SIZING OF STANDALONE PV-BATTERY-DIESEL HYBRID SYSTEM WITH A RULE-BASED ENERGY MANAGEMENT STRATEGY USING PARTICLE SWARM OPTIMIZATION

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DEDICATION

This project is dedicated to my supervisor, who had supported and guided me throughout the course of the project.

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ABSTRACT

This project proposes an optimal sizing of standalone PV-Battery-Diesel Hybrid System using Particle Swarm Optimization (PSO) algorithm. Generally, standalone system generates power using diesel generator offers a continuous and reliable source of energy. However, diesel generator is only operating efficiently for a considerable load demand but have low performance when the load is well below its rated capacity. In addition to that, the system operating & maintenance costs and CO_2 emission level are high. The main objective of this project is to determine an optimal configuration of the proposed standalone hybrid system to meet the targeted reliability index of the system while having the lowest Cost of Energy (COE). In this project, electrical load demand profile and meteorological data over a year are collected to form input parameters for the proposed hybrid system. A function of rule-based Energy Management Strategy (EMS) of the hybrid system, incorporating all the mathematical modelling of the system components is developed using MATLAB scripts. This function ties back to the main program of Particle Swarm Optimization (PSO), a renowned stochastic optimization algorithm that is also developed using MATLAB scripts. This project uses Loss of Power Supply Probability (LPSP) and Cost of Energy (COE) as objective functions. Optimal sizing was performed using PSO algorithm and the result shows the optimal configuration obtained has satisfied the targeted LPSP of 1% with the lowest COE of S$0.65 kWh.

ABSTRAK

Projek ini mencadangkan ukuran optimum Sistem Hybrid PV-Battery-Diesel mandiri menggunakan algoritma Particle Swarm Optimization (PSO). Secara amnya, sistem mandiri menjana tenaga menggunakan penjana diesel menawarkan sumber tenaga yang berterusan dan boleh dipercayai. Walau bagaimanapun, penjana diesel hanya beroperasi dengan cekap untuk permintaan beban yang cukup besar tetapi mempunyai prestasi yang rendah apabila beban berada jauh di bawah kapasiti pengenalnya. Selain itu, kos operasi & penyelenggaraan sistem serta tahap pelepasan CO2 adalah tinggi. Objektif utama projek ini adalah untuk menentukan konfigurasi optimum dari sistem hibrid mandiri yang dicadangkan untuk memenuhi indeks kebolehpercayaan yang disasarkan pada sistem sambil mempunyai Kos Tenaga (COE) terendah. Dalam projek ini, profil permintaan beban elektrik dan data meteorologi dikumpulkan selama setahun untuk membentuk parameter input untuk sistem hibrid yang dicadangkan. Fungsi Strategi Pengurusan Tenaga berdasarkan peraturan (EMS) sistem hibrid, menggabungkan semua pemodelan matematik komponen sistem dikembangkan menggunakan skrip MATLAB. Fungsi ini menghubungkan kembali ke program utama Particle Swarm Optimization (PSO), algoritma pengoptimuman stokastik terkenal yang juga dikembangkan menggunakan skrip MATLAB. Projek ini menggunakan Kehilangan Kekurangan Bekalan Tenaga (LPSP) dan Kos Tenaga (COE) sebagai fungsi objektif. Ukuran optimum dilakukan dengan menggunakan algoritma PSO dan hasilnya menunjukkan konfigurasi optimum yang diperoleh telah memenuhi LPSP yang disasarkan sebanyak 1% dengan COE terendah iaitu S$0.65 kWh.

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LIST OF ABBREVIATIONS

PSO	-	Particle Swarm Optimization
EHO	-	Elephant Herd Optimization
IHSA	-	Improved Harmony Search Algorithm
LSA	-	Lightning Search Algorithm
EMS	-	Energy Management Strategy
BMS	-	Building Management System
COE	-	Cost of Energy
NPC	-	Net Present Cost
ACS	-	Annual Cost
TAC	-	Total Annual Cost
LCC	-	Life Cycle Cost
LPSP	-	Loss of Power Supply Probability
LPS	-	Loss of Power Supply
PV	-	Photovoltaic
DG	-	Diesel Generator
ELF	-	Equivalent Loss Factor
LA	-	Level of Autonomy
EENS	-	Expected Energy Not Supplied
STC	-	Standard Test Condition
SOC	-	State of Charge
LD	-	Load Demand
EW	-	Energy Waste
MOPSO	-	Multi-objective Particle Swarm Optimization

