DEVELOPMENT OF FUZZY LOGIC FOR DEMAND RESPONSE AND STORAGE MANAGEMENT IN HYBRID ENERGY SYSTEM

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By

MOHAMMAD REZA MAGHAMI

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

Decemebr 2019

DEDICATIONS

In memory of my mother Zari Bashiri Zadeh.
***To** my Father Haj Gholam Reza Maghami*
With love and eternal appreciation
***T**o my beautiful sister Atefeh Maghami*
*And **To***
My lovely wife Fatima Gheitasi

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

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December 2019

Chairman : Professor Chandima Gomes, PhD
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A Hybrid Energy System (HES) is a system that integrates multiple energy sources obtained by synchronizing energy output. Previous work has confirmed that HES in off-grid applications is economically viable, especially in remote areas. The energy management system (EMS) used in existing HESs are complicated, costly and less reliable this is because of over-or under unit sizing or mismatch between supply and demand, despite several improvements made over the last decade.

The study was conducted to provide novel strategies for energy management of HESs by improving energy unit sizing and considering demand response program as well as storage management. The first objective of this thesis is to develop an existing computational model for optimising the sizing of micro-scale HES using Particle Swarm Optimisation (PSO). The second objective was to model and simulate an economic system in evaluating the performance and identifying the constraints in line with HES applications. Another objective of the study was to investigate the improvements that can be achieved in the storage management by minimising the mismatch between supply and demand during peak demand. The last objective was to design a real-time physical control system, by analysing the energy generation ability compared to load demand characteristics. The control unit should be able to be used in any weather condition.

MATLAB Simulink software was used to model, simulate, and analyse the entire HES. The developed model was used to optimise the HES with an off-grid load. The constructed HES included a wind turbine, a hydro turbine, and a photovoltaic array, which were used as primary energy systems along with a compact battery as a backup energy system to supply continuous power to the

load when the HES power was less than the load demand. Additionally, a Proton-exchange membrane fuel cells (PEMFC) was integrated into the system to harness excess energy from the hybrid system during the periods that the load demand was below the energy generation and the battery was fully charged. A Fuzzy Logic Controller (FLC) structure has been implemented in this system as the power management technique to control dispatch strategies and make optimum decisions. Due to the high cost of the energy storage system equipment, the combination of Energy Storage Management (DSM) and the Demand Side Management (DSM) was considered and subsequently, this could bring more reliability to the system.

The experimental aspect of the research was conducted in the Nectar Lab in Serdang, Malaysia. A Programmable Logic Controller (PLC) was used for implementing, monitoring and controlling the HES, i.e. the Power Management Box. The design of the control panel unit was mainly aimed to control the dispatch between Generation, Demand and the backup system. The PLC controller, after receiving the data from all components via Remote IO, decided the best optimum operation mode for a specific location by considering the above objectives.

The outcomes of this study, together with an economic analysis for a given system provide optimal costing and sizing for the planned system. The optimal cost of the system obtained in the economic analysis demonstrates that the system can be a good alternative for a grid isolated area and could be used as an off-grid system in areas of low demand.

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

PEMBANGUNAN MODEL LOGIK FUZI BAGI SAMBUTAN PERMINTAAN SERTA PENGURUSAN PENYIMPANAN DALAM SISTEM TENAGA HIBRID

Oleh

MOHAMMAD REZA MAGHAMI

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Pengerusi : Profesor Chandima Gomes, PhD
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Sistem Tenaga Hibrid (HES) adalah satu sistem yang mengintegrasikan pelbagai sumber tenaga yang diperolehi oleh output tenaga yang disegerakan. Kerja sebelum ini telah mengesahkan bahawa HES dalam penyelidikan luar grid secara ekonomi berdaya maju, terutama di kawasan terpencil. Sistem kawalan yang digunakan dalam HES adalah rumit, mahal dan tidak boleh dipercayai, walaupun terdapat beberapa sistem ekonomi kebelakangan ini. Kajian ini bertujuan untuk memberikan strategi baru untuk pengurusan tenaga dengan meningkatkan ukuran unit tenaga dan tindak balas permintaan serta meminimumkan lebihan penjanaan tenaga.

Tujuan penyelidikan ini adalah untuk mengembangkan dan membina sistem HES masa nyata untuk mengawasi, menyelaras, mengurus dan mengawal penyampaian tenaga dari sumber yang boleh diperbaharui serta proses pengisian dan pengosongan simpanan secara berkesan. Dengan menggabungkan kawalan dan pengurusan yang berkesan, strategi penyediaan tenaga dan pengurusan tenaga dalam HES masa nyata dapat dioptimumkan.

