Faculty of Electrical Engineering

OPTIMAL VIRTUAL MICROGRID DESIGN USING COMMUNITY ENERGY STORAGE FOR DISTRIBUTION NETWORKS

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OPTIMAL VIRTUAL MICROGRID DESIGN USING COMMUNITY ENERGY STORAGE FOR DISTRIBUTION NETWORKS

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A thesis submitted
in fulfillment of the requirements for the Master of Science
in Electrical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

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DECLARATION

I declare that this thesis entitled "Optimal Virtual Microgrid Design Using Community Energy Storage for Distribution Networks" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in the candidature of any other degree.

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APPROVAL

I hereby declare that I have read this thesis and in my opinion, this thesis is sufficient in terms of scope and quality for the award of Master of Science in Electrical engineering.

Signature : ……………………………………………….

Supervisor Name : Dr. Junainah Binti Sardi

Date : 28/12/2022

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DEDICATION

To my beloved mother “Nedal” and father “Yahya” and my dear late grandma “Hamedah”.

This is for you.

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ABSTRACT

Virtual microgrid is concerned with upgrading the traditional distribution network (DN) into smart DN using distributed energy resources. This research develops a framework for designing optimal virtual microgrid (VM) in two steps: boundary identification considering both structural characteristics and operating states of PV residential networks and sizing and locating Community Energy Storage (CES). The CES sizing and locating procedure is done in each VM with the goal of maximizing the economic benefit of CES deployment. The methodological tackling of the VM boundaries problem is achieved by identifying boundaries using two inputs: distribution line resistivity and transmitted power. Louvain heuristic algorithm is used for optimizing the VM partitioning. The CES optimal placement and sizing in the VMs are identified by maximizing the overall net present value (NPV) of CES deployment over a specific planning horizon. To tackle the CES allocation issue, Genetic Algorithm (GA) toolbox in MATLAB is utilized. The VM partitioning strategy was tested on IEEE 33-bus and to verify the algorithm robustness on a larger system, IEEE-118 bus system was used. When compared to previous work, the results of the VM partitioning using the proposed strategy showed lower line losses and higher electrical modularity. The impact of PV penetration level and its distribution to the VM partitioning was investigated on IEEE 33-bus and IEEE 69-bus distribution systems. Finally, VM partitioning for a 19-bus Malaysian distribution network is done. With respect to the second objective, the results of CES allocation strategy deployed on 19-bus Malaysian distribution network demonstrated that the proposed approach is capable of determining the optimal size, location and operating characteristics of CES in each VM, as well as maximising CES' total profit. This scenario is expected to achieve a revenue of 16.822 million MYR within the 20 years of CES deployment. Furthermore, it is observed that dispatching CES active power in each VM can lower peak demand, eliminate the violation of reverse power flow limits and reduce the cost of purchasing electricity from the grid. Sensitivity analysis shows that 40% penetration level of PV generation yields the highest NPV from CES deployment and starting the VM project in the next 20 years, i.e., year 2042 yields the highest BCR which is 5.22 due to ES cost reduction. The proposed framework can be used as a guideline for the power utilities and policy makers in developing a smart and reliable distribution network with higher renewable energy penetration.