LIST OF SYMBOLS

E	-	Energy
N_{pv}	-	Number of photovoltaic modules
N_{batt}	-	Number of batteries
N_{dg}	-	Number of diesel generators
P	-	Power
L	-	Load
V	-	Voltage
I	-	Current
v	-	Velocity
x	-	Position
w	-	Inertia Weight
c_1	-	Weight of local information
c_2	-	Weight of global information
r_1	-	Random real number
r_2	-	Random real number
χ	-	Constriction coefficient
α	-	Generator fuel curve intercept coefficient ($L/hr/kW_{rated}$)
β	-	Generator fuel curve slope ($L/hr/kW_{output}$)
℃	-	Degree Celsius

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CHAPTER 1

INTRODUCTION

1.1 Overview

In today's world, the network of the normal power grid become increasingly larger and complex mainly due to the rapid growth of the load demand for development opportunities and modernization[1]. Fossil fuel plays an important role as a constant source of energy for electricity generation by the grid and it dominates almost 80% as compared to other sources. However, heavily dependent on fossil fuel has led to the negative impacts such as high cost, source depletion and environmental pollution issues[2]–[5].

In order to reduce the reliance on fossil fuel owing to the rising demand of electric power, the implementation of using different sources of energy, particularly the renewable energy sources have seen been taking part to replace fossil fuel. Renewable energy sources are virtually free of environmental pollution, inexhaustible and found abundant in the planet earth[6]. Solar and wind energy is the most popularity and promising on among the globally available of renewable energy sources. It has been widely adopted by the researchers for their ongoing research.

While we appreciate the advantages on having a renewable energy, it is also well noted that this energy is intermittent and fluctuating by nature and hence adopting a renewable energy alone is not going to provide a continuous supply of power[7]. On account of various points as highlighted, microgrid has emerged and become increasingly popular. Microgrid is a smaller size of power network (de-centralized system) that can offer a continuous, resilient, stability and environmentally friendly of electricity[3]. Microgrid has a capability to operate in 2 modes. It can operate in grid-tie or standalone mode.

In grid-tie mode, microgrid is connected to main grid. In the standalone mode, the microgrid is isolated from the main grid and operate independently and it is also known as autonomous system[8]. Microgrid requires a combination of sources of energy for generation of electricity. A self-generated power like diesel generator provides a continuous electricity supply while a photovoltaic system or wind turbine is powered by a renewable source to provide a clean and environmental pollution free electricity supply. Batteries provisions offer high resiliency and stability of electricity supply. With all these combinations, microgrid is also term as "Hybrid System"[3]. Figure 1.1 illustrates the microgrid architectures as explained.

