ENERGY MANAGEMENT SYSTEM CONTROLLER INTEGRATED WITH SOLAR PHOTOVOLTAIC FOR SMART ENERGY UTILIZATION

by

KUMUTHAWATHE A/P ANANDA-RAO
1440911252

A thesis submitted in fulfillment of the requirements for the degree of Doctor of Philosophy

School of Electrical System Engineering
UNIVERSITI MALAYSIA PERLIS

2017

ACKNOWLEDGEMENTS

I would like to take this opportunity to acknowledge the support and helps of numerous people, without whom this report would not have been possible.

First and foremost, I would like to express my sincere gratitude and appreciation to UniMAP and UniMAP vice chancellor for giving me an opportunity to pursue my studies at UniMAP. Next, I thank to my supervisor, Ir. Dr. Rosnazri Ali for his invaluable guidance and support throughout this research execution which enables me to complete this study. I also would like to thank the Dean of School of Electrical System Engineering, lecturers and lab technicians for their advice and help along the entire research.

Next, I would like to express my gratitude to my husband, Mr Steven Taniselass who supports me and being the source of my strength and inspiration to complete this research successfully. I also would like to thank my parents and family members for their motivation and understanding throughout this project.

Before I end, once again I take this opportunity to thank the entire individual who direct or indirectly help me to complete this thesis. Thanks to all.

DEDICATION

To my husband, Mr Steven and my family

for their infinite love, support and encouragement…

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

GHG	Green House Gasses
CO_2	Carbon Dioxide
RE	Renewable Energy
PSH	Peak Sun Hour
PV	Photovoltaic
SEDA	Sustainable Energy Development Authority Malaysia
FIT	Feed-In Tariff
ESS	Energy Storage System
BESS	Battery Energy Storage System
AC	Alternating Current
DC	Direct Current
NiCd	Nickel Cadmium
NiMH	Nickel Metal Hydride
PbO_2	Lead Dioxide
Pb	Lead
H_2SO_4	Sulfuric Acid
C_6	Graphite
$LiCoO_2$	Lithium Cobalt Oxide
$LiMn_2O_4$	Lithium Manganese Oxide
$LiPF_6$	Lithium Hexafluorophosphate
NiOOH	Nickel Oxide Hydroxide

MH	Metal Hydride
KOH	Potassium Hydroxide
NaS	Sodium Sulphur
VRB	Vanadium Redox Battery
ZnBr	Zinc Bromine
PSB	Polysulphide Bromide Battery
NaNiCl	Sodium Nickel Chloride
I/O	Input/Output
SOC	State of Charge
GA	Genetic Algorithm
PSCAD	Power Systems Computer Aided Design
EMTDC	Electromagnetic Transient Design and Control
MPPT	Maximum Power Point Tracking
LL	Load Leveling
PS	Peak Shaving
LCD	Liquid Crystal Display
LED	Light Emitting Diode
PWM	Pulse Width Modulation
USB	Universal Serial Bus
ICSP	In-Circuit Serial Programming
SRAM	Static Random Access Memory
EEPROM	Electrically Erasable Programmable Read-Only Memory
IC	Integrated Circuit

MOSFET	Metal Oxide Semiconductor Field Effect Transistor
IDE	Integrated Development Environment
ADC	Analog to Digital Converter

LIST OF SYMBOLS

η	Efficiency
E_{out}	Electricity output
E_{in}	Electricity input
A	Ampere
mA	miliAmpere
Ah	Ampere-hours
V	Volt
mV	miliVolt
W	Watt
kW	Kilowatt
h	Hour
Wh	Watt-hours
kWh	Kilowatt-hours
Wh/L	Energy per unit volume
Wh/kg	Energy per unit mass
W/L	Power per unit volume
W/kg	Power per unit mass
%	Percentage
Ω	Resistance (ohm)
Q	Battery rated capacity
i(t)	Battery Current

$<$	Less than
$>$	More than
$\leq$	Equal or less than
$\geq$	Equal or more than
$=$	Equal
Hz	Hertz
F	Frequency
r	Ripple factor
$V_{r(pp)}$	Peak-to-peak ripple voltage
V_{DC}	DC voltage
$V_{p(rect)}$	Peak rectified voltage
V_{cc}	Supply voltage
R_L	Load resistance
C	Capacitor value
R	Resistor value

