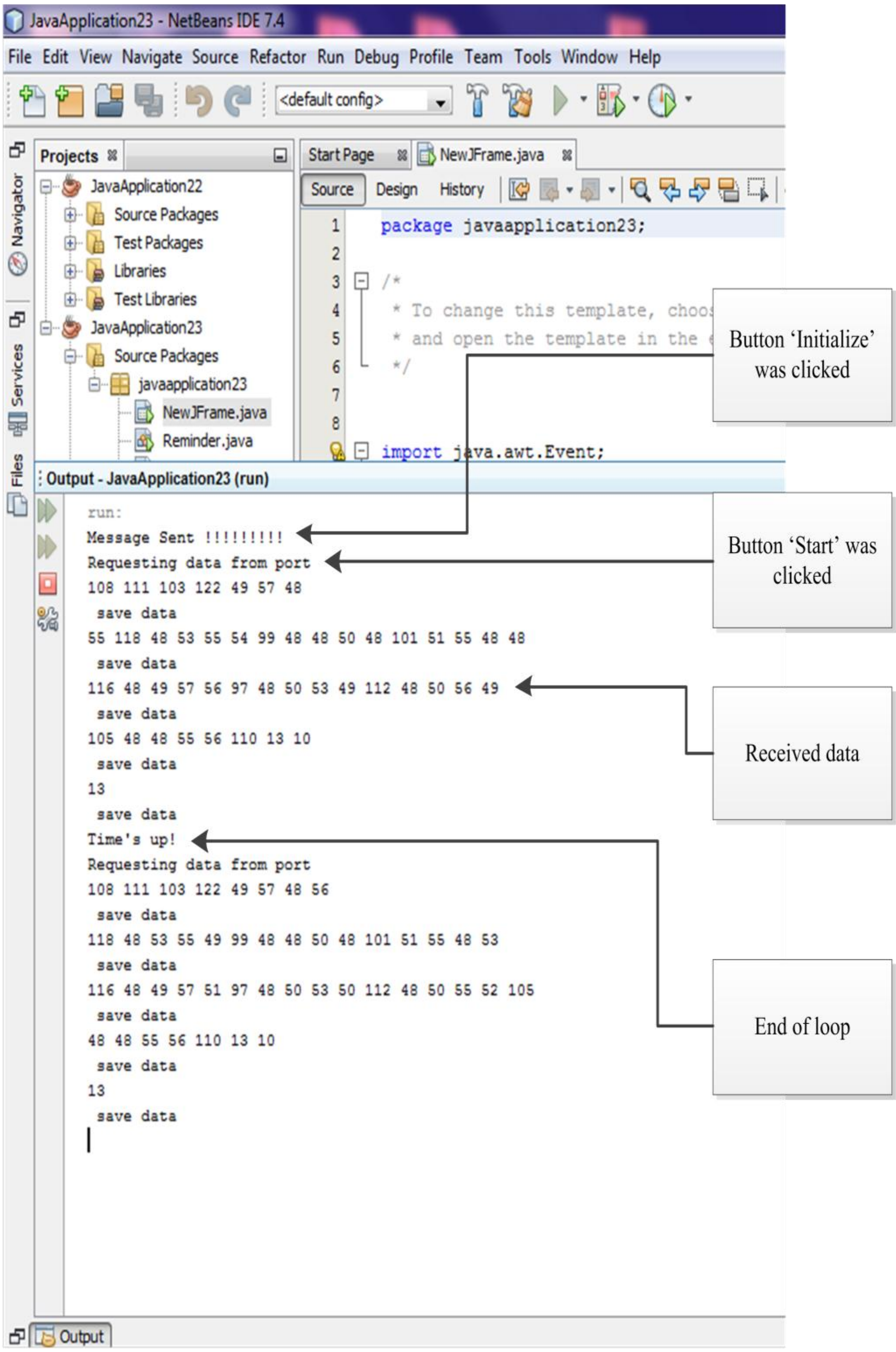


Figure 4.1: Output of control system

4.2 Results of Daily Power Generation

Data processing is done in main base using Netbeans software. The data received from LP2 are in a string format which contains time, ADC value of PV voltage and current, inverter voltage and current, ambience and panel temperature and solar radiation. For initialization, fixed ASCII character (logz) is added to the front of the string as shown in Figure 4.2 (a). Next, LP1 microcontroller adds time after ‘logz’ character followed by ‘v’ to acknowledge main base that the next 4 digits number is ADC values of PV voltage. Before adding PV current ADC value, ASCII character ‘c’ is added to differentiate one ADC value from another to facilitate data processing later. The same approach is used to every ADC value measured. For inverter voltage, ASCII character ‘e’ is added and character ‘t’ is used for inverter current. After LP1 has completed the string formatting as in Figure 4.2 (a), it transmits them to LP2. For ambience temperature, ‘a’ is chosen and character ‘p’ is assigned to panel temperature. Character ‘i’ is used for irradiation and character ‘n’ is put at the end of the string to express the end of one cycle of data transmission. LP2 will concatenate the string received from LP1 with new measured data that has been arranged as in Figure 4.2 (b) and send them to main base.

Data processing is done at main base. When button ‘Start’ is pressed, raw data received in the serial port is saved to text file. Then, every string is inspected. Only complete string which starts with ‘logz’ and ends with ‘n’ is read. After character ‘z’ is found, 4 digits number after the character is saved to txtTime. For other parameters, similar process is executed but with different start bit as assigned based on Figure 4.2.

Raw data are retrieved from text file and saved in CSV format file according to the column. Figure 4.3 shows the CSV file created and data stored on 11th of February 2014, from 12.00 am to 11.59 pm. Every first row in the CSV file created contains header from column A to L as shown in Figure 4.3. Data obtained from voltage and current measurement are compared with data obtained from FLUKE345 and FLUKE435 Series II. Figures 4.4-4.7 shows the plotted graphs from both measurements. After comparing both graphs, offset value is measured to calibrate the sensors. Analysis on sensors uncertainties are done in section 4.4.

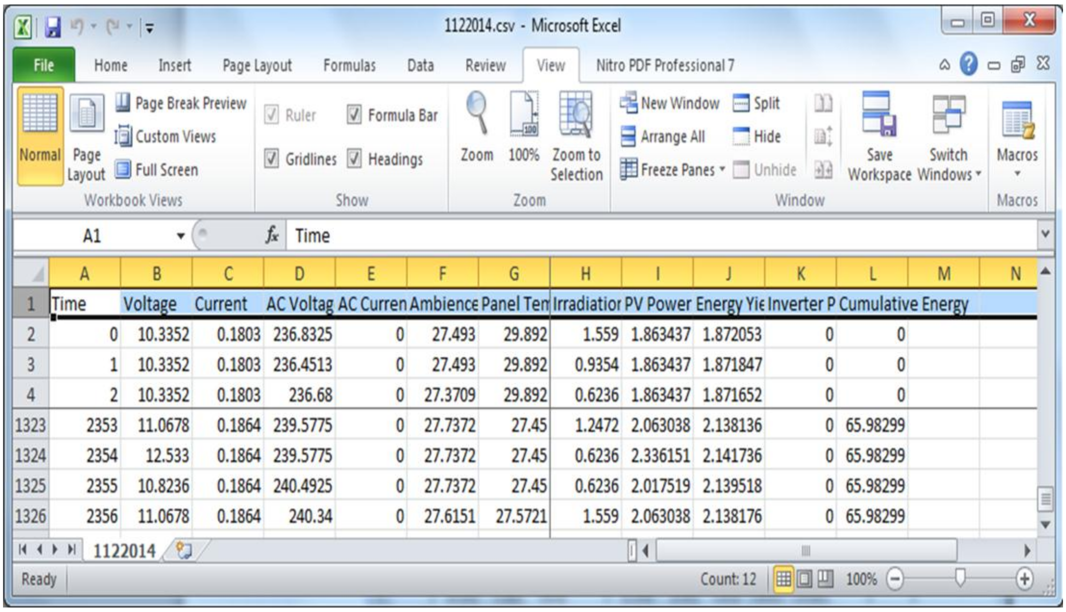
(a)

Initialize	Time	Start char	V_{pv}	Start char	I_{pv}	Start char	V_{ac}	Start char	I_{ac}
logz	xxxx	v	xxxx	c	xxxx	e	xxxx	t	xxxx

(b)

Start char	T_a	Start char	T_m	Start char	G	End char
a	xxxx	p	xxxx	i	xxxx	n

Figure 4.2: String format for data transmitted: (a) Logging point 1 (b) Logging point 2


1122014.csv - Microsoft Excel

	A	B	C	D	E	F	G	H	I	J	K	L
1	Time	Voltage	Current	AC Voltag	AC Curren	Ambience	Panel Ten	Irradiatior	PV Power	Energy Yie	Inverter P	Cumulative Energy
2	0	10.3352	0.1803	236.8325	0	27.493	29.892	1.559	1.863437	1.872053	0	0
3	1	10.3352	0.1803	236.4513	0	27.493	29.892	0.9354	1.863437	1.871847	0	0
4	2	10.3352	0.1803	236.68	0	27.3709	29.892	0.6236	1.863437	1.871652	0	0
1323	2353	11.0678	0.1864	239.5775	0	27.7372	27.45	1.2472	2.063038	2.138136	0	65.98299
1324	2354	12.533	0.1864	239.5775	0	27.7372	27.45	0.6236	2.336151	2.141736	0	65.98299
1325	2355	10.8236	0.1864	240.4925	0	27.7372	27.45	0.6236	2.017519	2.139518	0	65.98299
1326	2356	11.0678	0.1864	240.34	0	27.6151	27.5721	1.559	2.063038	2.138176	0	65.98299