Perisian MATLAB Simulink digunakan untuk memodelkan, mensimulasikan, dan menganalisis keseluruhan HES. HES yang dibina merangkumi turbin angin, turbin hidro, dan array fotovoltaik, yang digunakan sebagai sistem tenaga primer bersama dengan bateri padat sebagai sistem tenaga sandaran untuk membekalkan tenaga berterusan ke beban ketika daya HES kurang dari beban permintaan. Selain itu, Proton-exchange membrane fuel cells (PEMFC) disepadukan ke dalam sistem untuk memanfaatkan lebihan tenaga dari sistem hibrid semasa tempoh permintaan beban berada di bawah penjanaan tenaga dan bateri diisi penuh. Struktur Fuzzy Logic Controller (FLC) telah dilaksanakan dalam sistem ini sebagai teknik pengurusan daya untuk mengawal strategi

pengiriman dan membuat keputusan yang optimum. Aspek eksperimen penyelidikan dilakukan di Makmal Nectar di Serdang, Malaysia. Programmable Logic Controller (PLC) digunakan untuk melaksanakan, memantau dan mengendalikan HES, iaitu Power Management Box. Pengawal PLC, setelah menerima data dari semua komponen melalui Remote IO, memutuskan mod operasi optimum terbaik menurut peraturan kabur untuk lokasi tertentu dengan mempertimbangkan strategi di atas.

Hasil kajian ini mendapati analisis ekonomi untuk sistem yang diberikan memberikan kos dan saiz yang optimum untuk sistem yang dirancang. Kos optimum sistem yang diperoleh dalam analisis ekonomi menunjukkan bahawa sistem itu boleh menjadi alternatif yang baik untuk kawasan terpencil dan boleh digunakan sebagai sistem luar grid dalam untuk permintaan yang rendah.

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This thesis was submitted to the Senate of the 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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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AC	Annualized Cost
AC	Ant Colony Algorithm
AGC	Average Generation Cost
BESS	Battery Energy Storage System
Cainv	Cost Of Initial Investment
Caom	Cost of Operation And Maintenance
Carep	Annualized Replacement Cost
CC	Capital Cost
COE	cost of energy
DR	Demand Response
EENS	Energy Expected Not Supplied
EIR	Index Of Reliability
ELF	Equivalent Loss Factor
ENS	energy not-supplied
GA	Genetic Algorithm
NPC	net present cost
PDF	Probability Distribution Function
PLC	Program Logic Controller
PSO	Particle Swarm Optimization
PV	Photovoltaic
RES	Renewable Energy System
SA	Simulated annealing
SOC	State of Charge
SPV	standalone photovoltaic
TCS	Total Cost of the System

TIA	Totally Integrated Automation
WT	Wind Turbine
WTGU	wind generating units
XIC	Examine If Closed
XIO	Examine If Open
GHG	Emissions. Greenhouse gases
HES	Hybrid Energy System
HMI	Human Machine Interface
HOMER	Hybrid Optimization Model for Electric Renewable
HRES	Hybrid Renewable Energy System
LCC	Life-Cycle Cost
LCE	levelized cost of energy
LEE	Loss of Energy Expectation
LF	Load factor
LOL	loss of load probability
LOLE	Loss of Load Expectation
LPSP	loss of power supply probability
MACS	Multi-Agent Control System
MPPT	Maximum power point tracker

CHAPTER 1

INTRODUCTION

1.1 Motivation

Global warming, following the rising level of carbon dioxide in the air and increasingly limited global access to fossil and nuclear fuels, has necessitated urgent research in the area of alternative sources of energy to mitigate the looming energy crisis. Even now, Scientists are attempting to identify alternative sources of energy which can minimise environmental effects and address the ever-growing demand for energy supplies. The power generated through wind, solar and hydro are considered energy sources that are non-polluting, freely available and renewable. However, due to their unpredictability and weather dependence, the combination of renewable energy sources into Hybrid Energy Systems (HES) is a great opportunity for distributed power [1, 2].

1.2 Hybrid Energy System

A Hybrid Energy System is a mechanism that combines multiple sources of energy connected together to achieve a synchronised energy output. HES can be augmented with Photovoltaic (PV), Wind Turbine (WT), Hydro, Diesel Generator (DG), Fuel Cell and Biomass with an adjustable energy storage system in such a way which allows the entire system to satisfy power demands [3]. A Battery Energy Storage System (BESS) can be either equipped with an ultracapacitor or a rechargeable battery bank [4]. The best characteristic of this design is that instead of attempting to satisfy peak demand, the hybrid system power capacity rating will be set to meet the average demand. In this way, the HES would be economically more efficient and more effective than using fuel cells to supply the deficiency in the case of high load demand [5, 6]. However, one of the main issues in HES is related to managing and the control of distributed generation (DG). The dynamic interactions between the demand and the energy resources could result in critical issues of stability and power quality that in conventional systems are not common [7]. In such a case, it is important to manage the energy flow in the HES to ensure that the load demand is continuously supplied with power [8]. Many studies have considered the energy management of HES [9]. The conventional approaches [10-12] have been proven unstable in handling various changes in weather conditions and the consequent changes in generation. Advanced control techniques are available such as artificial neural networks and fuzzy logic that can easily integrate human intelligence into the complicated control system, based upon human knowledge and experience. The question that arises is can these control techniques further improve system performance by handling different changes without major difficulties [13], and what is the most suitable application to use.

