**UNIVERSITI PUTRA MALAYSIA**

# *SMART ENERGY METER WITH ADAPTIVE COMMUNICATION DATA TRANSFER ALGORITHM FOR ELECTRICAL ENERGY MONITORING*

**HAIZUM HANIM BINTI AB HALIM**

# SMART ENERGY METER WITH ADAPTIVE COMMUNICATION DATA TRANSFER ALGORITHM FOR ELECTRICAL ENERGY MONITORING

**By**

**HAIZUM HANIM BINTI AB HALIM**

**Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy**

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**Chairman : Assoc. Prof. Nashiren Farzilah Mailah, PhD**
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Smart Meter (SM) is an intelligent device with additional functions which include the ability to measure and record energy consumptions, and allows two-way communication with the utility for automated monitoring, and accurate billing management. Smart metering program has gained importance and started to be implemented in most developed country including Malaysia. The obvious problem in this SM is it uses single communication system as there was no contingency plan in transferring the data when the signal strength was weak or failure during data transfer process. In addition, single communication on the smart meter has limiting the location suitability of the meter. Thus, in this thesis, a new Smart Energy Meter (SEM) with adaptive data transfer algorithm is designed to accommodate the problem. The prototype of SEM is constructed based on the modern Smart Meter design and modified with additional control devices and sensors, so that it can measure, record and transfer the data using designated algorithm combining three types of communication system in one device; Wi-Fi, GSM and RF. The idea of combining three types of wireless communication is to ensure the data fully transferred to the data center accurately and promptly. The prototype is constructed through software and hardware development and has been programmed using Arduino IDE software. An algorithm for selecting communication system is developed by comparing Received Signal Strength Indicator (RSSI) of Wi-Fi and GSM with the priority given to Wi-Fi, followed by GSM and RF. The prototype has been tested on a laboratory scale for its functionality by measuring the electrical parameters using heating elements as the load, and its ability in transferring data through three communications and monitoring as well as communicating with the SEM from DIS. Index test on the algorithm performance is carried out at different locations and atmospheric for example in an indoor area of KEE 009 laboratory (normal weather), the outdoor area of KEE 009 laboratory in normal weather, multi storey building and during thunderstorm weather. In a conclusion, SEM prototype and adaptive communication data transfer algorithm with a combination of the three communication will be another method to solve a single communication problem

of SM and suitable in residential location that offered the proposed communication infrastructure.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

**METER TENAGA PINTAR DENGAN ALGORITMA PEMINDAHAN DATA KOMUNIKASI ADAPTIF UNTUK PEMANTAUAN TENAGA ELEKTRIK**

Oleh

**HAIZUM HANIM BINTI AB HALIM**

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Meter pintar (MP) adalah peranti pintar dengan fungsi-fungsi tambahan yang merangkumi kemampuan untuk mengukur dan merekod penggunaan tenaga konsumsi dan membenarkan komunikasi dua hala dengan utiliti untuk pemantauan automatik, dan pengurusan bil yang tepat. Program pemeteran pintar telah mendapat kepentingan dan mula dilaksanakan di kebanyakan negara maju termasuklah Malaysia. Masalah yang ketara dalam meter pintar ini ialah ia menggunakan sistem komunikasi tunggal sepertimana ia tiada rencana kontigensi dalam memindahkan data ketika kekuatan signal adalah lemah. Selain itu juga, komunikasi tunggal pada meter pintar telah mengehadkan kesesuaian lokasi pemasangan meter. Oleh itu, dalam tesis ini, Meter Tenaga Pintar (MTP) yang baru dengan algoritma pemindahan data yang adaptif telah direka untuk menangani masalah tersebut. Prototaip MTP dibina berdasarkan kepada rekabentuk Meter Pintar moden dan diolah dengan alat kawalan dan sensor agar dapat mengukur, merekod dan menghantar data menggunakan tiga jenis komunikasi dalam satu peranti; Wi-Fi, GSM dan RF. Idea untuk menggabungkan tiga jenis komunikasi tanpa wayar adalah untuk memastikan data dipindahkan sepenuhnya ke pusat data dengan tepat dan cepat. Prototaip telah dibangunkan melalui pembangunan perisian dan perkakasan dan telah diprogramkan dengan menggunakan perisian Arduino IDE. Algoritma pemilihan komunikasi dihasilkan dengan membandingkan nilai Indikator Kekuatan Isyarat Diterima (RSSI) Wi-Fi dan nilai GSM dengan keutamaan diberi kepada Wi-Fi, diikuti oleh GSM dan RF. Prototaip telah diuji dalam skala makmal untuk diuji kefungsiannya dengan mengukur parameter elektrik menggunakan elemen pemanas sebagai beban, dan keupayaannya dalam memindahkan data melalui tiga komunikasi dan pemantauan serta komunikasi antara MTP dan sistem antara muka data (DIS). Ujian indeks prestasikeatas algoritma dijalankan di lokasi dan atmosfera berbeza, contohnya kawasan tertutup makmal KEE 009 pada cuaca biasa, kawasan terbuka luar makmal KEE 009 dalam cuaca biasa, bangunan bertingkat dan semasa cuaca ribut petir. Kesimpulannya, prototaip SEM beserta algoritma pemindahan data komunikasi adaptif dengan gabungan