Figure 4.3: View of CSV file (11 February 2014)

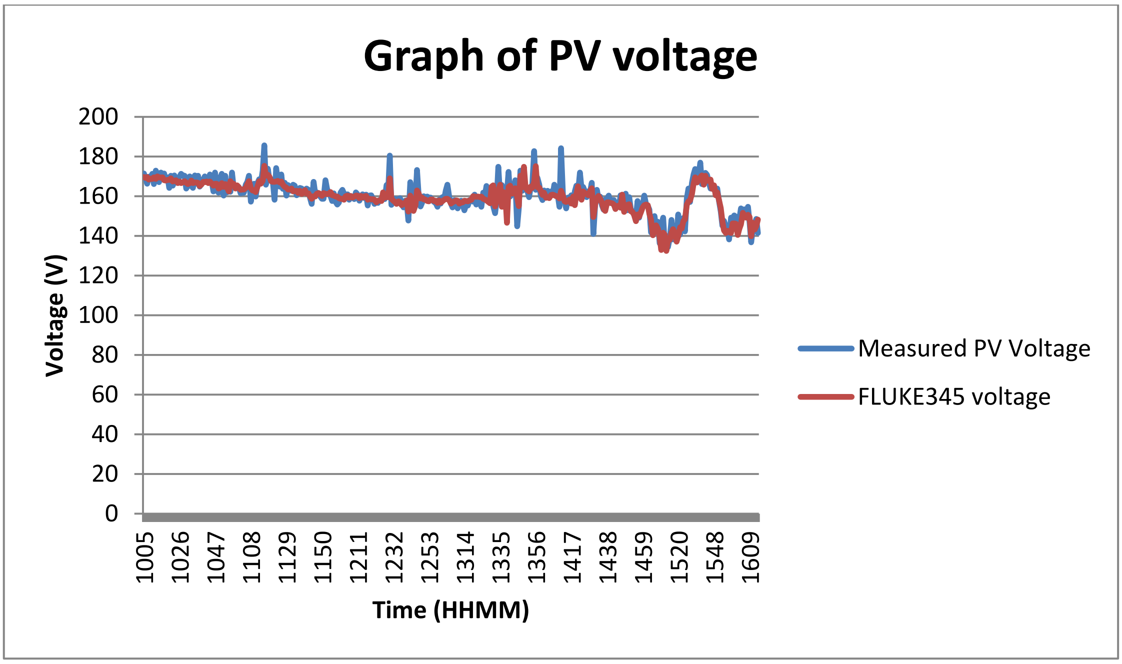


Figure 4.4: Comparison of measured and actual PV voltage

Figure 4.4 shows graph of measured PV voltage and measurement from FLUKE345. It is observed that the result of measured PV voltage has similar contour to FLUKE345 result. This confirms the accuracy of the developed DC voltage measurement system. Voltage sensor response time is 40 µs. It is evident from Figure 4.4 that a non-uniform voltage spike occurred in the measurement data. Due to the stochastic nature of solar irradiance, there are times where measurement is taken during sudden change of irradiance which causes the voltage spikes occurrence. Sudden change in irradiation is quite common due to Malaysia's cloudy atmosphere.

Graph of measured PV current and FLUKE345 are shown in Figure 4.5. Based on the figure, it is shown that both graphs have similar trend. Response time for current sensor is less than 1µs. There are some spikes shown in measured PV current because the developed system takes instantaneous values while the FLUKE345 shows average of readings. Although there is only one second difference when taking measurement, it may results in different measurement value recorded due to the rapid changes of irradiation. PV current rapidly changed when irradiation changed.

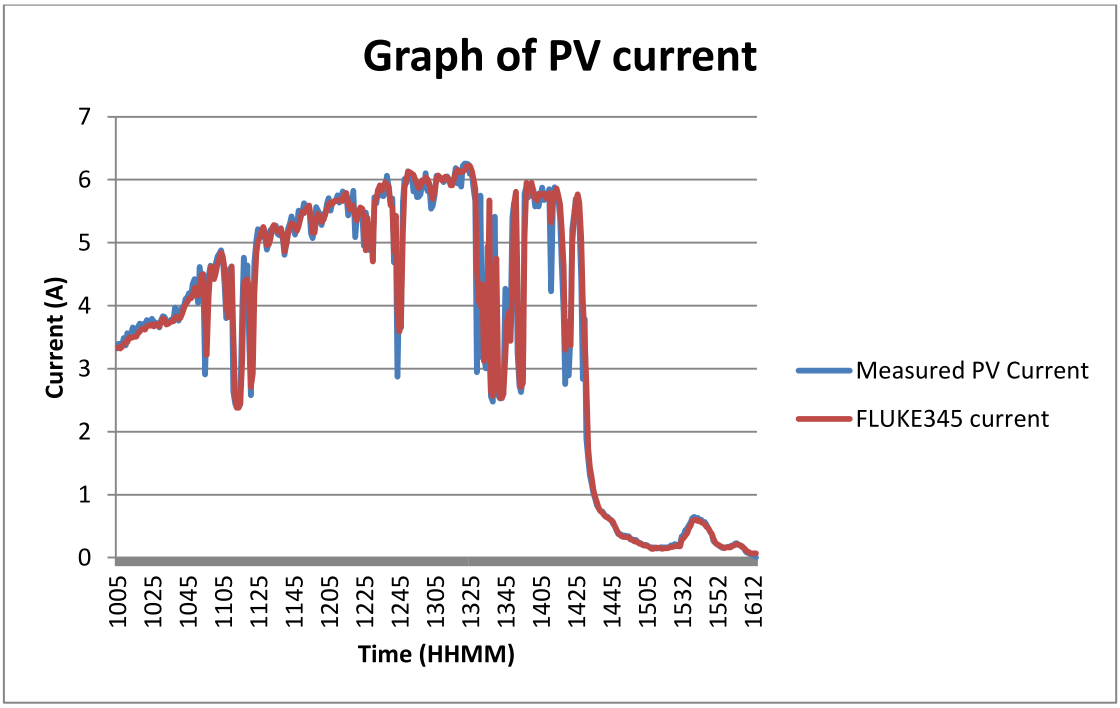


Figure 4.5: Comparison of measured and actual PV current

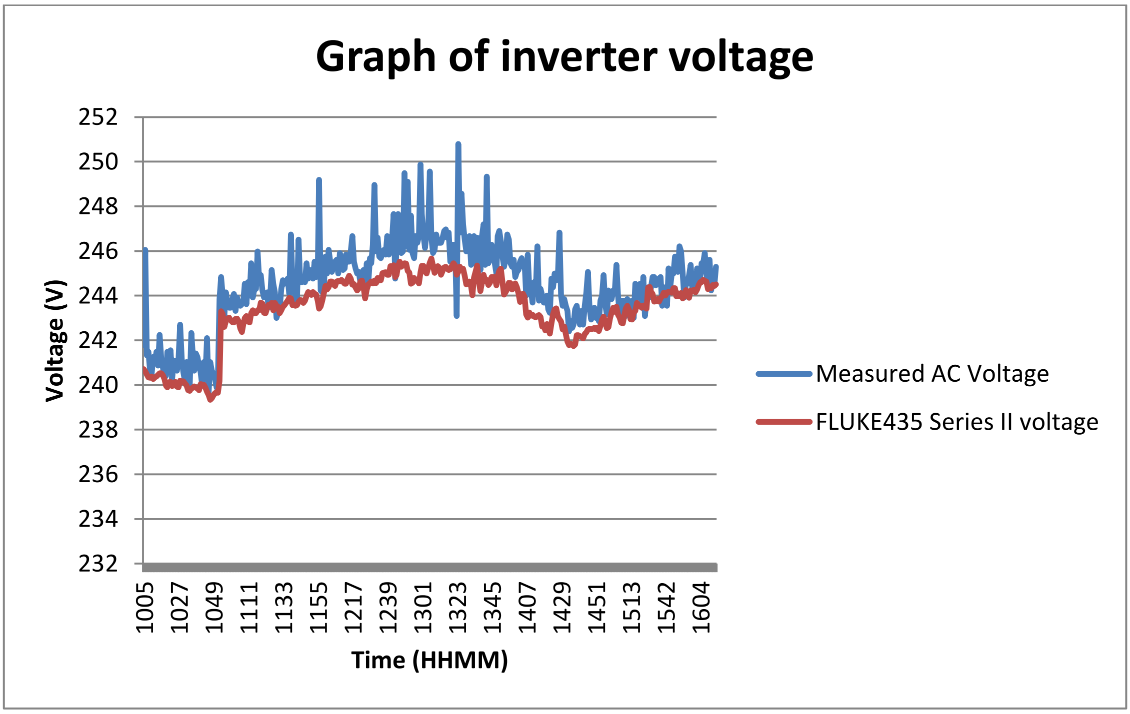


Figure 4.6: Comparison of measured and actual inverter voltage

Figure 4.6 shows the graphs of measured AC voltage and value of actual AC voltage measured with FLUKE435 Series II Power Quality and Energy Analyzer. Both graphs have similar shape despite large fluctuations in measured AC voltage. The fluctuations are due to the fact that FLUKE435 averages its reading, while the measured AC voltage does not perform any averaging. Graph in red trace is more stable because results are taken based on average voltage value for every complete signal while blue trace graph (measured voltage) is measured by taking the largest peak-to-peak voltage. RMS voltage is calculated based on the peak-to-peak voltage. Regardless of large fluctuations in measured AC voltage, error in measurement is still in acceptable range.