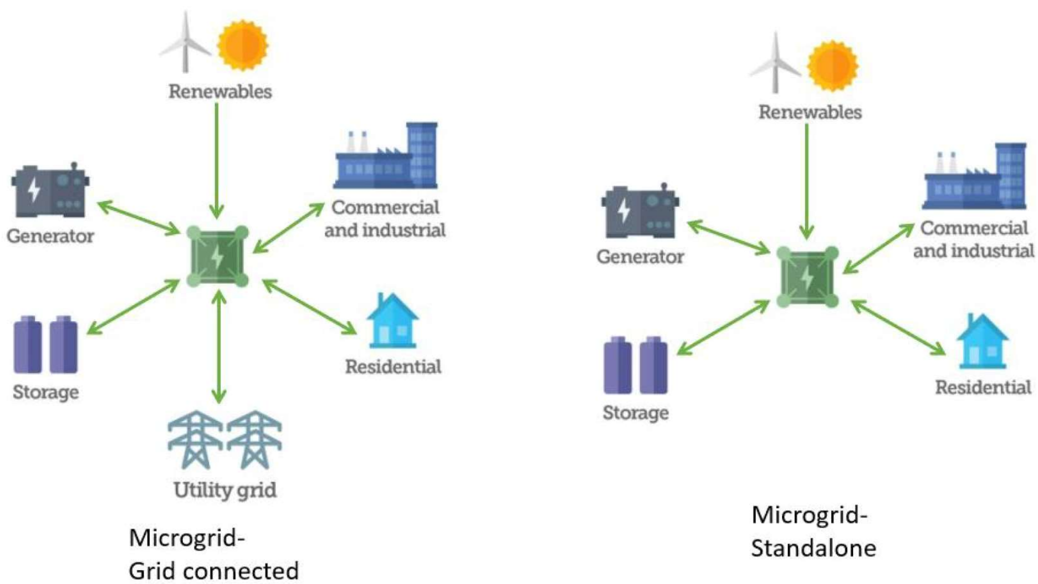

Figure 1.1 Microgrid Architectures

By principal, the function of the hybrid system is to generate and store the electricity energy for electricity network. It consists of an integration of renewable and non-renewable sources of energy for generation purpose and an energy storage system to store, provide stability and to reduce the fluctuation of the supply. With the combination of various components involved in hybrid system, it draws the interest of the researchers to size hybrid system that can work efficiently and economically. This sizing is term as "Optimal Sizing". It is about the optimal relationship amongst the components used in hybrid system that determine how well the system works is accordance to the objective as set. There are many sizing optimization techniques that have been developed by the researchers. These techniques will be discussed in chapter 2. As explained, a microgrid or also known as hybrid system can operate as grid-connected or standalone hybrid system. The classification of the hybrid system in accordance with size is presented in Table 1.1[8].

Table 1.1 Classification of Hybrid System

Classification	**Size**	**Typical Load**
Large	>100kW	Regional Loads
Medium	5kW up to 100kW	Isolated off grid communities
Small	<5kW	Remote homes

The grid-connected hybrid system works similar with standalone hybrid system except the fact that it is also work as a prosumer to produce and supply back the energy to the grid. As for the standalone hybrid system, there is no connection to the grid and hence the reliability of the supply is one of the major considerations that it needs to address. Reliability indices remain as an effective measure to justify the reliability of the system. Many researchers have also based on the indices as one of the considerations in their component sizing. This in turn addressing the system efficiency on how well a system provides an electricity supply to the load demand. The reliability indices will be discussed in chapter 2.

Another focus on the sizing will be the economic consideration. The aim is to size a system that is able to support the load demand the most and kept the expenditure cost at the lowest. There are many economic indices to base on for economic analysis. Each of them has their unique way and different parameters of calculations. These economic indices mainly focus on the system capital expenditure (CAPEX), operation and maintenance expenditure (OPEX), component replacement cost and fuel cost for diesel generator[8]. During component sizing optimization, many researchers have been using these economic indices for evaluation in economic analysis. The economic indices will be discussed further in chapter 2.

1.2 Problem Statement

Hybrid system offered numerous advantages over the traditional grid supply as highlighted in [2], [6], [8], [9]. They are listed as follows.

1. PV energy is a free source of energy that is sustainable.
2. Clean and environmentally friendly due to less CO_2 emission (less reliance on diesel generator.
3. Reduction of fuel consumption and hence cost saving (less reliance on diesel generator).
4. Lower operating and maintenance cost.
5. System is quieter and thus mitigation of noise pollution.

Having said the above benefits, however, hybrid system is more dynamic and complex as it involves an integration of several types of energy with various types of components involved. Each system component will have its own characteristics. There will be a high expectation of the system reliability for standalone hybrid system. The performance of the systems would depend mainly on the configuration. It will be only an optimal configuration that can ensure the hybrid system works efficiently and reliably at the lowest cost of energy (COE).

1.3 Project Objectives

This project focuses on the component sizing of standalone hybrid system with the combination of photovoltaic (PV) / battery / diesel generator. The objectives of the project are as follows.

1. To model a standalone hybrid system that consists of the components, namely PV / Battery / DG and develop a rule-based energy management strategy using MATLAB scripts.
2. To simulate a standalone hybrid system and perform the component sizing of the proposed hybrid system using MATLAB scripts.
3. To develop an optimization algorithm using MATLAB scripts, Particle Swarm Optimization and perform optimal sizing based on the defined reliability index (LPSP of 1%) and the lowest cost of energy (COE).
4. To determine the number of components (N_{pv}; N_{batt} & N_{dg}) based on the best configuration on meeting the objective function of LPSP = 1% and the lowest cost of energy (COE).

