UNIVERSITI PUTRA MALAYSIA

INCORPORATING DECENTRALIZED RENEWABLE ENERGY IN SMART GRID USING ZIGBEEPRO

SYED ZAHURUL ISLAM

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By

SYED ZAHURUL ISLAM

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

February, 2016

DEDICATIONS

To my parents Syed Golam Mostafa and Syeda Nurun Nahar

and my sister Syeda Mohsina Akhter

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the Doctor of Philosophy

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SYED ZAHURUL ISLAM

February 2016

Chair: Professor Norman Mariun, PhD, PEng
Faculty: Engineering

Distributed Renewable Generation (DRG) is one of the major components of the Smart Grid (SG) from where the real-time energy information is expected to export to control center for demand management and energy forecasting. For this export service, low-powered and low-data rate communication protocol, e.g. ZigBeePRO is targeted for achieving the DRG communication requirement where reliability and critical demand of data delivery are not mandatory. In this thesis, the aim is to determine seasonal performance evaluation and energy yield modelling of the two photovoltaic (PV) modules, namely, Amorphous Silicon (A-Si) and Crystalline Silicon (C-Si) for Feed-in-Tariff (FiT) or DRG. Several other properties of the DRG solar environment, such as presence of various dielectric constant materials and uneven presence of obstacles are also considered in the analysis. To achieve these aims, shortest and strongest Received Signal Strength Indicator (RSSI) weighted path signal of ZigBeePRO is modelled relying on a real test-bed, 35kW solar DRG at Universiti Putra Malaysia (UPM). ZigBeePRO radio, Waspmote embedded board, and electrical and environmental parameters' measurement sensors are coalesced into a sensor-node which are installed at the existing 10kW UPM solar DRG site. Based on the seamless acquiring and importing of these parameters from the DRG site to the control centre, the two types of PV modules' performance are analysed which show significant variations in energy yield in tropical Malaysia. Moreover, the performance of data collection also shows that ZigBeePRO is recommended over ZigBee S1 for this specific purpose of SG where there is no strict-time and high demanding requirement of data delivery.

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

MENGGABUNGKAN TENAGA BOLEH DIPERBAHARUI TIDAK BERPUSAT DALAM GRID PINTAR MENGGUNAKAN ZIGBEEPRO

Oleh

SYED ZAHURUL ISLAM

Februari 2016

Ketua: Profesor Norman Mariun, PhD, PEng
Fakulti: Kejuruteraan

Pengagihan Diperbaharui Agihan (PDA) merupakan salah satu komponen utama Grid Pintar (GP) di mana maklumat tenaga masa nyata dijangka bagi dieksport ke pusat pengawal untuk pengurusan permintaan dan ramalan tenaga. Untuk perkhidmatan eksport ini protokol komunikasi berkadar rendah dan berkuasa rendah seperti 'ZigBEEPRO', disasarkan mencapai keperluan komunikasi PDA di mana kebergantungan dan permintaan kritikal penghantaran data adalah tidak wajib. Tesis ini bertujuan untuk menilai prestasi berkala dan penghasilan tenaga permodelan dua modul sel suria yang dikenali sebagai Silikon Amorfus (ASi) dan Silikon Kristal (C-Si) dalam penggunaan tarif suap masuk atau PDA. Beberapa ciri lain disekitar solar PDA seperti kehadiran pelbagai bahan pemalar dielektrik dan kehadiran tidak sekata halangan juga diambil kira dalam analisis ini. Bagi mencapai matlamat tersebut, kesingkatan dan kekuatan Penunjuk Kekuatan Isyarat yang Diterima (RSSI) menjadi pemberat laluan isyarat ZigBeePRO dimodel berdasarkan pada tapak ujian sebenar, 35kW DRG solar di Universiti Putra Malaysia (UPM). Radio 'ZigBeePRO', papan tertanam 'Waspmote', dan deria pengukur elektrikal dan parameter persekitaran digabungkan ke dalam satu nod deria dan dipasang di tapak PDA Solar 10kW yang sedia ada di UPM. Berdasarkan kepada perolehan berterusan dan penerimaan parameter dari tapak PDA ke pusat kawalan, prestasi kedua –dua jenis modul PV dianalisis dan menunjukkan variasi ketara dalam penghasilan tenaga di kawasan tropika Malaysia. Selain itu juga, pelaksanaan pengumpulan data menunjukkan bahawa ZigBee PRO adalah disarankan berbanding ZigBee S1 khususnya untuk tujuan GP di mana tiada kekangan masa yang kritikal dan keperluan permintaan penghantaran data yang tinggi.