Pengawal Sistem Pengurusan Tenaga Disepadukan Dengan Sistem Fotovolta Solar Untuk Penggunaan Tenaga Pintar

ABSTRAK

Peningkatan berterusan penggunaan tenaga elektrik global dan gema isu berkaitan pemanasan global telah memberi isyarat kepada komuniti penyelidikan untuk mencari cara alternatif untuk menjana dan mengurus tenaga yang dihasilkan dengan cekap. Oleh itu, penyelidikan kejuruteraan dalam Tenaga Diperbaharui (RE) dan Sistem Tenaga Simpanan (ESS), terutamanya Sistem Tenaga Simpanan Bateri (BESS) telah diiktiraf sebagai penyelesaian utama dan mempunyai jaminan dalam menjana, menyimpan dan menggunakan tenaga elektrik pada tahap optimum, di samping meningkatkan penggunaan grid. Dengan kehadiran Tenaga Diperbaharui dan Sistem Tenaga Simpanan Bateri dalam sistem kuasa, adalah perlu untuk mempunyai suatu pengawal yang bertindak sebagai otak untuk mengabung semua sistem dengan berkesan. Oleh itu, rekabentuk dan pembangunan suatu pengawal adalah sangat penting dan memerlukan perhatian dalam usaha pelaksanaan untuk memenuhi keperluan untuk fungsi, kesederhanaan, mudah alih, kebolehharapan dan dalam kos yang murah. Oleh itu, kajian ini adalah khusus untuk merekabentuk dan membangunkan sebuah pengawal sistem pengurusan tenaga untuk Sistem Tenaga Simpanan Bateri disepadukan dengan sistem Fotovolta Solar (PV) untuk penggunaan tenaga pintar, yang berdasarkan aplikasi pengarasan beban dan penarahan puncak untuk masa nyata pengurusan kuasa arus ulang-alik. Fungsi utama pengawal ini adalah untuk memantau profil permintaan beban dan mengerakkan bateri sama ada untuk mengecas dari sistem Fotovolta Solar (PV) atau menyahcas untuk menghasilkan profil beban yang aras atau arahan puncak yang akan dilihat pada rangkaian grid, di samping mengekalkan penggunaan permintaan beban sebenar. Oleh itu, kajian ini dibahagikan kepada dua bahagian utama, untuk merekabentuk pengawal dengan menggunakan perisian Matlab Simulink dan untuk membangunkan pengawal prototaip berdasarkan pengawalmikro. Pengawalmikro dipilih kerana ciri-cirinya yang sesuai dengan sempurna untuk kerumitan rekabentuk pengawal ini. Selain itu, kaedah kawalan algoritma dan kajian parameter telah dilakukan dengan teliti dan ditakrifkan untuk mengesahkan kesahihan operasi dan fungsi pengawal. Pada masa yang sama, sebahagian daripada kerja simulasi rekabentuk dilakukan menggunakan pelbagai jenis bateri yang tersedia di pasaran untuk perbandingan prestasi dan pengesahan. Daripada keputusan simulasi dan ujian prototaip, dapat disimpulkan bahawa pengawal sistem pengurusan tenaga berfungsi dengan baik sama ada untuk menghasilkan profil permintaan beban yang aras atau arahan puncak. Keputusan simulasi menunjukkan purata 37.38% permintaan beban diratakan dan purata 32.55% daripada puncak beban dikurangkan jika dibandingkan dengan permintaan beban sebenar dalam keadaan operasi unggul. Malah, prestasi pengawal juga bertindakbalas cepat dan cekap dengan operasi serta-merta untuk mengarahkan bateri samada mengecas atau menyahcas berdasarkan perubahan permintaan beban. Secara keseluruhan, suatu pengguna mesra pengawal sistem pengurusan tenaga telah berjaya dibangunkan, yang menjimatkan kos dan mengurangkan bil utiliti dalam kajian ini.