Graph of measured AC current and actual current measured using FLUKE80I-110s are plotted in Figure 4.7. It is observed that the graph of proposed monitoring system has similar profile to the graph obtained from FLUKE80I-110s measurement. The time when measurement is taken from both systems may differ by few seconds. Due to the cloudy atmosphere in Malaysia (Wong, Lim, Tang, & Morris, 2014) that results in quick changes of solar irradiation, inverter current can experience rapid changes within the time frame of several seconds. As a result, the delay in measurement instance causes slight differences in the measurement values recorded.

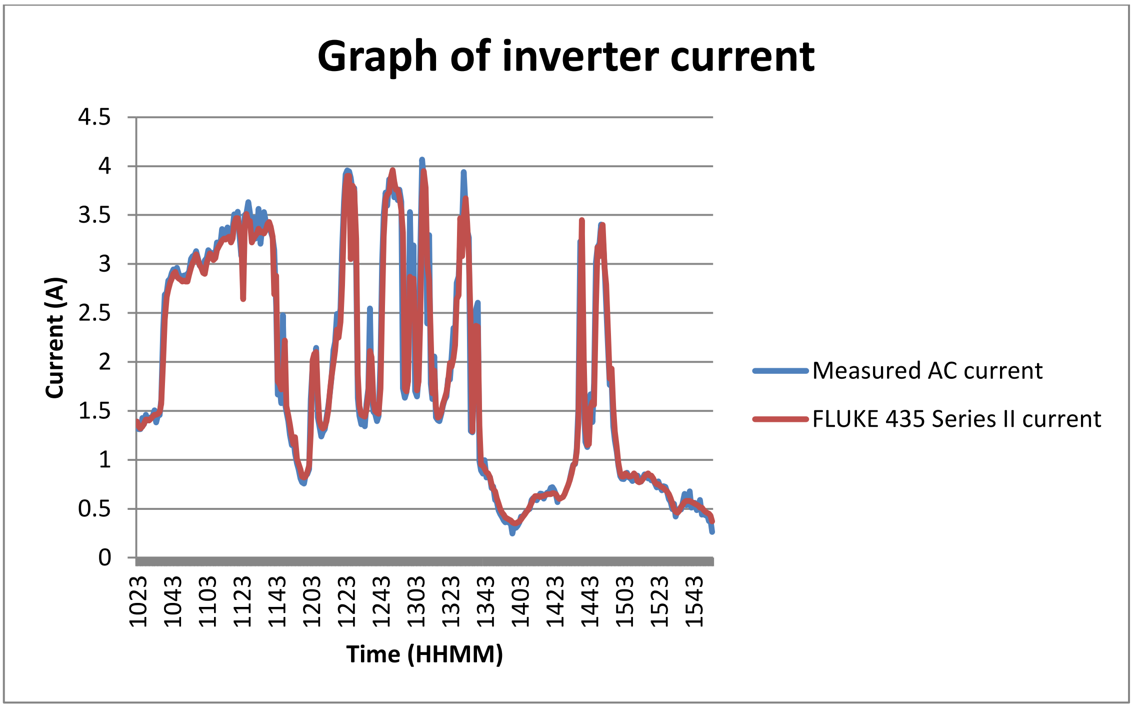


Figure 4.7: Comparison of measured and actual inverter current

4.3 Results of Online Monitoring

As mentioned previously in Chapter 3, the proposed system is also designed such that user can monitor the data online. There are three types of functions built in the online monitoring system web-page. One of the functions is displaying data in tabular form. Figure 4.8 shows the online monitoring system web-page which contains the data obtained from monitoring system arranged in tabular form. The snapshot of online web-page is captured on 11 February 2014 at 1013 hours. Displayed data are retrieved from CSV file saved at that time. Since the data measurements are done at a sampling interval of 1 minute, the refresh rate of the web page is set to be 1 minute as well. While this improves the responsiveness of the web page, the data displayed will always have a 1 minute delay from the real time data collected by the monitoring system. Figure 4.9 shows the CSV file saved on 11 February 2014. It proves that the data stored in CSV file are retrieved and displayed in table online.

Besides that, the online monitoring system web-page also consists of widgets located at the right side of the page as seen in Figure 4.8. The widgets display current date and time, current meteorological parameters obtained and also weather forecast from satellite. The information aids user to monitor current ambient, module temperature and irradiation. Users can also compare temperature parameter obtained from measurement with data from satellite.

To provide a clearer and more intuitive interpretation of the data, the online monitoring system web-page is also equipped with display graph function to allow the user to view the data in the form of graph. Figure 4.10 shows the graphs of completed measured data displayed online. In this figure, data on output PV voltage; output PV current; output inverter voltage; output inverter current; ambience temperature; module temperature; irradiation; instantaneous PV power; instantaneous inverter power and energy obtained from PV module are plotted. These graphs provide a better view and understanding for user to monitor and analyze the grid-connected PV system performance.

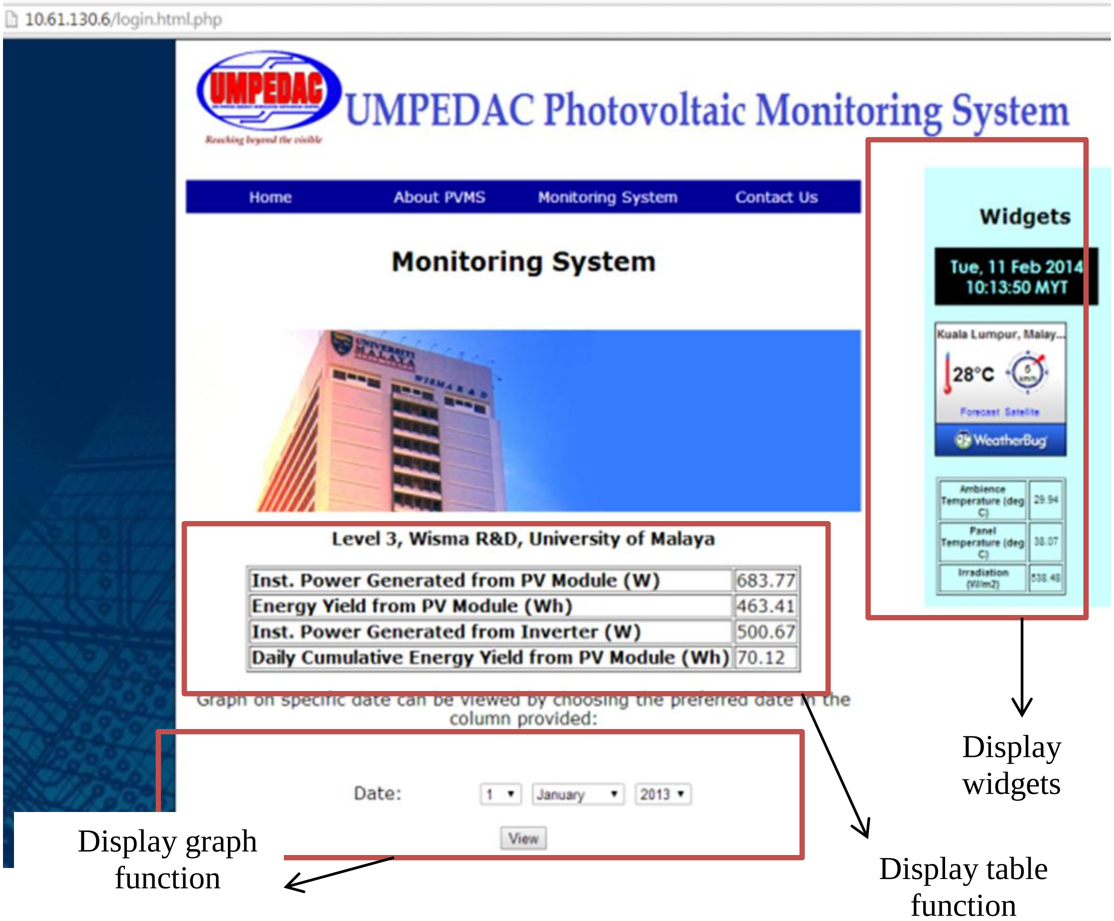
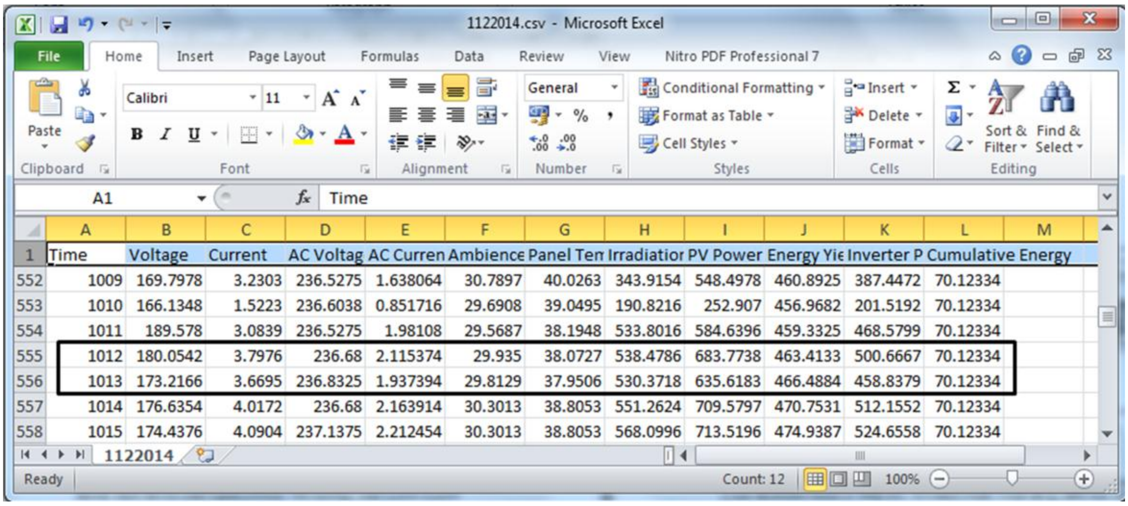