1.4 Scope of Project

This project scope focuses on the component sizing of the PV/Battery/DG hybrid system. The scope covers the selection of the actual building used for the case study and collection of the input data, for example: meteorological data and electrical load profile of the building. The data collection includes taking hourly meteorological data for year 2019 for both solar irradiance in w/m^2 and its corresponded ambient temperature in °C. The load profile shall be on hourly as well for year 2019 taking from BMS.

The procurement of the components' data sheet will also be part of the scope. The component specification used is as follows.

1. PV module (310W) - Polycrystalline cell with efficiency of 16%.
2. Battery type- lithium Iron Phosphate with capacity of 195AH per module.
3. 1,375KVA prime power diesel generator.
4. The system design shall base on energy or power flow (use interchangeably) as the input data is hourly data and the load profile is also in kW on hourly basis. Hence, in this context, power and energy will have the same value.
5. This would follow by the modeling of the system, energy management strategy, optimization technique using MATLAB scripts and finding an optimal configuration of the proposed hybrid system using Particle Swarm Optimization (PSO).

The scope covers the following assumptions made when designing a system.

1. System design life for 20 years.
2. The load profile is assumed to stay the same throughout a design life of 20 years.
3. Economic life span of the equipment – PV -20 years; DG- 10 years; battery- 5 years.
4. Exclude the battery self-discharge rate.
5. No modeling of inverter/converter.
6. Exclude CO_2 emission analysis.
7. Assume a constant battery capacity of battery over its lifetime.

1.5 Project Outline

For this project, standalone hybrid system with photovoltaic (PV) / battery / diesel generator will be the key focus. The project consists of five chapters, references, and appendices. The title of the five chapters are as follows.

1. Chapter 1: Introduction
2. Chapter 2: Literature Review
3. Chapter 3: Methodology
4. Chapter 4: Results & Discussions
5. Chapter 5: Conclusion & Future Works

The outline of each chapter, references and appendices is presented as follows.

Chapter 1 describes provide an overview and description of the standalone hybrid system. It includes problem statement, the objectives and scope of project.

Chapter 2 provides an introduction and discussion the research work undertaken by the researchers from year 2016 to 2020. Total 33 copies of articles were chosen for the review. The discussion includes the optimization techniques, reliability & economic indices, and mathematical modeling of the components used for this project.

Chapter 3 provides comprehensive methodology of the proposed standalone hybrid system. The modeling of system components and rule-based energy management strategy using MATLAB scripts are included in this chapter. The input data of the proposed system, optimization technique-PSO. The back-end process of the work, for example: activities/work schedule/Gantt Charts throughout the project period are also reported in this chapter.

Chapter 4 focuses on the simulation work process and provides simulation results obtained from MATLAB software. This chapter will also provide technical and economic analysis owing to the simulation results. Lastly discussions based on the results obtained will also be included.

Chapter 5 provides summary and draws conclusion of the project. Recommendation of future works will also be included in this chapter.

References provide 33 copies of reviewed articles in the recent six years. From year 2016 to year 2020.

Appendices provide meteorological data, data sheet of the system components and MATLAB scripts.

REFERENCES

[1] P. O. C. Malaquias and B. A. Souza, "Optimal Sizing of Stand-alone Hybrid Photovoltaic-wind-battery Energy System using PSO," 2019, doi: 10.18086/swc.2019.32.02.

[2] W. M. Hamanah, M. A. Abido, and L. M. Alhems, "Optimum Sizing of Hybrid PV, Wind, Battery and Diesel System Using Lightning Search Algorithm," *Arab. J. Sci. Eng.*, vol. 45, no. 3, 2020, doi: 10.1007/s13369-019-04292-w.

[3] F. Tooryan, H. HassanzadehFard, E. R. Collins, S. Jin, and B. Ramezani, "Optimization and energy management of distributed energy resources for a hybrid residential microgrid," *J. Energy Storage*, vol. 30, 2020, doi: 10.1016/j.est.2020.101556.