Energy Management System Controller Integrated With Solar Photovoltaic For Smart Energy Utilization

ABSTRACT

Continuous growth of global electrical energy consumption and the echo of global warming related issues have signaled research community to search an alternative way to generate and to efficiently manage the generated energy. Thus, engineering researches in Renewable Energy (RE) and Energy Storage Systems (ESS), especially Battery Energy Storage System (BESS) have been recognized as primary solution and having an assurance in generating, storing and using the electrical energy at optimum level, besides improving the grid utilization. With the presence of RE and BESS in a power system, it is necessary to have a controller which acts as the brain to interface all the system efficiently. Hence, the design and development of a controller become very crucial and need careful execution in order to meet the requirements for functionality, simplicity, portability, reliability as well as less cost. Therefore, this research is dedicated to design and develop an energy management system controller for BESS integrated with solar Photovoltaic (PV) system for smart energy utilization, which is based on load leveling and peak shaving applications for real-time AC power management. The main function of the controller is to monitor the load demand profile and trigger the battery to either charge from the solar PV or discharge to produce a leveled or shaved load profile that will be seen at the grid network, while maintaining the actual load demand usage. Hence, this research is divided into two main sections, to design a controller by using Matlab Simulink and to develop the prototype controller based on microcontroller. Microcontroller was chosen because of its features that suit the complexity of this controller design perfectly. Besides that, the control algorithm method and parameter study was carefully carried out and defined in order to verify the validity of the controller operation and function. At the same time, a part of the design simulation work is performed using different types of batteries that are available in market for performance comparison and verification. From the simulation and the prototype testing results, it is concluded that the energy management system controller is working well to either produce a leveled or shaved load demand profile. The simulation results shows an average of 37.38% load demand is leveled and an average of 32.55% of load peak is reduced when compared to the actual load demand in an ideal operating condition. Moreover, the controller performance is also immediate and efficient with its simultaneous operation to trigger the battery whether to charge or discharge based on the changes of load demand. Overall, a user friendly energy management system controller is successfully developed and achieved to save cost and to reduce the utility bills in this research.

CHAPTER 1

INTRODUCTION

1.1 Background Study

Energy plays an important role in our daily life and the demand is increasing from day to day due to the rapid growth of industrialization and world population. Energy consumption has become the defining factor for the development of any society as the usage of energy has been identified as a major input element for economic development in any country. According to the estimation done by International Energy Agency, an increment of 53% in global energy consumption is expected by 2030 (Ong, et. al., 2011). As an example, in Malaysia itself, the total energy consumption is expected to grow on average of 4.3% annually from 2004 to 2030 based on the macroeconomic indicators obtained from official publications of the Malaysian government (Ashourian, et. al., 2013).

Presently, the global energy resources are based on fossil fuels such as coal, oil and natural gas which are also known as conventional energy resources. Statistical data has indicated that coal reserves could last for about 200 years, oil for approximately 40 years and the natural gas for about 60 years with the current rate of energy consumption (Gurjar & Mahor, 2013). Hence, the reserves of fossil fuels are limited and the supply chain is expected to come to an end in the near future with the current trend of usage. Besides that, the large-scale utilization has negative environmental impacts on the environment. For example the increase in the emissions of Green House Gasses (GHG) such as carbon dioxide (CO_2) to our atmosphere has changed the world climate, leading to global warming issues. With these pressing situations, the search for a new form of energy which is climate-friendly as well as unharmful for living organisms is urgently needed. This has triggered the technological advancement in the utilization of renewable energy at a large-scale (NREL, 2001; Nejad, et. al., 2016).

Renewable Energy (RE) is generally defined as an energy that is harvested from resources which are continually replenished by nature such as sun, wind, hydropower, biomass, ocean energy and geothermal heat. RE is also often called as "clean" environmental friendly energy, green energy or sustainable energy which is derived directly from nature (NREL, 2001). Nowadays, RE is becoming popular in electricity generation because of the finite resources of fossil fuels (non-renewable) that currently dwindling. In addition, RE could also help to lessen the negative impacts on the environment.