Figure 4.8: Online monitoring system web-page on 11 February 2014 (10:13 hours)



	A	B	C	D	E	F	G	H	I	J	K	L
1	Time	Voltage	Current	AC Voltag	AC Curren	Ambience	Panel Ten	Irradiatior	PV Power	Energy Yie	Inverter P	Cumulative Energy
552	1009	169.7978	3.2303	236.5275	1.638064	30.7897	40.0263	343.9154	548.4978	460.8925	387.4472	70.12334
553	1010	166.1348	1.5223	236.6038	0.851716	29.6908	39.0495	190.8216	252.907	456.9682	201.5192	70.12334
554	1011	189.578	3.0839	236.5275	1.98108	29.5687	38.1948	533.8016	584.6396	459.3325	468.5799	70.12334
555	1012	180.0542	3.7976	236.68	2.115374	29.935	38.0727	538.4786	683.7738	463.4133	500.6667	70.12334
556	1013	173.2166	3.6695	236.8325	1.937394	29.8129	37.9506	530.3718	635.6183	466.4884	458.8379	70.12334
557	1014	176.6354	4.0172	236.68	2.163914	30.3013	38.8053	551.2624	709.5797	470.7531	512.1552	70.12334
558	1015	174.4376	4.0904	237.1375	2.212454	30.3013	38.8053	568.0996	713.5196	474.9387	524.6558	70.12334

Figure 4.9: View of CSV file (11 February 2014)

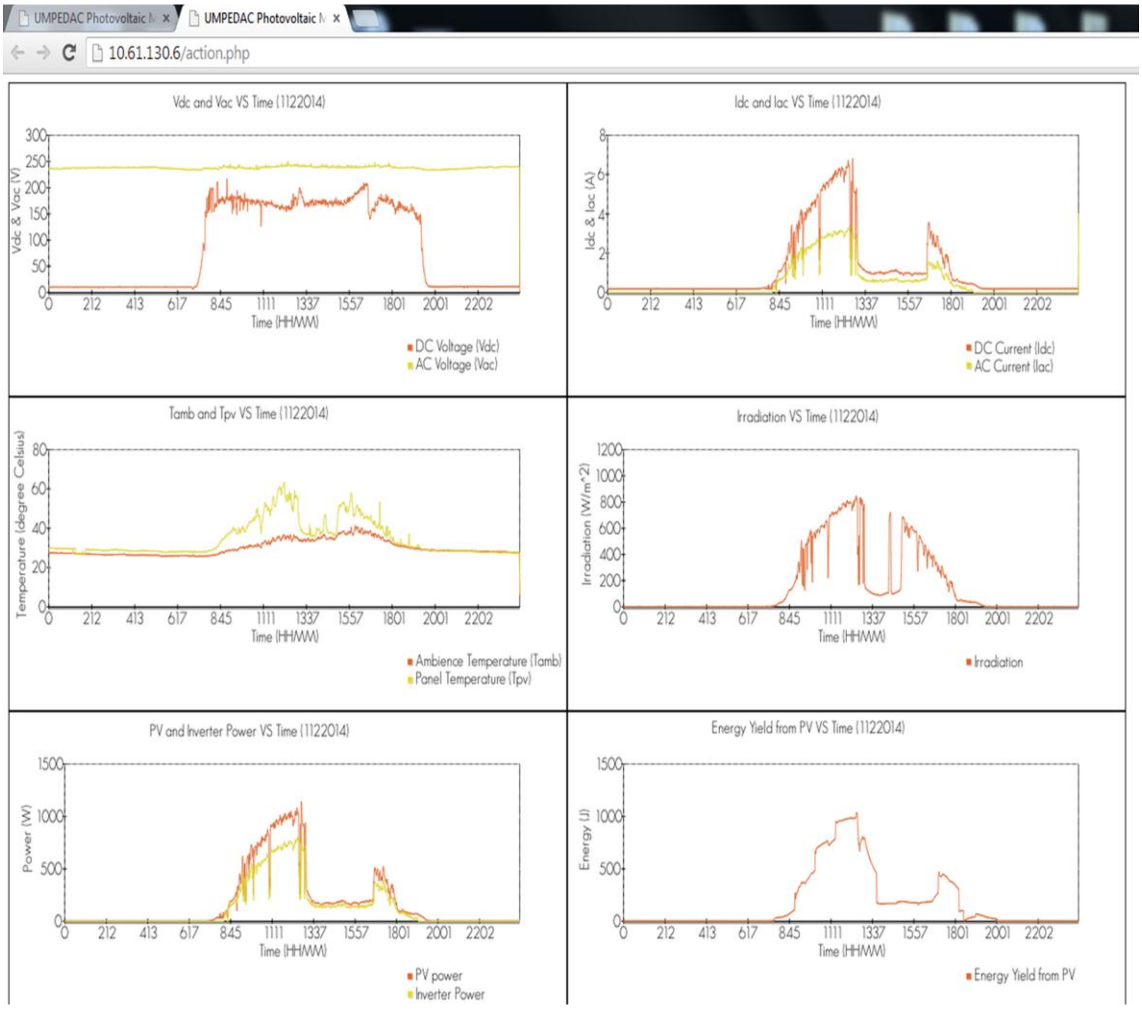


Figure 4.10: Graph view of completed monitored data (11 February 2014)

4.4 Uncertainty Analysis

In order to ensure the validity of measurement data, uncertainty or error analysis is required. Improper experimental setup and human error while taking measurements may also contribute to error in measurement (Jin, Ibrahim, Chean, Daghigh, & Ruslan, 2010). Errors can be divided into two types, which are random and systematic error. Random error is unpredictable and cannot be removed as it happen due to imprecision (Janjai et al., 2009). Systematic error cannot be eliminated also, but it can be reduced by calibrating the device used in experiment (Janjai et al., 2009).

Common error equation is given as in equation (4.1) (Schenck and Hawks, 1979).

$$x_i = x_m \pm \delta x_i \qquad (4.1)$$

Based on equation (4.1), x_i refers to the actual value of the variable while x_m is mean value of measured data and δx_i is the uncertainty in measurement.

The uncertainty of each device or instrument used for each measured variables as mentioned in the experimental setup are tabulated in Table 4.1. All the values in the table are obtained from the relevant data sheets. In order to ensure accurate readings are obtained, sensors are calibrated before measurement.

Table 4.1: Summary for device uncertainties

Parameter		Uncertainty
Voltage sensor (LV25)	Accuracy	±0.8%
	Linearity	<0.2%
	Thermal drift at (T=0 ºC to +25 ºC)	±1.0%
Current sensor (LA25)	Accuracy	±0.5%
	Linearity	<0.2%
	Thermal drift at (T=0 ºC to +25 ºC)	±1.0%
Temperature sensor (LM35DZ)	Accuracy	±2.0 ºC
	Non-linearity	±0.5 ºC
Irradiance (Pyranometer)		±5%

Every sensor and equipment used in this study has its own limitation or error during data measurement. In order to get a precise and accurate measurement, calculations to compute the error need to be carried out. Basic equation for expanded uncertainty is stated in equation (4.2) (Joint Committee for Guides in Metrology, 2008):

$$U = k.u_c(y) \qquad (4.2)$$

where *U* is expanded uncertainty, *k* is coverage factor, and *u(y)* is standard uncertainty.

By referring to the guideline, k is equal to 2 for estimation of uncertainty with 95% confidence interval. Based on the standard developed in Evaluation of Measurement Data – Guide to the Expression of Uncertainty in Measurement (GUM), total expanded uncertainty for voltage, current, temperature and power parameter can be calculated using equation (4.3) to equation (4.6) (Joint Committee for Guides in Metrology, 2008). Voltage sensor from LEM has uncertainty in accuracy, linearity, and thermal drift which are ±0.8%, ±0.2%, and ±0.1% respectively. Thermal drift at T = 0 ºC to +25 ºC is chosen because sensors are stored in a room with air-conditioning.

$$u_v = \sqrt{[(\delta accuracy)^2 + (\delta linearity)^2 + (\delta thermal)^2]} \quad (4.3)$$

$$u_v = \sqrt{[(\pm 0.8\%)^2 + (\pm 0.2\%)^2 + (\pm 1\%)^2]}$$

$$u_v = \pm 1.296\%$$

By using the same basic equation in (4.2), total expanded system uncertainty for current, u_c can be calculated as in equation (4.4). Accuracy, linearity and thermal drift for LA 25 current sensor are taken into account.

$$u_c = \sqrt{[(\delta accuracy)^2 + (\delta linearity)^2 + (\delta thermal)^2]} \quad (4.4)$$

$$u_c = \sqrt{[(\pm 0.5\%)^2 + (\pm 0.2\%)^2 + (\pm 1\%)^2]}$$

$$u_c = \pm 1.1358\%$$

For temperature parameter, sensor is calibrated using thermocouple and digital multimeter from Fluke (FLUKE179). Total expanded uncertainty for temperature is calculated based on equation (4.5) by combining accuracy and non-linearity parameter.

$$u_t = \sqrt{[(\delta accuracy)^2 + (\delta non - linearity)^2]} \tag{4.5}$$

$$u_t = \sqrt{[(\pm 2\,)^2 + (\pm 0.5)^2]}$$

$$u_t = \pm 2.0616\ ^{o}\mathrm{C}$$

Power is obtained from the product of voltage and current. Uncertainty for power measurement can be calculated based on equation (4.6).

$$u_p = \sqrt{[(u_v)^2 + (u_c)^2]} \tag{4.6}$$

In order to calculate uncertainty for PV power measurement, value u_v=±1.296% and u_c=±1.1358% are substituted into equation (4.6):

$$u_p = \sqrt{[(u_v)^2 + (u_c)^2]}$$

$$u_p = \sqrt{[(\pm 1.296\%)^2 + (\pm 1.1358\%)^2]}$$

$$u_t = \pm 1.7233\%$$

Energy is the product of power and time (hour) as shown in equation (4.7).

$$E = P \times h \tag{4.7}$$

where *E* is energy, *P* is power, and *h* is hour. Based on equation (4.7), uncertainty for parameter *h* can be neglected. Therefore, uncertainty for energy, u_e is equal to uncertainty for power, u_p which is ±1.7233%.