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I certify that a Thesis Examination Committee has met on 4 February 2016 to conduct the final examination of Syed Zahurul Islam on his thesis entitled "Incorporating Decentralized Renewable Energy in Smart Grid using Zigbeepro" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

Members of the Thesis Examination Committee were as follows:

Jasronita binti Jasni, PhD
Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Borhanuddin bin Mohd Ali, PhD
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Norhisam bin Misron, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Saifur Rahman, PhD
Professor
Virginia Polytechnic Institute and State University
United States
(External Examiner)

ZULKARNAIN ZAINAL, PhD
Professor and Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 25 May 2016

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

Norman Mariun, PhD
Professor, Ir
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Hashim Hizam, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Mohammad Lutfi bin Othman, PhD
Senior Lecturer, Ir
Faculty of Engineering
Universiti Putra Malaysia
(Member)

BUJANG BIN KIM HUAT, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

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Signature: ______________________

Name of Chairman of Supervisory Committee:
Y. Bhg. Prof. Ir. Dr. Norman Mariun

Signature: ______________________

Name of Member of Supervisory Committee:
Prof. Madya Dr. Hashim Hizam

Signature: ______________________

Name of Member of Supervisory Committee:
Ir. Dr. Mohammad Lutfi bin Othman

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LIST OF MATHEMATICAL SYMBOLS

M	A 2D matrix consisted of $r_{i,j}$
T	Acyclic minimum weighted based path
θ	Angle between two antennas' polarization direction
G_{Tx}/G_{Rx}	Antenna gain for T_x/R_x
n_i	Any fully functional device (FFD) node
p, i, j	Any integer number
A	Area
ρ_{STC}	A-Si/C-Si module efficiency in STC
I_{avg}/I_{max}	Avg/max output current of A-Si/C-Si module
n_c	Central PAN coordinator
f	Channel operating frequency
C_t	Channel traffic
ϵ	Dielectric constant
$d_{i,j}$	Distance between n_i and n_j
D	Distance between T_x and R_x
H_a/H_s	Effective/structural antenna height
E_i	Energy consumption at i mode
Π	Energy yield from A-Si/C-Si module
H	Humidity
α	Incident angle
I_m	Module current
t_m	Module temperature
t_{coff}	Module temperature coefficient
β	Number of network
P_{out}	Output power of A-Si/C-Si module
V	Output voltage of A-Si/C-Si module
τ	Path loss exponent
H_{Tx}/H_{Rx}	Placement height of transmitter/receiver antenna
$\mathbb{Z}$	Positive integer number set
P_d	Power per unit area
ϱ, φ	Probability of medium and high luminance day respectively
PL	Propagation path loss
R_{ray}	Propagation path loss for two-ray model
I	Set of interconnections of the graph
G	Set of nodes
Z	Solar irradiance
S	Sun hour
P	Temporarily created edge set
ΔH	Terrain irregularity parameter
T_x/R_x	The transmitter/receiver

T_u	Throughput of unslotted CSMA-CA
Δ	Time delay for T_u
N	Total no of days in dry season
k	Total number of nodes
P_t	Total transmitted power
P_{Tx}/P_{Rx}	Transmission/received power of antenna
R_{TM}/R_{TE}	Transverse magnetic/electric reflection coefficient
ζ	Very careful siting constant
λ	Wavelength
$r_{i,j}$	Weight between n_i and n_j (or RSSI value)

LIST OF ABBREVIATIONS

ADC	Analog-to-Digital Converter
APL	Application Layer
A-Si	Amorphous Silicon
BE	Backoff Exponent
BI	Beacon Interval
BP	Backoff Period
CAPER	Center for Advanced Power and Energy Research
CCA	Clear Channel Access
CLH	Cluster Head
C-Si	Carbon Silicon
CSMA/CA	Carrier Sense Multiple Access Collision Avoidance
DRG	Distributed Renewable Generations
FFD	Fully Function Device
FiT	Feed-in-Tariff
HAN	Home Area Network
LOS	Line of Sight
MAC	Media Access Control
MS Access DB	Microsoft Access Database
NWL	Network Layer
OPE	Output Power Efficiency
PAN	Personal Area Network
PER	Packet Error Ratio
PHEV	Plug-in Hybrid Electric Vehicle
PLC	Power Line Communication
PR	Performance Ratio
PV	Photovoltaic
RE	Renewable Energy
RFD	Reduced Function Device
RSSI	Received Signal Strength Indicator
RTC	Real Time Clock
SG	Smart Grid
STC	Standard Temperature Condition
TE	Transverse Electric
TM	Transverse Magnetic
TNB	Tenaga Nasional Berhad
UPM	Universiti Putra Malaysia
WLAN/WiFi	Wireless Local Area Network
WS	Wireless sensor
WSN	Wireless Sensor Network