[4] M. Zolfaghari, N. Ghaffarzadeh, and A. J. Ardakani, "Optimal sizing of battery energy storage systems in off-grid micro grids using convex optimization," *J. Energy Storage*, vol. 23, 2019, doi: 10.1016/j.est.2019.02.027.

[5] S. Mandal, K. K. Mandal, and B. Tudu, "A new self adaptive particle swarm optimization technique for optimal design of a hybrid power system," 2016, doi: 10.1109/PCITC.2015.7438175.

[6] S. Poonam, P. Manjaree, and S. Laxmi, "Comparison of traditional and swarm intelligence based techniques for optimization of hybrid renewable energy system," *Renew. Energy Focus*, vol. 35, 2020, doi: 10.1016/j.ref.2020.06.010.

[7] J. C. Alberizzi, J. M. Frigola, M. Rossi, and M. Renzi, "Optimal sizing of a Hybrid Renewable Energy System: Importance of data selection with highly variable renewable energy sources," *Energy Convers. Manag.*, vol. 223, 2020, doi: 10.1016/j.enconman.2020.113303.

[8] A. L. Bukar and C. W. Tan, "A review on stand-alone photovoltaic-wind energy system with fuel cell: System optimization and energy management strategy," *Journal of Cleaner Production*, vol. 221. 2019, doi: 10.1016/j.jclepro.2019.02.228.

[9] M. Gharibi and A. Askarzadeh, "Size optimization of an off-grid hybrid

system composed of photovoltaic and diesel generator subject to load variation factor," *J. Energy Storage*, vol. 25, 2019, doi: 10.1016/j.est.2019.100814.

[10] A. Haffaf, F. Lakdja, and R. Meziane, "Hybrid pv/battery/diesel power source sizing and simulation under dsm strategies," *J. Electr. Electron. Eng.*, vol. 13, no. 1, 2020.

[11] K. Anoune *et al.*, "Optimization and techno-economic analysis of photovoltaic-wind-battery based hybrid system," *J. Energy Storage*, vol. 32, 2020, doi: 10.1016/j.est.2020.101878.

[12] H. Rezk, M. Alghassab, and H. A. Ziedan, "An optimal sizing of stand-alone hybrid PV-fuel cell-battery to desalinate seawater at Saudi NEOM city," *Processes*, vol. 8, no. 4, 2020, doi: 10.3390/PR8040382.

[13] S. Kumar, T. Kaur, S. Upadhyay, V. Sharma, and D. Vatsal, "Optimal Sizing of Stand Alone Hybrid Renewable Energy System with Load Shifting," *Energy Sources, Part A Recover. Util. Environ. Eff.*, 2020, doi: 10.1080/15567036.2020.1831107.

[14] M. A. Ashraf, Z. Liu, A. Alizadeh, S. Nojavan, K. Jermsittiparsert, and D. Zhang, "Designing an optimized configuration for a hybrid PV/Diesel/Battery Energy System based on metaheuristics: A case study on Gobi Desert," *J. Clean. Prod.*, vol. 270, 2020, doi: 10.1016/j.jclepro.2020.122467.

[15] O. H. Mohammed, Y. Amirat, and M. Benbouzid, "Particle swarm optimization of a hybrid wind/tidal/PV/battery energy system. Application to a remote area in Bretagne, France," in *Energy Procedia*, 2019, vol. 162, doi: 10.1016/j.egypro.2019.04.010.

[16] C. Mekontso, A. Abubakar, S. Madugu, O. Ibrahim, and Y. A. Adediran, "Review of Optimization Techniques for Sizing Renewable Energy Systems," *Comput. Eng. Appl. J.*, vol. 8, no. 1, 2019, doi: 10.18495/comengapp.v8i1.285.

[17] A. Aggarwal and D. Nagpal, "Sizing and financial optimization of hybrid PV/battery/diesel system," 2018, doi: 10.1109/ICPEICES.2018.8897382.

[18] M. Elloumi, R. Kallel, and G. Boukettaya, "A comparative study of GA and APSO algorithm for an optimal design of a standalone PV/battery system," 2018, doi: 10.1109/SSD.2018.8570449.