Most renewable energies come either directly or indirectly from the sun. Energy from the sun or so called solar energy can be used directly for generating electricity at homes and also extended to a wide variety of commercial and industrial uses. Besides that, the sun's heat also drives the winds, whose energy is captured with wind turbines which can generate electricity. Moreover, the heat and the winds also cause the ocean or river water to evaporate. When this water vapor turns into rain and flows from downhill into rivers or streams, the energy generated can be captured by using hydroelectric power. Likewise, sunlight causes plants to grow. This so called biomass energy is then stored in organic matter that is made up from dead plants and is also known as bioenergy. Thus, hydropower and biomass energies are also from the sun indirectly. In contrast, geothermal energy is from the natural heat of the earth while tidal energy is from the gravitational pull of the moon and the sun upon the earth.

Currently, RE resources have grown to supply an estimated of 19.2% of global final energy consumption in 2014 and are continuing to grow strongly. Fig. 1.1 depicts RE as mainly divided into two categories: modern renewables and traditional biomass. Modern renewables contributes 10.3% of overall energy which comes from hydropower, wind, solar, geothermal, biofuels and modern biomass. In this category, the highest energy supplied is from hydropower. It supplies 3.9% of the overall power as the hydro capacity is growing steadily from the large base. The remaining modern renewables provided an approximately of 6.4% of the final energy consumption in 2014 and have been experiencing a rapid growth in many developed and developing countries alike. Meanwhile, traditional biomass such as woodfuels and animal or plant matters contributes 9% of final total energy which is primarily used for cooking and heating in rural areas at developing countries where it could be considered as RE resources (REN21, 2016). At same time, energy experts expect that in the year 2050, over 50% of all electricity could be generated by using RE resources such as sunlight, wind, rain, tides and geothermal heat (Ashourian, et. al., 2013).

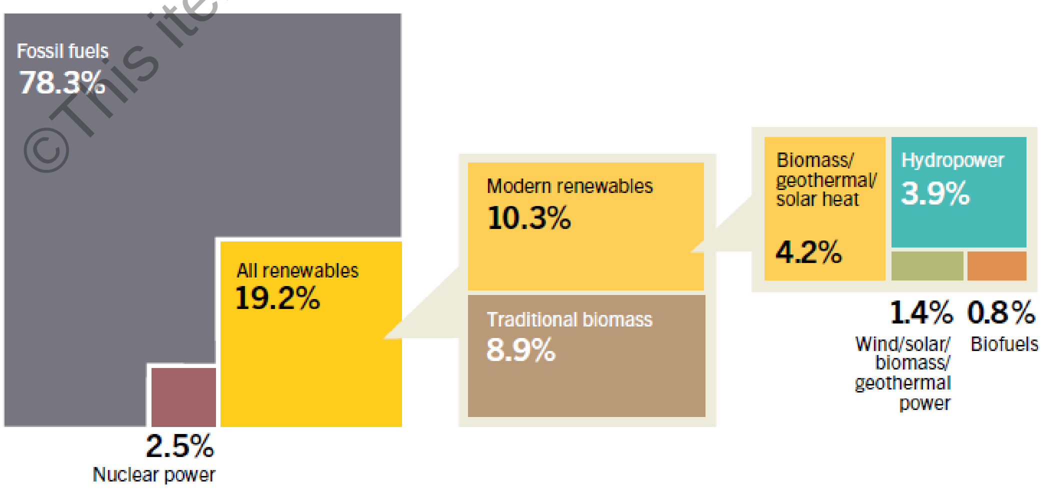

Figure 1.1 : Estimated Renewable Energy share of global final energy consumption in 2014 (REN21, 2016)

The situation in Malaysia is also no different where the government has devoted a great deal of attention to RE as an alternative power source. As a tropical country, Malaysia is generally hot all year around with an average standard Peak Sun Hour (PSH) value about 4 to 5 hours where it has the high potential of electricity generation by using solar power (Dimas, et. al., 2011). There are many operational and on going projects in Malaysia particularly emphasizing on solar Photovoltaic (PV) as it is the most economical in the long term although it has a high upfront cost. This can be seen in Fig. 1.2, which shows national RE goals in Malaysia where the main focus is to increase solar PV usage (SEDA, 2015). Besides that, Sustainable Energy Development Authority Malaysia (SEDA) has implemented a Feed-In Tariff (FIT) to ensure RE becomes a viable as well as attractive long-term investment for both industries and individuals.