System uncertainties for every measured parameter are summarized in Table 4.2. Every parameter has different system uncertainties, i.e. ±1.296% for voltage; ±1.1358% for current; ±2.0616 ºC for temperature; ±1.7233% for power and energy. Uncertainty for irradiation parameter is taken directly from LICOR datasheet which is ±5%. Uncertainty for power parameter is higher compared to other parameters. This is due to the fact that power is calculated based on product of voltage and current. Hence, uncertainty for power is the combination of voltage uncertainty and current uncertainty. However, the uncertainties are still under ≤ ±5% range and are considered acceptable.

Table 4.2: Summary for system uncertainties

Parameter	**Uncertainties**
Voltage, u_v	±1.296%
Current, u_c	±1.1358%
Temperature, u_t	±2.0616 ºC
Irradiation, u_i	±5%
Power, u_p	±1.7233%
Energy, u_e	±1.7233%

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In this research, implementation of a web-based wireless monitoring system for 1.25 kW_p grid-connected PV system is presented. The work covers the whole process of the web-based wireless monitoring system development, starting from system structure design, hardware implementation, control system programming to the programming of the web-based monitoring interface. The system is developed using Java and C programming language. A wide range of sensors are used to ensure the important electrical and atmospheric parameters are obtained to observe the performance and stability of the PV system. Using the XBee device, the monitoring system is equipped with a simple and effective wireless data transmission capability. This allows the system to be controlled remotely from the control PC. Results obtained show that the system is equipped with online viewing feature to ease user in monitoring the system through the internet. Besides that, this system is equipped with controlling system to control the system from main control PC without human existence on-site. By utilizing the proposed system, user may increase range extension between the system and main control. As a conclusion, a simpler data acquisition system with control and online features is built to cater the needs of monitoring grid-connected photovoltaic system. The system has provided an uncertainty of $\leq \pm 5\%$.

5.2 Recommendations

i. For larger PV plant implementation, more data transmission nodes should be added to the monitoring system.

ii. For future testing, the monitoring system should have larger size storage for data backup.

iii. Printed circuit board is placed in a noise-free container to avoid any signal interference.
iv. Online control function can be added as additional control features besides PC-based control.
v. Use different plotting graph application for quicker response time when displaying graph.
vi. Use device or instrument with high precision to minimize error in measurement.
vii. Comparison between the developed monitoring method (Zigbee) with other conventional method, such as wired-type or the internet-based.

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LIST OF PUBLICATIONS AND PAPERS PRESENTED

Journal Articles

1. Shariff, F., Rahim, N. A., & Hew, W. P. (2015). Zigbee-based data acquisition system for online monitoring of grid-connected photovoltaic system. *Expert Systems with Applications*, *42*(3), 1730–1742. doi:10.1016/j.eswa.2014.10.007

Conference Papers

1. Shariff, F., Rahim, N. A., & Ping, H. W. (2013). Photovoltaic remote monitoring system based on GSM. 2013 IEEE Conference on Clean Energy and Technology (CEAT), 379–383. doi:10.1109/CEAT.2013.6775660. Publication year: 2013
2. Shariff, F., Rahim, N. A., & Ping, H. W. (2013). PV remote monitoring system based on GSM. *Power and Energy Conversion Symposium (PECS 2012).* Publication year: 2012

APPENDIX A: FIGURE OF EQUIPMENT/COMPONENT USED IN RESEARCH

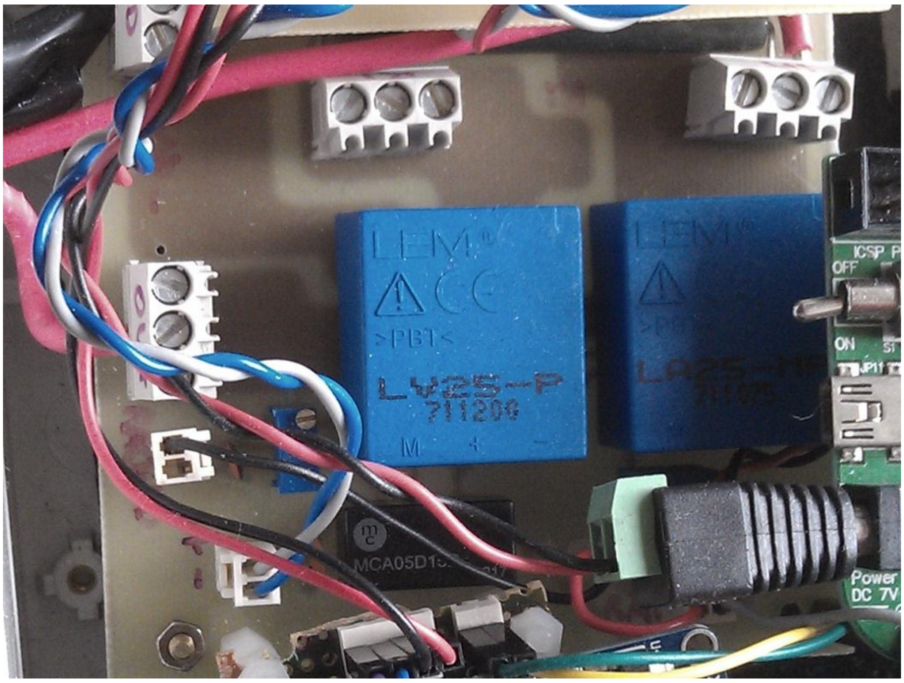

Figure A.1: PV voltage and current transducer sensor's circuit (DC)