REKA BENTUK OPTIMUM MIKROGRID MAYA MENGGUNAKAN PENYIMPAN TENAGA KOMUNITI UNTUK RANGKAIAN PENGAGIHAN

ABSTRAK

Mikrogrid maya (VM) boleh menaiktaraf rangkaian pengagihan elektrik tradisional (DN) kepada DN pintar menggunakan sumber tenaga teragih. Penyelidikan ini membangunkan rangka kerja untuk merekabentuk VM optimum dengan dua langkah iaitu pengenalpastian sempadan dengan mengambil kira kedua-dua ciri, struktur dan keadaan operasi rangkaian pengagihan elektrik dengan PV serta pensaizan dan pengesanan Penyimpan Tenaga Komuniti (CES). Prosedur penentuan saiz dan lokasi CES dilakukan dalam setiap VM dengan matlamat untuk memaksimumkan manfaat ekonomi penggunaan CES. Metodologi menangani masalah sempadan untuk VM dicapai dengan menggunakan dua input iaitu kerintangan talian agihan dan kuasa yang dihantar. Algoritma heuristik Louvain digunakan untuk mengoptimumkan pembahagian VM. Lokasi dan saiz optimum CES dalam VM dikenal pasti dengan memaksimumkan jumlah nilai kewangan semasa bersih (NPV) penggunaan CES pada tempoh projek tertentu. Untuk mengenalpasti lokasi dan saiz optimum CES, Algoritma Genetik (GA) dalam MATLAB digunakan. Strategi pembahagian VM telah diuji pada sistem pengihan elektrik IEEE 33-bas. Metodologi yang dihasilkan ini turut diuji pada sistem IEEE 118-bas untuk memastikan keberkesanannya pada sistem yang lebih besar. Hasil dapatan simulasi telah dibandingkan dengan strategi yang dicadangkan oleh penyelidik-penyelidik lain sebelumnya. Perbandingan tersebut menunjukkan bahawa pembahagian VM menggunakan strategi yang dicadangkan lebih berkesan dalam meminimumkan kehilangan talian dan meningkatkan modulariti elektrik. Kesan tahap penembusan PV dan pengagihannya kepada pembahagian VM telah disiasat pada sistem pengagihan IEEE 33-bas dan IEEE 69-bas. Akhirnya, pembahagian VM untuk rangkaian pengagihan Malaysia 19-bas telah ditentukan. Berkenaan dengan objektif kedua, hasil simulasi bagi rangkaian pengagihan Malaysia 19-bas menunjukkan bahawa strategi yang dicadangkan mampu menentukan saiz optimum, lokasi dan ciri operasi CES dalam setiap VM, serta memaksimumkan jumlah keuntungan perlaksanaan projek CES. Senario ini dijangka mencapai keuntungan sebanyak 16.822 juta MYR dalam tempoh 20 tahun penggunaan CES. Strategi penentuan kuasa aktif CES yang dicadangkan dalam setiap VM juga boleh mengurangkan beban elektrik puncak, mengelakkan pelanggaran had aliran kuasa terbalik dan mengurangkan kos pembelian elektrik daripada grid. Analisis sensitiviti menunjukkan bahawa 40% tahap penembusan penjanaan PV menghasilkan NPV tertinggi daripada penggunaan CES dan memulakan projek VM pada 20 tahun yang akan datang iaitu tahun 2042 menghasilkan Nisbah Keuntungan terhadap Kos (BCR) tertinggi iaitu 5.22 disebabkan pengurangan kos CES. Rangka kerja yang dicadangkan boleh dijadikan rujukan oleh syarikat utiliti kuasa dan pembuat polisi dalam membangunkan rangkaian pengagihan elektrik yang pintar dan mampan dengan lebih banyak penggunaan tenaga boleh diperbaharui.

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LIST OF ABBREVIATION

AEP	-	American Electric Power
BCR	-	Benefit To Cost Ratio
BES	-	Battery Energy Storage
BTSO	-	Backtracking Search Optimization
CES	-	Community Energy Storage
DER	-	Distributed Energy Resource
DG	-	Distributed Generation
DN	-	Distribution Network
DOD	-	Depth Of Discharge
ECS	-	Electrical Coupling Strength
ELECTRA	-	Electricity Grid Committed Towards Long-Term Research Activities
ES	-	Energy Storage
ESS	-	Energy Storage Systems
GA	-	Genetic Algorithm
GSO	-	Grid system operator
ICT	-	Information and Communication Technology
LP	-	Linear Programming
MESTECC	-	Malaysia's Ministry of Energy, Science, Technology, Environment, and Climate Change

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MILP	-	Mixed-Integer Linear Programming
NPV	-	Net Profit Value
O&M	-	Operation And Maintenance
P2P	-	Peer To Peer
PCS	-	Power Conversion System
PPF	-	Probabilistic Power Flow
PSO	-	Particle Swarm Optimization
PV	-	Photovoltaic
PVSG	-	Solar PV System and Smart Grid Research Laboratory
RPV	-	Rooftop Photovoltaic
RSM	-	Responsive Surface Method
SDN	-	Smart Distribution Network
SEDA	-	Sustainable Energy Development Authority Malaysia
SES	-	Shared Energy Storage
T&D	-	Transmission And Distribution
VM	-	Virtual Microgrid