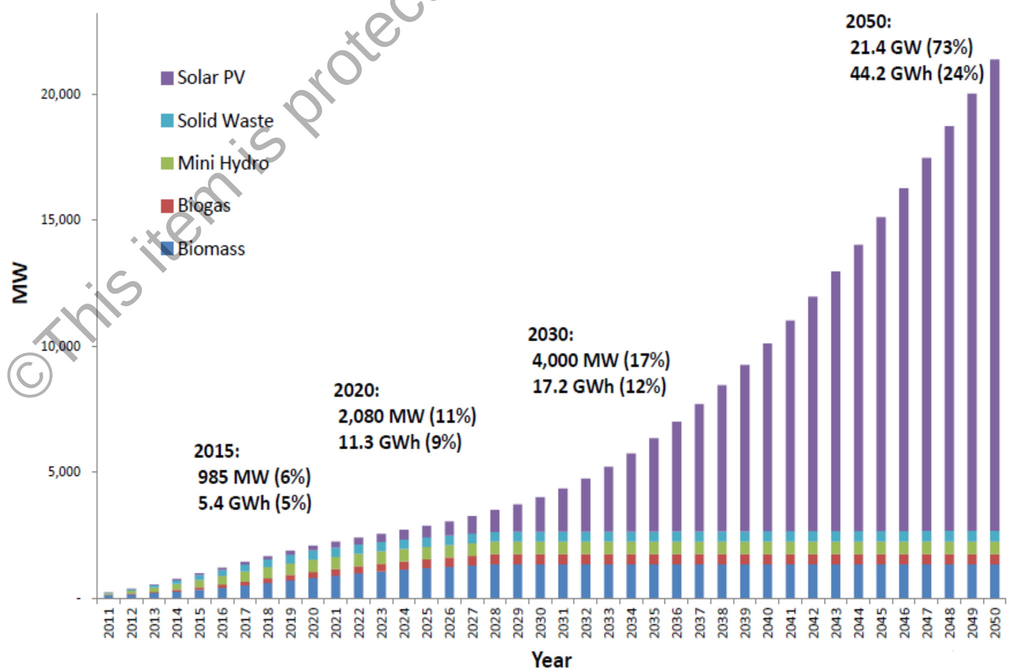

Figure 1.2 : National RE growth/ trend in Malaysia (SEDA, 2015)

However, these RE resources have an unpredictable random behavior and their output power is unstable due to weather dependency. For example, solar energy can only be harnessed during daylight and non-cloudy days while wind speed can range from calm to hurricane-speed. Thus, it is really difficult to generate a steady supply of electricity from RE as it is likely to be unpredictable. In addition, power quality is an important factor from the point of view of both consumer and utility as the power systems are designed to operate at sinusoidal voltage at given frequency. Any significant changes in voltage magnitude, frequency and purity of the waveform are considered as power quality problems which can affect the entire system (Zahedi, 2011). Besides that, in this new era, most of the modern electrical devices and appliances are based on microprocessor controllers and power electronic devices, which are more sensitive to voltage variations. Therefore, in order to fully utilize RE resources for electricity generation, a proper solution is required to produce and maintain the energy balance with consistency. Fortunately, the problems caused by the variable nature can be partially or wholly overcome by integrating RE resources with an energy storage technology to ensure continuous and quality power generation.

Energy Storage System (ESS) is generally described as either electrical or thermal storages which engulfed a wide range of energies, technologies and applications (Baker, 2008). The electrical energy storage system is widely used and is defined as the process of converting electrical energy from a power network into a form that can be stored and converted to electrical energy when needed (Ibrahim, et. al., 2012). Such a process enables the production of a steady supply of electricity at any time. In addition, it also enhances the reliability of RE, besides increasing the resilience of power systems during emergency situations (Palizban & Kauhaniemi, 2016). Thus, engineering development in ESS is growing rapidly over the past few decades and has drawn the attention of the research community (Chalamala, et. al., 2014). Besides that, integration with energy storage improves transmission stability and reduces transmission congestion for grid system operators. For customers, it reduces time-of-use as well as demand charges and also losses from poor power quality and unreliable services (Peters & Malley, 2008).