According to a World Bank report, over two billion people around the world live in rural areas without a power grid. Also, because of the global rise in the level of energy consumption, coupled with reports of a decline in the level of accessibility to energy, researchers and energy experts have found the need to provide alternative methods of energy production. This situation, from the local point of view this has generated support for Renewable Energy (RE) exploitation in some developing countries in a more economical way by using hybrid renewable energy [14]. These areas are a huge potential market for HES in meeting their energy requirements. Today, the use of HES is working tremendously in favour of renewable energy system exploitation. This is especially true for Hybrid Renewable Energy (HRE) systems that have enormous potential to provide secure, reliable and high quality energy for clients, mainly in the operation of a micro-grid for isolated situations [15]. A wide range of studies have reported that HES in off-grid applications is economically workable, mostly in isolated areas [16, 17]. In some cases, instead of using a diesel power supply system that competes economically with integrating various systems into a hybrid system, such as a hybrid system is more efficient and sometimes the best option for the isolated regions. Currently, the integration of renewable energy into a supply system is a growing commitment in the energy sector. Since some renewable energy sources (RES) are closely associated with intermittency, therefore integration of more than one of the resources may be helpful in eliminating the related variability.

Most scientists believe that there is no single standard definition of a hybrid system because scientists have mostly tried to identify such a system based on their understanding of the concept. A HES is described as a standalone power generation system, which contains more than two energy generation sources, whose end-use energy is basically electricity [16, 18]. Furthermore, HES for power generation is fundamentally a productive means of enhancing sustainable development in the electric power industry. This is an ideal technique for reducing emissions. Greenhouse gas (GHG) emissions from energy consumption and power generation can be reduced using a HES [19]. Promoting the sacredness of sustainable development is a direct affirmation of important international communities and organisations as prominently promoted in the Kyoto Protocol. From an ideal view, sustainability is the integration of numerous concepts ranging from policy creation to engineering creativity.

Currently, the promise held out by the suggestion of the application of HESs in the energy sector has attractively paved ways to power generation on both a small and a large scale using RES. The individual downsides of different RES can be eliminated by promoting a HES application for electric power supply by applying the most cost-effective logic. Moreover, power production is also highly connected to efficiency, economy, and dispatch strategies. So the optimal combination of different RES is of critical concern.

1.3 Problem Statement

Integrating RES as a system is gaining attention due to limitations in providing satisfactory performance from individual sources. Since the nature of the climate is intermittent, an individual RE is unable to meet the load demand properly. Hence, integrating RE sources improves the system by supplementing operation to enable provision of maximum power delivery. In general, there is a large potential for hybrid renewable energy systems to utilise RES for maximising the generation and distribution of electrical energy as well as increasing the worldwide demand for electricity. However, there are several technical challenges in HES mainly associated with an intermittent climate and the nature of renewable energy sources. These challenges associated with the HES should be examined thorough research in multiple areas. Some notable areas recognised previously are:

1. Obtaining proper unit sizing for energy sources and storage is critical in determining the cost and reliability of the system. Optimal resource supervision in the HES is necessary to achieve an acceptable level of cost and reliability. Over-sized and under-sized HES components may result in an increase in costs and possible failure of the system[20]
2. Demand side management and storage management of HES could be further improved to minimise mismatch between supply and demand curves. The unpredictability of the load demand must be taken into account to provide a more appropriate Battery Energy Storage System(BESS) [21]. It is highly significant to integrate a BESS into the HES to maintain a continuous electricity supplement in the periods where renewable energy sources are not available. Moreover, BESS is also vital for storing excess energy when renewable energy sources are at their peak. If this excessive energy can be stored, it can be utilised during sudden events where renewable energy sources become unavailable.
3. The computational control models with higher usability and stability can be applied to any situation with in-situ measurements as input parameters. When the HES system is fully operational it requires good supervision, coordination, management and control for every subsystem. Therefore, the control system is responsible for supervising, coordinating, managing and controlling various tasks assigned to each subsystem in order to perform different types of system operation and functionality. By employing such proper supervision etc., high efficiency for operation and functionality can be achieved for the overall system.