tiga jenis komunikasi boleh menjadi kaedah baru untuk menyelesaikan masalah komunikasi tunggal SM dan pemasangannya juga sesuai dimana-mana lokasi kediaman yang menawarkan infrastruktur komunikasi yang dicadangkan.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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**Declaration by Members of Supervisory Committee**

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
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| | |
|---|---|
| A | Ampere |
| AC | Alternating Current |
| ADSL | Asymmetric DSL |
| AMI | Advanced Metering Infrastructure |
| AMR | Automated Meter Reading |
| ASU | Arbitrary Strength Unit |
| BACnet | Building, Automation and Control network |
| BAN | Building Area Network |
| BB-PLC | Broadband Power Line Communication |
| BPL | Broadband over Power line |
| BTS | Base Transceiver Station |
| $CO_2$ | Carbon Dioxide |
| CPU | Central Processing Unit |
| Csv | Comma–separated value |
| CT | Current Transformer |
| DA | Distribution Automation |
| DAU | Data Aggregator Unit |
| DC | Direct Current |
| DCU | Data Concentrator Unit |
| DG | Distributed Generation |
| DIS | Data Interface System |
| DMS | Distribution Management Systems |
| DSL | Digital Subscriber Line |

| | |
|---|---|
| DSM | Demand Side Management |
| DSO | Distribution Systems Operators |
| EMRA | Energy Market Regulatory Authority |
| EMS | Energy Metering Systems |
| EN | European Standards |
| ERP | Enterprise Resources Planning |
| EToU | Enhanced Time of Use |
| E2PO | Energy Efficiency Program Office |
| FiT | Feed-in Tariff |
| FRAM | Ferroelectric Random-Access Memory |
| FTP | File Transfer Protocol |
| GPIO | General Purpose Input Output |
| GPRS | General Packet Radio Service |
| GSM | Global System for Mobile |
| HAN | Home Area Network |
| HEMS | Home Energy Management System |
| HES | Head End System |
| IC | Intergrated circuit |
| ICIS | Integrated Customer Information Systems |
| ICPT | Imbalance Cost-Pass Through |
| IDE | Integrated Development Environment |
| IEC | International Electrotechnical Commission |
| IHD | In-home Display |
| IoT | Internet of Things |

| | |
|---|---|
| IP | Internet Protocol |
| LAN | Local Area Network |
| LCD | Liquid Crystal Display |
| LED | Light-emitting Diode |
| LPC | Large Power Customers |
| LPWAN | Low Power Wide Area Network |
| LV | Low Voltage |
| LTE | Long-Term Evolution |
| LTE-M | Long Term Evolution for Machine |
| MCO | Movement Control Order |
| MCU | Micrcontroller Unit |
| MDAS | Meter Data Acquisition System |
| MDMS | Meter Data Management System |
| MESITA | Malaysian Electricity Supply Industries Trust Account |
| M2M | Machine – to – Machine |
| NAN | Neighborhood Area Network |
| Nb-IoT | long term evolution for machine |
| NB-PLC | Narrowband Power Line Communication |
| NC | Normally Close |
| NEEAP | National Energy Efficiency Action Plan |
| NO | Normally Open |
| NTL | Non-Technical Losses |
| OMS | Outage Management System |
| OPC | Ordinary Power Customers |