CHAPTER 1

INTRODUCTION

1.1 Motivation

Human beings are struggling to overcome two compelling and daunting challenges: the challenges of self-development and the needs for a more effective system of international security. These interlinked challenges are inevitably connected with energy. All aspects of development from plummeting poverty to convalescent transportation system, latest energy service is highly required. The present electrical power or energy management system has been serving energy since six decades. It is fully depended on fossil fuel that includes coal, natural gas, diesel, and oil or alternatively nuclear fuel. These energy sources are also called non-renewables and it is depleting day by day. One of the major concerns of depletion non-renewable sources is unprecedented growth in world population. The statistics of Population Division of the United Nations has projected over 2 billion more people than are alive today which yields 9 billion people in 2050 (Zabel, 2009; Mariun, 2011). To meet the demand specifically in energy sector of this huge population is going to be one of the major challenges. However, to date, there is no scientific unanimity on when non-renewable energy will be debilitated. The environmental impact is another challenge for carbon emissions and greenhouse effect (includes other greenhouse gases) from non-renewables. The growth in global emissions of CO_2 from non-renewables over the past ten years was four to five times greater than for the preceding 10 years. The consequences of global warming could lead to disturb natural ecosystem such as melting polar ice caps and mountain glaciers would result in the rising sea level and coastal inundation. The changing climate would alter forests and crop yields, lead to famine, threaten to plant and animal habitats, and extinct to some species. These effects mainly bring us to thinking about carbon free energy sources or six renewable sources such as wind, solar, biomass, water (hydropower), ocean wave, and municipal solid waste (Mariun, 2011).

The present power grid has remained unchanged in its basic structure for more than 100 years even though the power demand has been increased few times with the increasing population. Huge advancement of computer, communication and related technologies has occurred for last decades; however, deployment of these modern technologies has not been fully implemented in the ageing electrical grid. This causes a significant effects on the present grid system such as blackouts (Kuzlu et al., 2014). The major causes of blackouts for the last 45 years are absence of system automation, poor response and failure of mechanical devices, lack of automated demand management system, single-way communication, disparity between demand and supply management, fuel scarcity, cascading failure, and others (Gungor et al., 2010, 2011). A statistical report states that a rolling blackout across Sun Microsystems estimates blackout-cost US$1 million every minute (Mariun, 2011).

Therefore, it motivates us to think a fully advantageous, efficient and complete integration of computer and communication in power grid system. To meet the demand of 9 billion people, the future electricity management will have to be automated, intelligent, and effective to integrate renewable generations. In addition, assets management, minimum involvement of manpower, smarter and enhanced monitoring systems can be envisaged to deal with varieties of adventitious that replace the present grid in terms of digitization, adaptability, sustainability, and customization. Moreover, to address the problems of mismatch between the energy supply and demand, distribution capacity, generation fuels, and the associated price volatility, a robust two-way communication based intelligent network is inevitable for the future grid or in other word, Smart Grid (SG). When there is a question of integrating different components of SG such as electrical vehicle, smart home/building, distribution management, and Distributed Renewable Generations (DRG), an information and communication technology based infrastructure should be enabled to import energy information from the distributed side to the control center (Kuzlu et al., 2014; Bilgin and Gungor, 2012; Wang et al., 2010). In more specific, the aim of the future SG is to maximize the self-healing and autonomy of the system, remote monitor and management of intelligent devices in real-time, make utilities able to attain energy production of DRG, deployment of advanced technologies to improve and secure the power industry.