Various types of energy storage systems exist due to their distinctive characteristics which are suitable for different applications as illustrated in Fig. 1.3. Electrochemical energy storage system, also known as Battery Energy Storage System (BESS) is the most popular method for storing electricity in the form of chemical energy. This is due to their outstanding characteristics such as availability in a wide range of capacity from small to a big scale system and fast response. It is also mobile and flexible enough to be fitted to either high power or high energy applications (Eurobat, 2013). Additionally, BESS also balanced the short-term power and long-term energy management to ensure continuous electricity generation (Chalamala, et. al., 2014).

Besides that, BESS is also the most popular choice in the modern electrical grid system because it provides a wide array of solutions to many key issues that affect the power system (Chua, et. al., 2013). This is due to its unique potential to provide energy storage services at all levels of grids from generation, transmission, distribution or to consumer. In addition, BESS are also seen as necessary with the introduction of future intelligent grid technologies such as smart grid and smart pricing because BESS can provide load shifting and peak shaving from low electrical demand periods to peak demand periods (Heymans, et. al., 2014).

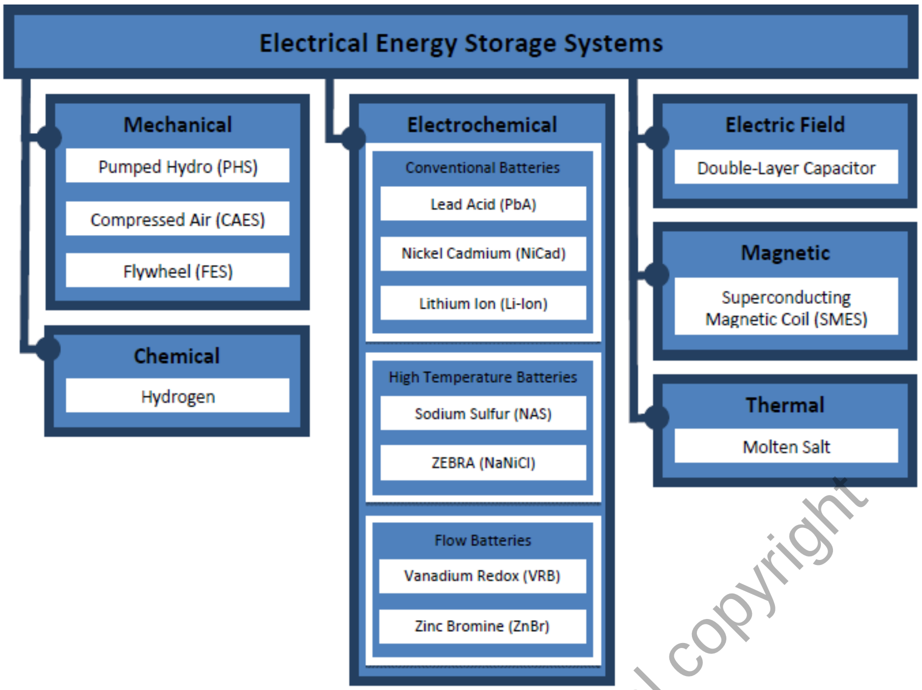

Figure 1.3 : Classification of the electrical energy storage systems (Carnegie, et. al., 2013)

1.2 Problem Statement

Continuous increase in the global energy consumption with the limitation of fossil fuels supply and the negative environmental impacts has led the global community to utilize RE resources. However, production of a continuous and smooth power from RE resources is a real challenge. At the same time, it is important to have a balanced and effective usage of energy for maximum performance without adding any significant cost to the services. In addition, synchronization between the generated power and load demand is essential to avoid any wastage of energy and to improve on the grid network utilization in power generation. Moreover, with the introduction of future intelligent grid technologies such as smart grid, smart metering and smart pricing, a sense of uncertainty may arise among the consumers. This is because the consumers