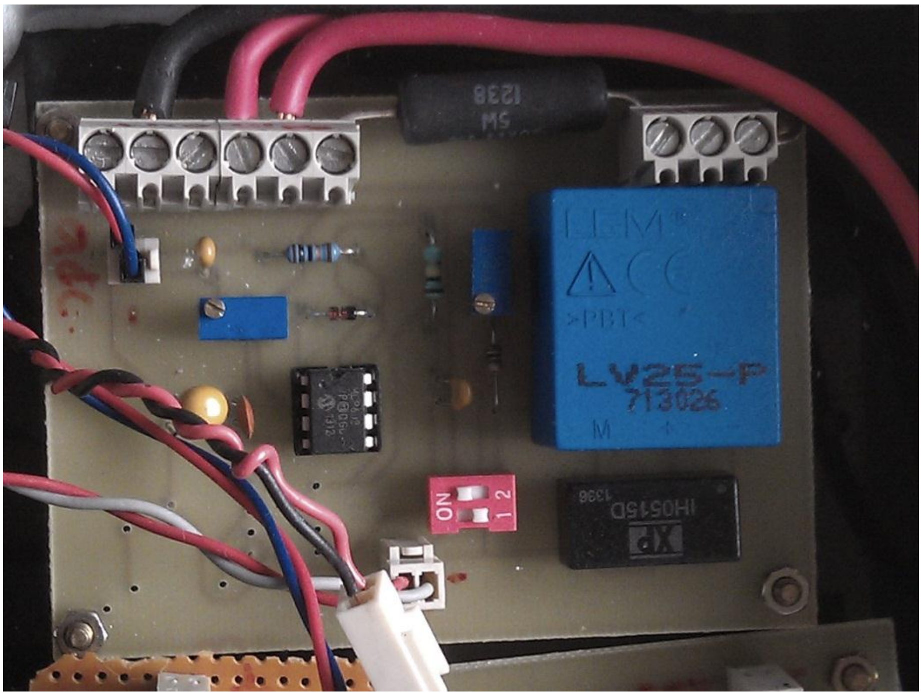

Figure A.2: Inverter voltage transducer sensor's circuit

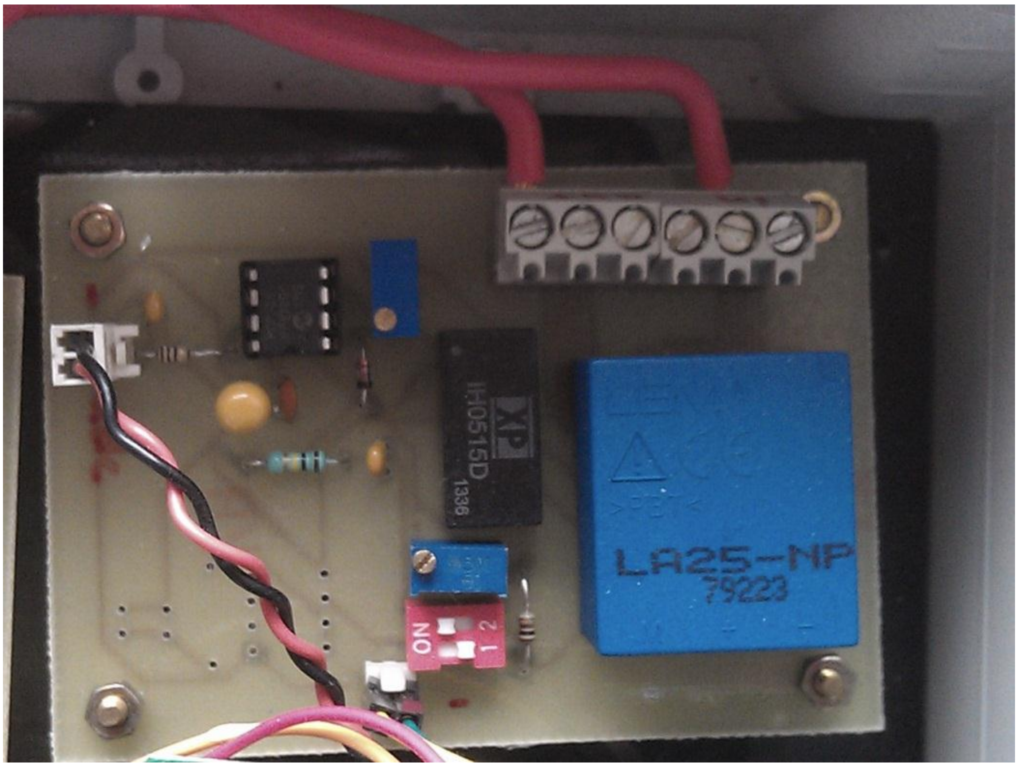

Figure A.3: Inverter current transducer sensor circuit

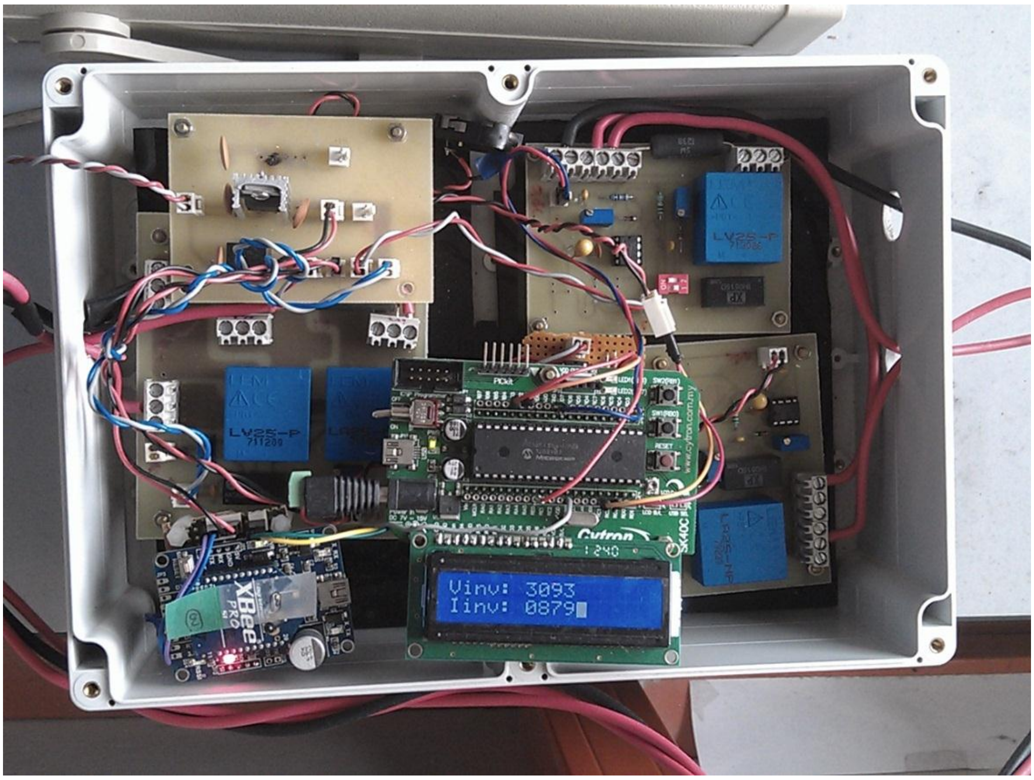

Figure A.4: Logging Point 1 (LP1) circuit

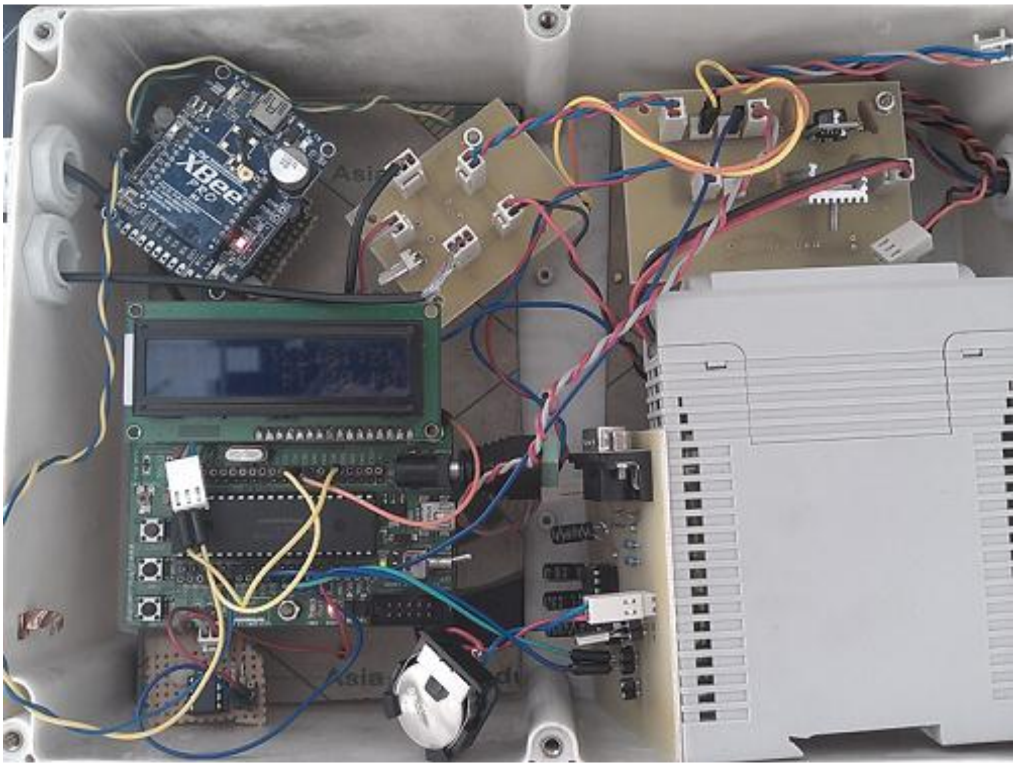

Figure A.5: Logging Point 2 (LP2) circuit

APPENDIX B: FIGURE OF EQUIPMENT/COMPONENT USED IN RESEARCH

Figure B.1: LV 25 voltage sensor

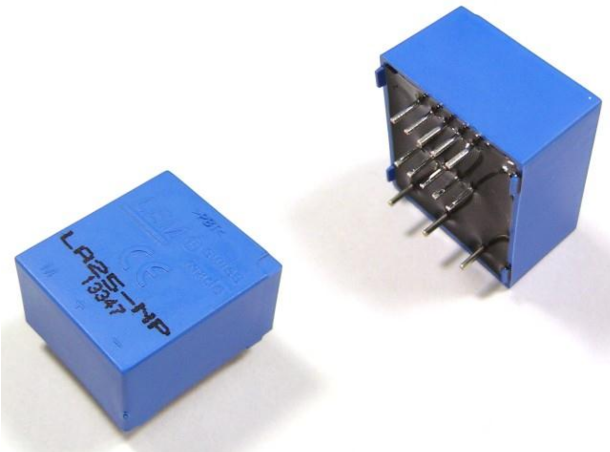

Figure B.2: LA 25 current sensor

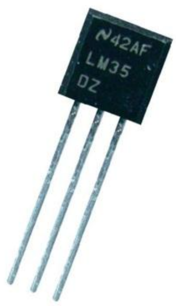

Figure B.3: LM35DZ temperature sensor

Figure B.4: LICOR pyranometer

Figure B.5: XBEE-Pro Series 1

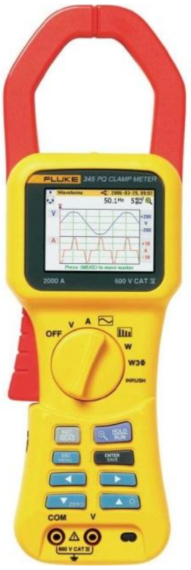

Figure B.6: FLUKE 345 power quality clamp meter

Figure B.7: FLUKE 179 digital multimeter

Figure B.8: FLUKE 435 Series II Power Quality Analyzer

APPENDIX C: SPECIFICATIONS OF EQUIPMENT/COMPONENT USED IN RESEARCH

Table C.1: Specification of LV 25 voltage sensor

Parameter	Description
Electrical data	
Primary nominal RMS current, I_{PN}	10 mA
Primary current measuring range, I_P	-14 mA to 14 mA
Secondary nominal RMS current, I_{SN}	25 mA
Conversion ratio, K_N	2500:1000
Supply voltage, V_C	± (12 to 15)V
Current consumption, I_C	10(@±15 V)+I_S mA
RMS voltage for AC isolation test, V_d	2.5 kV
Accuracy	±0.8%
Linearity	<0.2%
Offset current, I_O @I_P=0, T_A=25 ºC	±0.15 mA (max)
Thermal drift of I_O (0 ºC to +25 ºC) (+25 ºC to +70 ºC)	Typical: ±0.06 mA, Max: ±0.25 mA Typical: ±0.10 mA, Max: ±0.35 mA
Response time	40 µs
General data	
Operating temperature, TA	0 ºC to 70ºC
Mass	22 g