| | |
|---|---|
| OPTR | Off Peak Tariff Rider |
| PAN | Premise Area Network |
| PC | Personal Computer |
| PCB | Printed Circuit Board |
| PER | Packet Error Ratio |
| PHEV | Plug-in Hybrid Electric Vehicles |
| PIC | Programmable Interface Controller |
| PLC | Power Line Communication |
| PV | Photovoltaic |
| RE | Renewable Energy |
| RF | Radio Frequency |
| RLYOD | Request Data |
| RLYOF | Relay Off |
| RLYON | Relay On |
| RSSI | Received Signal Strength Indication |
| SCADA | Supervisory Control and Data Acquisition |
| SEDA | Sustainable Energy Development Authority |
| SEM | Smart Energy Meter |
| SG | Smart Grid |
| SIM | Subscriber Identity Module |
| SM | Smart Meter |
| SMOC | Smart Meter Operation Center |
| SMS | Short Message Service |
| SMT | Surface Mount Technology |

| | |
|---|---|
| SoC | Systems-on-Chip |
| TNB | Tenaga Nasional Berhad |
| ToU | Time of Use |
| TRM | Technology Roadmap |
| UART | Universal Asynchronous Receiver Transceiver |
| UK | United Kingdom |
| USA | United State of America |
| USB | Universal Serial Bus |
| V | Voltage |
| VDSL | Very high-bit rate DSL |
| WAN | Wide Area Network |
| WiMAX | Worldwide Interoperability for Microwave Access |
| WMN | Wireless Mesh Network |
| XAMPP | Cross-platform, Apache, MySQL, PHP and Perl |
| 2G | Second Generations |
| 3G | Third Generations |

## LIST OF NOTATIONS

| | |
|---|---|
| A | Ampere |
| DBm | Unit to measure absolute power in desibel miliwatts |
| I | Current |
| kWh | Unit of energy consumption in kilo Watt hour |
| kW | Unit of energy in kilo Watt |
| M | Meter |
| V | Volt |

# CHAPTER 1

# INTRODUCTION

## 1.1 Research background

Inevitably, electricity has become an essential facility in our daily needs. In order to ensure sufficient and efficient energy can be supplied, a good electricity management is implemented by establishing involvement and cooperation of various interest groups especially the energy providers, energy commissioners and consumers. Other than that, advanced infrastructure and upgraded systems have also contributed to a good electricity management.

As the technologies grow throughout the years, the energy meter has been revolutionized from an electromechanical meter to Automated Meter Reading (AMR), and the application of AMR is broadened by integrate it with other infrastructure to form a system known as Advanced Metering Infrastructure (AMI). The energy meter that started from an electromechanical meter has been upgraded to a digital meter that gives a more accurate meter reading with a one-way communication known as AMR. Then, it has been enhanced to AMI, a unique system consisting of a smart meter (SM) with two-way communication and integrated with meter data management system (MDMS) to boost metering industry (Ab Halim et al., 2014).

SM is a modernized and digitized electronic device equipped with a two-way communication system, sensors and microprocessor to control the entire SM operation which is to measure electrical parameters such as voltage (V), current (I), energy (kW), power consumption (kWh), and power factor (PF) for better measuring, recording and monitoring purposes. SM is also able to increase energy efficiency, be integrated with renewable energy resources and also supporting a new generation of intelligent appliances and plug-in electric vehicles (Syed et al., 2013).

SM with communication system has created an advancement and accessibility in energy monitoring systems where it is able to transmit the electrical data directly to the energy provider and execute specific tasks assigned to it. A new transformation to SM is it gives the power utilities the authority to remotely control the SM to connect and disconnect electricity to users especially in the event of arrears in billing. Besides that, with advanced capability of SM, the utilities are able to manage the demand in electricity during peak load and decreasing the outage events through SM operations (Tjernberg, 2015). The emergence of SM has minimized the usage of manpower in manual meter data collection, thus making the energy management activities more efficient, reliable and cost effective.