By considering the problems stated, this research focuses on designing, developing, implementing, integrating and constructing a real-time HES system to effectively supervise, coordinate, manage and control the power delivery in Solar, Hydro, and wind RESs, as well as the BESS charging and discharging processes. Through incorporating effective control and management, the power delivery and energy management strategy in the real-time HES can be optimised. Previously, there have been various techniques and methods integrated into HESs developed to achieve maximum power deliverability while ensuring that the technical challenges are addressed.

1.4 Research Aims and Objectives

This thesis aims to develop a novel EMS for HESs that will coordinate distribution renewable energy sources, energy storages and load demand in order to minimise operation and power loss of system. This study was carried out to achieve the following objectives:

1. To improve a cost optimized sizing algorithm using PSO for HES including PV, Hydro and WT at a given location.
2. To design a simulated HES based on the improved sizing algorithm.
3. To implementation HES including a control panel unit containing a PLC controller.
4. To investigate the improvements that can be made to the storage management by minimizing the mismatch between supply and demand during peak demand by using FLC.

1.5 Scope and Limitations of The Study

This thesis focuses on a HES design which consists of a solar module, Wind Turbine, micro Hydro and battery storage.

1. A PSO algorithm will be improved by considering annual cost, initial cost and the operational of cost of six components. This is in order to optimise the HES and thus make the system efficient and cost effective.
2. The input variables are divided into three groups: Environmental data (solar irradiation, wind velocity and amount of rainfall), Load Demand (The average energy demand to be 11.1 kW/day) and component market price
3. The optimum size of the HES was compared with HOMER software and a Genetic Algorithm.
4. MATLAB Simulink tool box version 2019a was used to model the HES. After designing each subsystem model individually, several simulations were conducted to make sure the model responded correctly and could function properly when connected to the other systems.
5. The IEEE 5BUS was employed to test the power flow of the system through PLCSIM virtualization (TIA Portal).
6. Advanced FLC was employed to provide proper energy management in both experimental and simulation situations.

This study is expected to achieve the stipulated objectives. However, there are several limitations in this study as listed below:

1. This research considered the cost of six main components in the studied hybrid system, i.e., Photovoltaic panel, Wind turbine, Fuel Cell, battery, converter and hydro. Other accessory devices were neglected.
2. A water pump has been used to run a micro turbine and it will be replaced with the runoff from water catchment on the roof of a building.
3. Use of an Education Laboratory proposed 100 PEM Fuel Cell.
4. Environmental data collected from the Metrological site of Universiti Putra Malaysia for a period of one month and its located three kilometres from the Lab.
5. Limited application devices have been used as an adjustable load in order to consider the effect of demand response. Due to limited power generation from the real system only a limited load demand was considered in this study.

1.6 Research Contributions

The main contribution of this research is developing efficient methods to solve the critical issues in the field of a hybrid managing system. To elaborate, the novelties of the current research are as follows:

1. The sizing algorithm is improved for determining initial sizing of the HES.
2. An Advanced Fuzzy Logic Controller is proposed to following the power management strategies(Dispatch Strategies, Demand Response, Storage management)
3. Demand Response Management is efficiently employed to shift the peak demand that leads to lowering the number of components.
4. A control panel unit is implemented using a PLC controller to manage and monitor the HES management strategies.

1.7 Organisation of the Thesis

In this section, the present study is compiled and briefly explained in stages corresponding to the research that has been undertaken. The current thesis consists of six main chapters, including introduction, literature review, methodology, simulation results analysis and discussion, the recommendations for future works and references.

Chapter One provides a general background of this research topic. Moreover, it discusses briefly the statement of the problem, objectives of the study, and research contributions. The scope and some limitations of the study are also explained.

Chapter Two reviews previous work related to the research topic that exists in the literature. The background studies aid to elaborate and understand the possible improvement of the hybrid system in detail. The selected past research and references are also discussed briefly in this chapter.

Chapter Three introduces and explains the methodology followed in this study to achieve the research objectives. The process begins with an explanation of the PSO Optimiser as forecast data for a specific location. Then, the forecast data is implemented to search for the optimal unit sizing HES model to be used as a simulation tool in both approaches and to improve the system by using demand side management and energy storage management. The hybrid system modelling is developed for real-time and simulation dispatch using the above strategy. Finally, implementation of PLC control in order to reach the above objectives is described.

Chapter Four presents the experimental and simulation results, analysis and discussion of the hybrid system. The characteristic behaviour is described of how the hybrid system adapts to the various operating conditions. Subsequently, each hybrid system component is analysed and reviewed using defined parameters.

Chapter Five concludes the thesis with a focus on the final discussion and a summary of the conclusions. Recommended possible future works in related areas are discussed in brief.

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