Table C.2: Specification of LA 25 current sensor

Parameter	Description
Electrical data	
Primary nominal RMS current, I_{PN}	25 A
Primary current measuring range, I_{PM}	0 to ±36 A
Secondary nominal RMS current, I_{SN}	25 mA
Conversion ratio, K_N	1-2-3-4-5:1000
Supply voltage, V_C	±15 V
Current consumption, I_C	10+I_S mA
Accuracy	±0.5%
Linearity	<0.2%
Offset current, I_O @I_P=0, T_A=25 ºC	Typical:±0.05 mA, Max:±0.15 mA
Magnetic offset current, I_{OM}	Typical:±0.05 mA, Max:±0.15 mA
Thermal drift of I_O (0 ºC to +25 ºC) (+25 ºC to +70 ºC)	Typical: ±0.06 mA, Max: ±0.25 mA Typical: ±0.10 mA, Max: ±0.35 mA
Response time	<1 µs
General data	
Operating temperature	-40 ºC to 85 ºC
Mass	22 g

Table C.3: Specification of LM35DZ temperature sensor

Parameter		Description
Supply voltage		+35 V to -0.2 V
Output voltage		+6 V to -1.0 V
Output current		10 mA
Range		-55 ºC to 150 ºC
Operating temperature		0 ºC to 100 ºC
Casing		Plastic (TO-92)
Accuracy	T_A=+25 ºC	Typical: ±0.6 ºC, Max: ±1.5 ºC
	T_A=+150 ºC	Typical: ±0.9 ºC
	T_A=-55 ºC	Typical: ±0.9 ºC
Nonlinearity		±0.2 ºC
Sensor gain		10.0 mV/ ºC
Long term stability		±0.08 ºC
Impedance output		±0.25 ºC
Unit		ºC

Table C.4: Specification of LICOR pyranometer

Parameter	Description
Response time	10 µs
Operating temperature	-40 to +65 °C
Size	2.38 cm diameter x 2.54 cm height
Weight	28 g
Sensitivity	± 2%
Light spectrum waveband	400 to 1100 nm
Detector:	High stability silicon photovoltaic detector (blue enhanced)

Table C.5: PV module specification

Parameter	Description
Manufacturer	Mitsubishi Electric
Model name	PV-AE125MF5N
Cell type	Polycrystalline silicon, 156mm x 156mm
Number of cells	36 cells in series
Maximum power rating, Pmax	125 W
Warranted minimum Pmax	118.8 W
Tolerance of maximum power rating	+10/-5%
Open circuit voltage, VOC	21.8 V
Short circuit current, ISC	7.9 A
Maximum power voltage, Vmp	17.3V
Maximum power current, Imp	7.23 A
Normal operating cell temperature (NOCT)	47.5 ºC
Maximum system voltage	DC 1000V
Fuse rating	15 A
Dimensions	(1495 x 674 x 46) mm
Weight	13.5 kg
Module efficiency	12.4%
Certificate	IEC 61215 edition 2 (static load test 2400 Pa passed)

Table C.6: Grid-connected inverter specification

Parameter	Description
Type	SPI2000-B
Maximum array open circuit voltage	500 Vdc
Maximum array short circuit current	13 Adc
MPPT voltage range	150-450 Vdc
Nominal input voltage	360 Vdc
Maximum operating PV input current	11 Adc
Rated grid voltage	230 Vac
Rated grid frequency	50 Hz
Maximum continuous output power	2000 W
Maximum continuous output current	11 Aac
Protective class	I
Ingress protection rating	IP65
Grid connected standard	VDE 0126-1-1

Table C.7: 24LC1026 EEPROM specification

Parameter	Description
Supply voltage	2.5 to 5.5 V
Current consumption	450 µA
Write time	3 ms
Capacity	1024 kbit
Operating temperature	-40 to 85 ºC

Table C.8: XBEE-Pro Series 1 specification

Parameter	Description
Performance	
Indoor range	100 m
Outdoor range	1500 m
Transmit power output	60 mW
RF data rate	250,000 byte per second
Serial interface data rate	1200 to 115200 byte per second
Receiver sensitivity	-100 dBm (1% packet error rate)
Power requirements	
Supply voltage	2.8 to 3.4 V
Transmit current	137 mA to 227 mA
Idle/ receive current	55 mA(@3.3 V)
Power down current	<10 µA
General	
Operating frequency	ISM 2.4 GHz
Dimensions	2.438 cm x 3.294 cm
Operating temperature	-40 to 85 ºC
Antenna	Integrated whip
Networking & security	
Network topologies	Point-to point, point-to-multipoint, peer-to-peer
Number of channels	12 direct sequence channels

Table C.9: DS1307 specification

Parameter	Description
Supply voltage	4.5 to 5.5 V
Operating temperature	0 °C to 70 °C
Battery voltage	2.0 to 3.5 V
Current consumption	<500 nA
Interface	Two-wire (serial)

APPENDIX D: SOURCE CODES

Source codes for Logging Point 1 (LP1)

Source codes for Logging Point 1 (LP1)

```
#include <18f4553.h>
#fuses HS,NOWDT,NOPUT,NOPROTECT,NODEBUG,NOBROWNOUT,NOLVP,NOCPD
#device adc=12
#use delay(clock=20000000)
#use rs232(baud=9600, xmit=PIN_C6, rcv=PIN_C7,parity=N, bits=8,ERRORS,stream=XBEE)

#include <string.h>
#include <math.h>
#include <stdio.h>
#include <stdlib.h>
#include "display.c"
#include "ds1307.c"
#include "headerCY.c"

    char LINE1[] = {"V:"};
    char LINE2[] = {"C:"};
    char LINE5[] = {"I:"};
    char LINE6[] = {"Vinv:"};
    char LINE7[] = {"Iinv:"};
    int16 voltage, current, invvoltage, v_avg, c_avg;
    int sec, hrs, day, month, yr, dow;
    int min,min2,iresult;
    int16 inv_max,invc_max,i,inv,invc,invcurrent,invv;
    int16 inv_min,invc_min;
    short int exit,exit1,exit2;
    volatile char string1[16];
    volatile char string2[2];
    volatile char string3[50];
    char *pos;
    char test[] = "start";
    char txte[] = "Error";
    char txt4[] = "UMPEDAC";
    char txt5[] = "MONITORING";
    volatile int counter_read=0;
    volatile int counter_read2=1;
    short int command;
    int16 address=0x0000;

void save();
void SerialInt();
void monitoring();
void check_command();
void main()
{

  lcd_init();      // always call this 1st
  ds1307_init();
  init_ext_eeprom();
  delay_ms(1000);
  setup_adc_ports(NO_ANALOGS);
  setup_adc(ADC_OFF);
  setup_psp(PSP_DISABLED);
  setup_spi(SPI_SS_DISABLED);
```

```
  setup_timer_0(RTCC_INTERNAL|RTCC_DIV_1);
  setup_timer_1(T1_DISABLED);
  setup_timer_2(T2_DISABLED,0,1);
  setup_comparator(NC_NC_NC_NC);
  setup_vref(FALSE);
  delay_ms(500);
  setup_adc_ports(AN0_TO_AN6);
  setup_adc(adc_clock_div_8);
  setup_comparator(NC_NC_NC_NC);

// Set date for -> 30 March 2012 Fri
// Set time for -> 15:20:55

//  ds1307_set_date_time(30,12,13,1,14,59,00);
  lcd_display_str(0,txt4);
  lcd_display_str(1,txt5);
  delay_ms(500);
  lcd_display_str(0,Clear_disp);
 lcd_display_str(1,Clear_disp);
  exit=1;
  exit1=1;
  exit2=1;

 while(1)
 {exit=1;
  exit1=1;
  exit2=1;
 do{
 output_low(PIN_B6);
 gets(string1);
 lcd_display_str(0,string1);
 pos = strchr(string1, 's');
  if ((string1[pos-string1] == 's')&&(string1[pos-string1+1] == 't')&&
  (string1[pos-string1+2] == 'a')&&(string1[pos-string1+3] == 'r')&&(string1[pos-string1+4] == 't'))
  {
  lcd_display_char(1,1,string1[pos -string1]);
  lcd_display_char(1,2,string1[pos -string1+1]);
  lcd_display_char(1,3,string1[pos -string1+2]);
  lcd_display_char(1,4,string1[pos -string1+3]);
  lcd_display_char(1,5,string1[pos -string1+4]);
      do{
      exit2=1;
      monitoring();
      delay_ms(500);
      do
      {
      enable_interrupts(INT_RDA);
      enable_interrupts(GLOBAL);

      if(command==1)
      {
      disable_interrupts(INT_RDA);
      disable_interrupts(GLOBAL);
      output_high(PIN_B6);
      check_command();
       }
      else
      {
      disable_interrupts(INT_RDA);
      disable_interrupts(GLOBAL);
       delay_ms(500);
       exit2=0;
      }
```

```
        }while(exit2!=0);
    }while(exit!=0);
    }
    else
    {lcd_display_str(1,txte);
    }
  }while(exit1!=0);
  }
}
void check_command()
{
      exit=0;
      exit1=0;
      exit2=0;
      command=0;
      //reset_cpu();
}
void monitoring()
{
         ds1307_get_date(day,month,yr,dow);
         ds1307_get_time(hrs,min2,sec);

         lcd_display_date(0,0,day,month,yr);
         lcd_display_time(1,0,hrs, min2, sec);
         delay_ms(1000);
         lcd_display_str(0, Clear_disp);
         lcd_display_str(1, Clear_disp);

         //pv voltage
         set_adc_channel(0);  //ra0/an0
         delay_ms(2000);
         for(i=0;i<500;i++)
         {
         voltage = read_adc();
         if(i==0)
         {v_avg=voltage;}
         else{
         voltage = v_avg+voltage;
         delay_us(20);
         v_avg=voltage;}
         }
         voltage=v_avg/500;
         lcd_display_str(0, LINE1);
         lcd_display_num2(0,3,voltage);
         delay_ms(1000);

         //pv current
         set_adc_channel(1);  //ra1/an1
         delay_ms(2000);
         for(i=0;i<500;i++)
         {
         current = read_adc();//((adc*0.0196)/200)*1000
         if(i==0)
         {c_avg=current;}
         else{
         current = c_avg+current;
         delay_us(20);
         c_avg=current;}
         }
         current=c_avg/500;
         lcd_display_str(1, LINE2);
         lcd_display_num2(1,3,current);
         delay_ms(1000);
```

```
         lcd_display_str(0, Clear_disp);
         lcd_display_str(1, Clear_disp);

         //inverter voltage
         set_adc_channel(5);  //re0/an5
         delay_ms(1000);
         for(i=0;i<658;i++)
        {
        inv=read_adc();
        delay_us(20);
        if(i==0)
        {inv_max=inv;
        inv_min=inv;
        }
        if (inv>inv_max)
        {
           inv_max=inv;
        }
        if(inv<inv_min)
        {
           inv_min=inv;
        }
        }
       invv=inv_max-inv_min;
        lcd_display_str(0, LINE6);
        lcd_display_num2(0,6,invv);

         //inverter current
         set_adc_channel(6);  //re1/an6
         delay_ms(1000);
        for(i=0;i<658;i++)
        {
        invc=read_adc();
        delay_us(20);
        if(i==0)
        {invc_max=invc;
        invc_min=invc;
        }
        if (invc>invc_max)
        {
           invc_max=invc;
        }
        if(invc<invc_min)
        {
           invc_min=invc;
        }
        }
        invcurrent=invc_max-invc_min;
         lcd_display_str(1, LINE7);
         lcd_display_num2(1,6,invcurrent);
         delay_ms(1000);
         sprintf(string3,"logz%02u%02uv%04Luc%04Lue%04Lut%04Lu",hrs,min2,voltage,current,     invv,
invcurrent);
         delay_ms(1000);
         puts(string3);
         delay_ms(1000);
         putc(0x0D);
         lcd_display_str(0, Clear_disp);
         lcd_display_str(1, Clear_disp);
         save();
          do{
                 ds1307_get_time(hrs,min,sec);
                 delay_ms(1000);
```

```
        }while (min==min2);
}
void save()
{
  write_ext_eeprom (address,hrs);
  address=address+1;
  write_ext_eeprom (address, min2);
  address=address+1;
  write_16_ext_eeprom (address, voltage);
  address=address+2;
  write_16_ext_eeprom (address, current);
  address=address+2;
  write_16_ext_eeprom (address, invv);
  address=address+2;
  write_16_ext_eeprom (address, invcurrent);
  address=address+2;
}
#INT_RDA
void SerialInt()
{
  string2[counter_read]=getc();
  if(string2[counter_read]=='X')
  {
  command=1;}
}
```