1.2 Problem Statement

Lack of two-way communication and monitoring can cause many problems in the future SG including demand management, energy forecasting, and power outage (Kuzlu et al., 2014; Uzun et al., 2014; Zheng et al., 2013). The effectiveness and efficiency of the next generation SG will be determined by the automated and intelligent management of diversified DRG where delivering real-time data to the SG control center plays a pivotal role in building the two-way communications (Wang and Khanna., 2011; Yan et al., 2013). In Feed-in-Tariff (FiT) application, 5-15% energy reduction is possible through online monitoring of consumers' energy consumption displayed at their portals (Erlinghagen et al., 2015). Moreover, like many other countries, Malaysia's existing power grid is not yet improved with current generation of information and communication technologies; so a unidirectional energy flow from generation to the consumer persists. Due to the lack of a two-way communications, Tenaga Nasional Berhad (TNB) does not have real-time information about actual DRG or FiT production that fluctuates with climate change. In this situation, TNB is unable to balance between the consumer load and the supply of electricity through demand management and energy forecasting program. With this problem, TNB cannot motivate its consumers to reduce the consumption at peak-hour by updating their real-time FiT production in energy portal/mobile application.

In the 10th Malaysia plan, crystalline type PV modules have been widely used due to their attractive efficiencies. The efficiencies of the PV modules are specified by the manufacturer in standard temperature condition (STC)-1000W/m^2 incident irradiance, 25^{o}C module temperature, and 1.5 air mass. However, PV module efficiency in STC is not applicable for Malaysia climate condition since 33^{o}C ambient temperature can significantly affect the open circuit voltage by -104 mV/^{o}C of the PV (Femia et al., 2012). This can reduce 0.0015^{o}C^{-1} and 0.004 0.005^{o}C^{-1} at the fill factor (FF) and output power respectively, considering silicon cell at energy band gap of 1.2 (Skoplaki and Palyvos, 2009).

It indicates that the performance of different PV modules varies from STC measurement and energy yield, depending on geographical position and climatic condition. Based on Malaysia's real climate variation, there should be an analysis on performance of Malaysian Energy Commission recommended PV modules and its energy yield for maximum gain or return on investment considered from the FiT system. Moreover, it is important to meet the DRG communication requirement for energy data import service from the DRG or FiT sites to the control center in terms of cost effectiveness, flexibility, and interoperability.

1.3 Research Aim and Objectives

The aim of this research is to integrate solar DRG to the SG control center using ZigBeePRO protocol where there is no strict delay time and high demanding requirement of data delivery.

The objectives are:

i. To design a two-way data communication network for solar DRG considering flexible and low-powered ZigBeePRO protocol and its propagation path loss,

ii. To implement energy monitoring system through importing AC-DC electrical parameters of the solar modules and environmental parameters of the solar DRG site,

iii. To analyze the PV modules' performance in terms of energy yield in kWh, that is, the deviation from the STC stated by the modules' manufacturers, in a manner analogous to the FiT system.

1.4 Thesis Contribution

The contribution of this thesis can be summarized as follows:

I. DRG communication network modelling and simulation –In this contribution, ZigBeePRO Wireless Sensor Network (WSN) and its RSSI based shortest path technique is modelled in terms of a real test-bed, 35kW solar power plant as a DRG in UPM. Different properties of the solar DRG site such as antenna placement and uneven presence of obstacles are investigated for the performance analysis of ZigBeePRO network namely propagation path loss and energy consumption. Electromagnetic ZigBeePRO wave-effect due to the presence of these properties causes transmission impairment which is considered in the modelling by analysing dielectric constant materials, transverse electric and magnetic polarizations, and two-ray model. With this, considering ZigBeePRO communication and DRG environmental properties, a propagation path loss model is obtained and validated comparing with the relevant research works. In addition, electrical and environmental parameters of the 35kW solar DRG and its packet structure are analysed compatible for Libelium manufactured ZigBeePRO-embedded sensor node. The relevant energy consumption for shortest path technique is evaluated as a function of Packet Error Ratio (PER) through comparing with other ZigBee topologies.

II. Simulation framework prototype implementation –In this contribution, an initial version of the proposed simulation framework is developed, i.e. the WS node is created using ZigBeePRO radio, measurement circuits, sensors, and embedded boards. The WS nodes are installed based on the previous contribution on modelling into the inverter/UPM-feeder at the UPM 10kW solar DRG site. The ZigBeePRO protocol based communication network is implemented for monitoring both AC and DC electrical parameters of the solar module and environmental parameters of the solar site from the control center and also adjacent data substation. Instead of ZigBeePRO, ZigBee S1 is utilized as WS node and comparison is performed in terms of RSSI in this DRG environment. This initial version of the ZigBeePRO framework and prototype is ready to use and can be expanded for large DRG integration.