[19] A. Chauhan and V. K. Dwivedi, “Optimal sizing of a stand-alone PV/wind/MHP/biomass based hybrid energy system using PSO algorithm,” in *2017 6th International Conference on Computer Applications in Electrical Engineering - Recent Advances, CERA 2017*, 2018, vol. 2018-January, doi: 10.1109/CERA.2017.8343292.

[20] P. D. Raja and K. P. Detroja, “Optimal sizing of PV panels and battery for grid connected load under dynamic pricing,” in *2018 Indian Control Conference, ICC 2018 - Proceedings*, 2018, vol. 2018-January, doi: 10.1109/INDIANCC.2018.8307972.

[21] A. L. Galindo Noguera, L. S. Mendoza Castellanos, E. E. Silva Lora, and V. R. Melian Cobas, “Optimum design of a hybrid diesel-ORC / photovoltaic system using PSO: Case study for the city of Cujubim, Brazil,” *Energy*, vol. 142, 2018, doi: 10.1016/j.energy.2017.10.012.

[22] A. Moses, A. Landeros, and M. F. Abdel-Fattah, “Particle swarm optimization for sizing hybrid power systems incorporating demand response,” 2018, doi: 10.1109/RTUCON.2018.8659835.

[23] R. Ayop, N. M. Isa, and C. W. Tan, “Components sizing of photovoltaic stand-alone system based on loss of power supply probability,” *Renewable and Sustainable Energy Reviews*, vol. 81. 2018, doi: 10.1016/j.rser.2017.06.079.

[24] F. A. Khan, N. Pal, and S. H. Saeed, “Review of solar photovoltaic and wind hybrid energy systems for sizing strategies optimization techniques and cost analysis methodologies,” *Renewable and Sustainable Energy Reviews*, vol. 92. 2018, doi: 10.1016/j.rser.2018.04.107.

[25] C. D. Rodnguez-Gallegos *et al.*, “Placement and sizing optimization for PV-battery-diesel hybrid systems,” in *IEEE International Conference on Sustainable Energy Technologies, ICSET*, 2017, vol. 0, doi: 10.1109/ICSET.2016.7811761.

[26] C. K. Nayak and M. R. Nayak, “Optimal size and cost analysis of standalone PV system with battery energy storage using IHSA,” 2017, doi: 10.1109/SCOPES.2016.7955599.

[27] N. I. Abdul Aziz, S. I. Sulaiman, S. Shaari, I. Musirin, and K. Sopian, “Optimal sizing of stand-alone photovoltaic system by minimizing the loss of

power supply probability," *Sol. Energy*, vol. 150, 2017, doi: 10.1016/j.solener.2017.04.021.

[28] A. Maleki and F. Pourfayaz, "Optimization of grid independent diesel-based hybrid system for power generation using improved particle swarm optimization algorithm," 2017, doi: 10.1109/IPSC.2015.7827735.

[29] B. Shi, W. Wu, and L. Yan, "Size optimization of stand-alone PV/wind/diesel hybrid power generation systems," *J. Taiwan Inst. Chem. Eng.*, vol. 73, 2017, doi: 10.1016/j.jtice.2016.07.047.

[30] M. D. A. Al-falahi, S. D. G. Jayasinghe, and H. Enshaei, "A review on recent size optimization methodologies for standalone solar and wind hybrid renewable energy system," *Energy Conversion and Management*, vol. 143. 2017, doi: 10.1016/j.enconman.2017.04.019.

[31] C. O. Okoye and O. Solyalı, "Optimal sizing of stand-alone photovoltaic systems in residential buildings," *Energy*, vol. 126, 2017, doi: 10.1016/j.energy.2017.03.032.

[32] C. D. Rodríguez-Gallegos, K. Rahbar, M. Bieri, O. Gandhi, T. Reindl, and S. K. Panda, "Optimal PV and storage sizing for PV-battery-diesel hybrid systems," in *IECON Proceedings (Industrial Electronics Conference)*, 2016, pp. 3080–3086, doi: 10.1109/IECON.2016.7794062.

[33] C. Shang, D. Srinivasan, and T. Reindl, "An improved particle swarm optimisation algorithm applied to battery sizing for stand-alone hybrid power systems," *Int. J. Electr. Power Energy Syst.*, vol. 74, 2016, doi: 10.1016/j.ijepes.2015.07.009.