Source codes for Logging Point 2 (LP2)

```
#include <18F4553.h>
#fuses HS,NOWDT,NOPUT,NOPROTECT,NODEBUG,NOBROWNOUT,NOLVP,NOCPD
#device adc=12
#use delay(clock=20000000)
#use rs232(baud=9600, xmit=PIN_C6, rcv=PIN_C7,parity=N, bits=8,ERRORS,stream=XBEE)

#include <string.h>
#include <math.h>
#include <stdio.h>
#include <stdlib.h>
#include "display.c"
#include "ds1307.c"
#include "headerCY.c"

    char LINE3[] = {"Ta:"};
    char LINE4[] = {"Tpv:"};
    char LINE5[] = {"I:"};
    int16 temp_a,  temp_p, irr,temp_c=0,i;
    int16 temp_b=0;
    int sec, hrs,day,mon,yr,dow;
    int min,min2;
    short int exit,exit2;
    volatile char string1[25];
    volatile char string2[25];
    volatile char string3[50];
    char *pos;
    char txt4[] = "UMPEDAC";
    char txt5[] = "MONITORING";
    char txte[] = "waiting..";
    char txt6[] = "logz0000v000c001e002t003";
    volatile int counter_read=0;
    volatile int counter_read2=1;
    short int command=0;
    int16 address=0x0000;
```

```
void save();
void SerialInt();
void monitoring();
void check_command();
int16 sense(int adcv)
//sense voltage pv
{
  int16 voltO;
  int a;
  long INT reading,minimum,maximum,average;
  long INT total_reading = 0;

  set_adc_channel(adcv);
  delay_us(20);
  voltO = read_adc (); // initial test
  reading =voltO;
  total_reading = total_reading+reading;
  minimum = reading;
  maximum = reading;

  for (a=0;a<9;a++)
  {
    voltO = read_adc();
    reading = voltO;
    total_reading = total_reading+reading;

    if (reading < minimum)
    {
      minimum = reading;
    }

    if (reading > maximum)
    {
      maximum = reading;
    }
  }

  average = (total_reading-(minimum+maximum))/(8);
  voltO = average;
  delay_us(5);

 return (voltO);
}
void main()
{

  lcd_init();      // always call this 1st
  ds1307_init();
  init_ext_eeprom();
  delay_ms(1000);
  setup_adc_ports(NO_ANALOGS);
  setup_adc(ADC_OFF);
  setup_psp(PSP_DISABLED);
  setup_spi(SPI_SS_DISABLED);
  setup_timer_0(RTCC_INTERNAL|RTCC_DIV_1);
  setup_timer_1(T1_DISABLED);
  setup_timer_2(T2_DISABLED,0,1);
  setup_comparator(NC_NC_NC_NC);
  setup_vref(FALSE);
  delay_ms(500);
  setup_adc_ports(AN0_TO_AN7);
  setup_adc(adc_clock_div_8);
```

```
  setup_comparator(NC_NC_NC_NC);

// Set date for -> 30 March 2012 Fri
// Set time for -> 15:20:55

//  ds1307_set_date_time(21,1,14,2,18,02,00);
  lcd_display_str(0,txt4);
  lcd_display_str(1,txt5);
  delay_ms(500);
  lcd_display_str(0,Clear_disp);
  lcd_display_str(1,Clear_disp);
  exit=1;

 while(1)
 {
 ds1307_get_date(day,mon,yr,dow);
 ds1307_get_time(hrs,min2,sec);
 lcd_display_date(0,0,day,mon,yr);
 lcd_display_time(1,0,hrs, min2, sec);
 delay_ms(1000);
 gets(string1);
 lcd_display_str(0,string1);
 pos = strchr(string1, 'l');
  if ((string1[pos-string1] == 'l')&&(string1[pos-string1+1] == 'o')&&
  (string1[pos-string1+2] == 'g')&&(string1[pos-string1+3] == 'z'))
  {
  lcd_display_char(1,1,string1[pos -string1]);
  lcd_display_char(1,2,string1[pos -string1+1]);
  lcd_display_char(1,3,string1[pos -string1+2]);
  lcd_display_char(1,4,string1[pos -string1+3]);

        exit=1;
        monitoring();
        delay_ms(2000);
  }
  else
  {lcd_display_str(1,txte);
  }
 }
}
void monitoring()
{
        exit2=1;
        ds1307_get_time(hrs,min2,sec);
        lcd_display_time(1,0,hrs, min2, sec);
        delay_ms(1000);

        //ambience temperature
        temp_a= sense(3);
        lcd_display_str(0, LINE3);
        lcd_display_num2(0,4,temp_a);

        //panel temperature
        temp_p=sense(5);
        lcd_display_str(1, LINE4);
        lcd_display_num2(1,5,temp_p);

        lcd_display_str(0, Clear_disp);
        lcd_display_str(1, Clear_disp);

        //irradiation
        set_adc_channel(4);  //ra5/an4
        irr = read_adc(); //adc*0.0196*10.22/0.04
```

```
        lcd_display_str(0, LINE5);
        lcd_display_num2(0,3,irr);
        sprintf(string3,"%25sa%04Lup%04Lui%04Lun",string1,temp_a,temp_p,irr);

        puts(string3);
        delay_ms(1000);
        putc(0x0D);
        delay_ms(1000);
        save();
        delay_ms(5000);
         do
         {
          enable_interrupts(INT_RDA);
          enable_interrupts(GLOBAL);

          if(command==1)
          {
          disable_interrupts(INT_RDA);
          disable_interrupts(GLOBAL);
          output_high(PIN_B6);
          exit2=0;
          }
          else
         {
         disable_interrupts(INT_RDA);
         disable_interrupts(GLOBAL);
         delay_ms(1000);
         puts(string3);
         delay_ms(1000);
         putc(0x0D);
         ds1307_get_time(hrs,min,sec);
         if(min != min2)
         {exit2=0;}
         }
       }while(exit2!=0);

        lcd_display_str(0, Clear_disp);
        lcd_display_str(1, Clear_disp);

}
void save()
{
 write_ext_eeprom (address,hrs);
 address=address+1;
 write_ext_eeprom (address, min2);
 address=address+1;
 write_16_ext_eeprom(address,temp_a);
 address=address+2;
 write_16_ext_eeprom(address,temp_p);
 address=address+2;
 write_16_ext_eeprom(address,irr);
 address=address+2;

}
#INT_RDA
void SerialInt()
{
   string2[counter_read]=getc();
   if(string2[counter_read]=='R')
   {
   command=1;}
}
```