There are several communication technologies for SM application for wired or wireless systems. Andreadou et al. (2016) has listed several popular wired and wireless communication in low voltage (LV) communication for smart metering application. They are Power Line Communication (PLC); Narrowband PLC (NB-PLC) and Broadband PLC (BB-PLC), Digital Subscriber Line (DSL) and Fiber Optics. While for wireless systems, they are ZigBee, Cellular technologies (GSM/GPRS-3G-LTE), Worldwide Interoperability for Microwave Access (WiMAX) and Low Power Wide Area Network (LPWAN) (Andreadou et al., 2016).

In light of this evolution in SM technologies, numerous studies have been conducted worldwide investigating the integration of communication systems with SM. Malaysia has implemented Smart Metering Program by conducting SM Pilot test in 2015 to assess the reliability of the SM and the effectiveness of different types of communication technology used by the SM. The outcome of this pilot test has led to the implementation of SM system across Malaysia region.

## 1.2 Problem Statement

The presence of the SM has changed the way of energy consumption data being measured, recorded and stored by the power utilities. No more manual data collection as today, with the SM all data of the energy consumption of the users can be delivered to the utilities automatically via communication system technology. Communication plays an important role in ensuring that the energy meter data are correct, consistent and reliable. The data from SM should be in real-time data, continuous reading and recording measurement of load analysis as well as consumption profiling.

SM communication applies to both wired and wireless communication and it functions accordingly to their characteristics. For wireless communication, it offers advantages in terms of feasibility, ease in installation and lower operating cost. However, it is susceptible to interference and spectrum resource (Zahurul et al., 2016). While, wired communication such as PLC technology is a preferred choice and cost effective since it reuses the existing power-grid infrastructure. But, this PLC has reliability issues due to noise, high signal attenuation, interference from nearby devices, and high loss data rate (Sadat et al., 2017).

In 2015, Tenaga Nasional Berhad (TNB) as the main energy provider in Malaysia has conducted a pilot test project on the SM system to test the reliability of three difference communication; i.e. Global System for Mobile (GSM), radio frequency (RF) and PLC (Tenaga Nasional, 2016; Mohandass, 2015). Based on the pilot test results, where the data was collected from 1$^{st}$ June 2015 until 15$^{th}$ September 2015 at Melaka site, the highest percentage data received from the tested meter was 99.89% and the lowest percentage of 89.02%, with the total average percentage data received was 98.05%. The remaining data that failed in transferring to the data center was concluded due to poor networking, which further caused delays and backlog in data stored in the meter (Mohandass, 2015). The SM used in this pilot test was equipped with single communication, where the single communication could malfunction at some time. It was entirely dependent on the strength and the limitation of the communication during the data transmission process. Other findings from the pilot test were data delayed due to weak RF links, poor GPRS coverage and LAN interface on the PLC data center unit was down. Figure 1.1 shows the results of SM's network performance at Smart Meter Pilot test in Melaka.