III. Prototype validation –In this contribution, the prototype is validated by efficient data monitoring from the DRG site. In the validation, Amorphous Silicon (A-Si) and Crystalline Silicon (C-Si) PV modules are targeted to evaluate for five days' data collection during dry season in respect of Malaysia climate. The obtained prediction model based on data analysis estimates total energy yield during dry season in kWh for the FiT monthly reimbursement. Through sensing technology, another validation is conducted by investigating the temperature effect on A-Si PV module's performance.

1.5 Scope of the Research

The scope of this research is as follows.

The research work is focused on evaluation the seasonal performance and energy yield modelling of the two PV modules, namely, amorphous silicon

(A-Si) and crystalline silicon (C-Si) for FiT or DRG system. In this regard, a number of performance parameters including electrical and environmental have been collected using a smart wireless communication system with the aim of higher data collection rate over a period of five days during the dry season in Malaysia. Further, an experiment is conducted considering the A-Si PV module in both indoor and outdoor condition to investigate the temperature effect on A-Si module's performance in terms of efficiency and output power through an automatic resistor selection system.

In the smart WS based system, low energy consumption protocol, ZigBeePRO is used for fulfilling the communication requirement of the DRG/FiT. Accordingly, the microcontroller program using Arduino UNO is developed in the automatic resistor selection system in such a way that it wakes up every hour and reads the 13 different voltages produced by the PV module across the 13 different resistive loads and the current pass through each load. Considering this WS nodes suitable for installing at each PV modules, the shortest and strongest RSSI weighted path algorithm is modelled for the DRG (importing energy data from PV inverter to the control center) by examining the real test-bed UPM solar DRG.

The outcome from the shortest path algorithm is followed in hardware implementation where deploying WS nodes for electrical and environmental parameters' measurement of the solar power plant. Embedded board coalesced sensors are programmed according to the measurement parameters of the solar panel. The parameters from the distributed WS nodes are collected at nearby data substation into a local database using LabVIEW implemented program. In addition, a MAC supported router placed at distribution site also collects data from the WS nodes and saves temporarily into its local database, which is then synchronised with the control center permanent database. The synchronization between the two databases is conducted through UPM optical fiber network at every defined interval.

In order to conduct the comparison analysis between ZigBee S1 and ZigBeePRO in the DRG environment, RSSI data are investigated for the both communication networks. In this case, the limitations in poor signal strength and significant data loss are observed for ZigBee S1 module.

1.6 Thesis Organization

The rest of the thesis is organised as the following.

Chapter 2 starts with literature reviews on different types of communication technologies in SG and comparison analysis among them. It highlights on the solar energy related work. The PV module evaluation is reviewed extensively based on the recent researches. Then it describes the influential features as well as shortcomings of ZigBee and ZigBeePRO as a WSN, in the concern of choosing for the DRG monitoring in smart grid application. The shortcomings are identified based on previous researches and relevant solutions are discussed. The chapter also explains other wireless technologies that have been proposed by other researchers for different domains of SG. The SG roadmap of TNB Malaysia, present progress, and comparison scenario with other countries are also presented in this chapter. Finally, this chapter is concluded with a discussion that why ZigBeePRO is chosen for the DRG monitoring over other communication technologies.

Chapter 3 highlights the relevant issues that have been considered for the modelling. Before that, it gives a brief overview of PV electrical parameters, relevant model equations, and temperature effect on output power and efficiency. The energy consumption cost for different methods and different network parameters are explained. Then it analyses dielectric object material, reflection coefficients, and the two-ray model in the concept of UPM solar DRG environment. Based on the terrain of UPM DRG site, antenna heights and transmission impairment are also analysed in this chapter.

Chapter 4 discusses on the shortest and strong RSSI weighted path modelling for the 35kW solar DRG. Then, the experimental setup based on WS node are explained here. Program for sensor data acquisition using LabVIEW and it's linked with MS access DB, managing polymorphic function in LabVIEW are illustrated too. The complete installation of the implemented WS node at UPM solar DRG premises is explained. Finally, it discusses WS node fabrication using ZigBee S1 and RSSI field measurement experiment.

Chapter 5 presents the implementation of data collection using the proposed methodology. The collected energy and environmental data are analyzed in this chapter for PV modules performance evaluation and modeling. This chapter is closed with an experimental analysis on obtained RSSI for ZigBee S1 and ZigBeePRO in the UPM solar DRG environment.

Finally, Chapter 6 concludes this research work and an outline of interesting perspectives for future research.

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