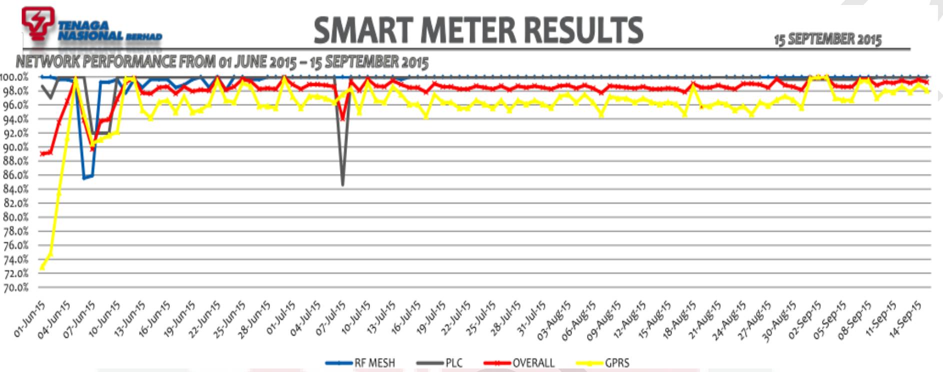


**Figure 1.1: Results of SM's Network Performance at Smart Meter Pilot Test in Melaka** (Mohandass, 2015)

Even though there have been numerous communication technologies had been proposed, communication is still the most critical issue in smart metering (Lipošüak & Boškoviü, 2013). The selected communication standards must ensure that the data transmission within the network is secure, cost-effective, low power, providing large area coverage and high security. Design, maintenance and challenge with data transfer are the most hindrance issues in smart metering, where communication are the most critical part to be considered (Depuru et al., 2011). Unfortunately, most of the communication technologies available have drawbacks such as distance limitations, signal failures in poor conditions and distant location noise (Yusoff et al., 2015; Bilal et al., 2012). The lack in stability in communication system has caused the SM to fail in sending the data adequately and in real-time to the utility where such data was important for billing and monitoring purposes. Communication failure and incompetency in monitoring have affected energy management including energy forecasting, fraud in electricity, demand management and power outage (Erlinghagen, Lichtensteiger & Markard, 2015). In some cases, utilities are installing SM based on available communication infrastructure offered on that location even that is not the best solution (Lloret et al., 2016). Those situations are contributed to a poor networking effect on the metering performance.

Additionally, costing issues is always a hindrance factor in the installation of SM, since the price of SM determined by the manufacturing, installation, communication infrastructure and operating cost (Al-Omary et al., 2012). The design of the SM is considered many aspects, for example, the technology use, cost of the device, communication technology (type of the network, cost of the network devices, range of the network and many more) (Depuru et al., 2011). An additional charge is applied when external devices are needed to permit the communication, modification on the network or expertise trainer for maintenance purpose (Lloret et al., 2016). Relying on a single communication has caused the SM to have to find solution faced from communication issues. To make it worst, in some occasion, the utility has to return to manually collecting the meter reading. The expense of maintaining the system and infrastructure has contributed to the high costs where maintenance is required to ensure the reliability of the system either in automation or manual. Hence, the SM has to be built with the best communication system to ensure that the data would reach the data center adequately and in real-time.

The motivation of this work is to propose a solution in providing a reliable and efficient Smart Energy Meter (SEM) taking into account to Malaysia energy and communication infrastructures. As one of the main problems on the current single communication system SM, the proposed SEM must be able to operate in more than one type of communication system and these communication systems must be able to switch among them effortlessly whenever there is an interruption on the communication signals. Wi-Fi, GSM and RF communication system have been chosen as these three are the one used by the TNB in their electricity measurement and monitoring system. The proposed SEM will evaluate the strength of the communication signals and determine the best communication system for it to transfer the energy data measured by the proposed SEM. An adaptive communication data transfer algorithm is written that is able to evaluate the communication system and switched among the communication system if in any instance interruption occurs during data transfer.

## 1.3 Aim and research objectives

The aim of this work is to develop a SEM prototype capable of transferring data reliably without failure. The objectives in this works are:

1. To develop a SEM capable of measuring electrical parameters and monitoring energy consumptions
2. To design and develop an adaptive communication selection algorithm for reliable data transfer by employing Wi-Fi, GSM and RF communication systems
3. To develop data interface system for monitoring in order to verify SEM reliability in measuring and transferring data

## 1.4 Scopes of work

The scope of this work is divided into three sections; hardware development, software programming and data interface system (DIS).

i. Hardware Development

The hardware development involves the construction of a SEM prototype, which consists of several components and circuits that integrate electrical, electronics and communications elements. It has Microcontroller Unit (MCU), several integrated circuits and sensors to measure power consumptions and three communication integrated circuits or modules to transfer data to DIS by a two-way communication system. MCU is responsible in managing all SEM tasks and energy metering Integrated Circuit (IC) is used to measure and calculate energy consumptions by pulse counting. Three types of communication that have been installed in the SEM are Wireless Fidelity (Wi-Fi), GSM and RF.

ii. Software Programming

Operation and communication algorithm have been developed for the SEM using Arduino programming. The algorithm is responsible in managing the overall operation of SEM and determining the best communication system for data transferring. The communication algorithm will measure and compare the Received Signal Strength Indication (RSSI) of Wi-Fi and GSM, the highest RSSI value will be selected to transfer the data from the SEM to the DIS.

iii. Interfacing System

In order to monitor the data received from the SEM, a DIS has been built. The DIS has been created with GSM gateway and RF transceiver that is connected to a Personal Computer (PC). Several software has been used to display the data received through different communication system which are Hercules Setup for displaying data received from GSM and RF communication, and data that received from Wi-Fi communication will be displayed in localhost website created by Cross-platform, Apache, MySQL, PHP and Perl (XAMPP) software and MySQL database. The data collected from both applications are then converted to comma–separated value (.csv) file and displayed in Microsoft Excel file. The verification of reliability of SEM prototype and software system can be monitored using this interface system.

## 1.5 Contribution of research

This research work is to propose a new SEM prototype with communication selection algorithm in transferring data to the DIS. A contribution of this work can be summarized as follows:

i. SEM prototype

A prototype of the proposed SEM has been designed and constructed. This SEM can measure and stores the electrical parameters i.e. voltage, current and energy consumption. At certain set interval, it will transfer the data to the utilities by selecting the strongest communication system and switched to the next communication system in the event of faults fulfilling its objective in transferring data without failed. This prototype is equipped with MCU, energy metering IC, Liquid Crystal Display (LCD), and three types of communication; i.e. Wi-Fi, GSM and RF. The prototype is designed for single phase application and developed by using basic devices in order to minimize the production cost and simplicity in structure.

ii. Communication selection algorithm

A propose technique of this prototype is on a communication selection algorithm that has been designed and developed using Arduino programming. The algorithm is responsible in evaluating the strength of the communication system based on the RSSI value and then the algorithm will select which communication system will be given the priority to transfer the energy data from the SEM to the data center. It will give priority to Wi-Fi, GSM and RF communication of this order. The highest RSSI value indicates that the communication system exhibits strong signal to get a good wireless connection and able to transmit the data from the SEM to DIS. For example, in the beginning Wi-Fi is set as the main communication on the SEM and during data transfer event, if the communication selection task detected RSSI of Wi-Fi falls lower than the accepted level, it will switch to GSM to continue transmit the data. The communication algorithm has been designed to always give priority to the strongest communication system based on the RSSI value in the order of Wi-Fi, GSM and RF communication and switched to the next communication system if interruption occurs during data transfer event.

An operation algorithm has also been designed and developed to manage and control the functionality of the SEM. The SEM is occupied with several function, there are connect/disconnect function and request data function. Connect/disconnect function is created to cut-off or reconnect the supply, and request data function to get data immediately from the SEM.

iii. Data Interface System (DIS)

A DIS was developed to collect and store all the data from the SEMs for monitoring purpose. DIS has been built by using PC, RF transceiver and GSM gateway. A simple localhost website is created through XAMPP software and MySQL database for data transferring through Wi-Fi communication, while Hercules Setup utility is set for data transferring through GSM and RF communication. All data from both localhost website and Hercules can be converted into Microsoft Excel file for monitoring and storage purpose.

## 1.6 Thesis layout

The thesis is organized in 5 chapters. Chapter 1 gives brief instruction on the SM, its problems, aim and objectives of the work, the contributions and scope of the work.

Chapter 2 starts with energy meter revolutions and the introduction of SM and AMI. The communication in smart metering is reviewed extensively including the influential features as well as the issues arise in SM application. The case study on SM program in Malaysia and other developing countries is discussed concisely. Other researchers' works on SM is revised to finds the similarities and variations on their functionality and performance. Finally, this chapter is concluded with a discussion the selection factors of the three communication for the proposed SEM.

Chapter 3 describes the methodology and the processes of designing and constructing the SEM prototype and its evaluation procedures. The development process includes designing the circuits' layout, fabrication of printed circuit board (PCB) and component assembly. The SEM is programmed to be used for specific software programming to construct main operation included designated tasks. Overall operation of the prototype and the series of tests that had been conducted to prove the reliability, capabilities and efficiency of the prototype is clarified in detailed in this chapter.

Chapter 4 explains an experimental results and research findings of the SEM prototype evaluation. The results demonstrate the reliability of the data from the prototype SEM and the successes of the data transfer process. The research findings are discussed thoroughly its relevance and adaptability to the present situation in the energy management and the utility use. The findings could be useful as the basis for future studies for product improvement and upgrading metering system.

Finally, Chapter 5 concludes this thesis research work and an outline of interesting perspectives for future research.

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