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LIST OF SYMBOLS

$\overline{G_{ij}}$	-	Conductance between Bus *i* and Bus *j* in VM
$\overline{P_{ij}}$	-	Transmitted Power in Line *i, j*
$\overline{W_{i,j}}$	-	Composite Weight Index
$E_{ij(24)}$	-	Energy transmitted in Line *i, j* for 24 hours
G'	-	Normalized Conductance
L_{nj}	-	Real Load Power in Bus *j* at Hour n
P'	-	Normalized Active Power
PV_{nj}	-	PV Generated Power in Bus j at Hour n
R_{ij}	-	Electrical Distance between Bus *i* and Bus *j* in VM
x'	-	Normalized value
x_{max}	-	Maximum Value
x_{min}	-	Minimum Value
C_{CES}	-	CES Capital Cost
$E_{L\ VM}$	-	Total Load Consumed by All Loads in All VMs
$E_{PV\ VM}$	-	Total Energy Generated by All PVs In All VMs
P_D	-	Substation's Total Active Power Demand at Hour t
PL_{PV}	-	PV Penetration Level in Distribution System
P_{ch}	-	Charging Threshold
P_{dis}	-	Discharging Threshold

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$W_{i,j}$	-	Edge Composite Weight Index Between Buses i and j
EA	-	Energy Arbitrage Profit
L	-	Location of Energy Storage Units
Q	-	Modularity
S	-	Size of Energy Storage Units
α	-	Proportion Coefficient
β	-	Proportion Coefficient
F	-	Inflation Rate
IR'	-	Effective Interest Rate
IR	-	Interest Rate
LCT	-	Levelized Annual Cost of Gas Combustion Turbines
LR	-	Energy Loss Reduction Profit
OM	-	Operation and Maintenance Costs
PG	-	CES's Peaking Power Generation Reduction Profit
RC	-	Profit of CES Renting Cost
$RCO2$	-	Reduction In CO2 Emission Profit
TDB	-	Transmission And Distribution System Upgrade Deferral Profit
c	-	VM of Several Buses
k	-	Sum of the Weights of the Lines Attached to Bus
δ	-	Kronecker Delta Function

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LIST OF PUBLICATIONS

1. Alawami, H., Sardi, J. and Gan, C.K., 2021. Virtual Microgrid Partitioning Considering Structure and Characteristics of Smart Distribution Networks. *International Journal of Renewable Energy Research (IJRER), 11(4), pp.1578-1589.* (Scopus index) (WOS index)

2. Alawami, H., Sardi, J. and Gan, C.K., 2021. Allocation of Shared Energy Storage Units for Malaysian Residential Network with Rooftop PVs. *Malaysian Technical Universities Conference on Engineering and Technology (MUCET).* (Scopus index)

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Virtual microgrids (VMs) are virtually islanded systems developed from conventional distribution networks (CDNs) where each partition must contain enough distributed energy resources to maintain the following electrical characteristics: self-adequacy, self-sufficiency and self-healing; and have information and communication technologies (ICTs) between partitions for optimized energy management. To justify the economic feasibility of VMs, a business model is needed to increase the utility's and consumers' profits.

Community energy storage (CES) can be defined as the deployment of modular, distributed energy storage device at or near locations in the utility distribution system that are close to residential and business end customers. Using CES in the VMs can solve numerous technical challenges caused by high penetration of PV in the traditional power grids. While CES could potentially solve numerous technical issues, its high cost remains a barrier to its deployment. So, cost benefit analysis of CES deployment in the traditional grid that can justify its investment cost and motivate its deployment is needed.

This chapter of the thesis presents a general framework for this research. It covers the motivation behind this study and related problem statements. This chapter also presents the research objectives and research contributions. The chapter finishes with an overview of the research project, including an explanation of its structure and a research plan.

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1.2 Motivation

Nowadays, with the increase of environmental awareness of climate change, unstable fuel costs, and outdated electricity grid infrastructure and technologies, there have been initiatives from governments and institutes to move towards the smart grid and green energy. Malaysia's Ministry of Energy, Science, Technology, Environment, and Climate Change (MESTECC) has set a goal for renewable energy to generate 20% of the country's power by 2025, up from 2% today (Syakirah et al., 2021). The government wants to make sure that the national grid is ready for the integration of renewable energy sources in energy generation. Due to feed-in-tariff programs, the increased deployment of distributed generation, particularly renewable-based power, has resulted in a revolution in the utilization of distribution networks and the creation of smart-grid concepts (Razali et al., 2019). Smart grids are primarily meant to make the integration of renewable energy sources easier, as well as to improve system dependability and efficiency.

Although increased photovoltaic (PV) generation has several benefits, its widespread use in traditional power grids poses significant technological obstacles. Reverse power flow, voltage fluctuations, power quality concerns, and other difficulties are among these obstacles. In the meantime, energy storage (ES) is prohibitively expensive in terms of both capital and operating costs. As a result, utilities are being cautious about integrating ESs into their networks since they are uncertain of the economic value of doing so considering the high cost of ESs. This research proposes a framework of Virtual Microgrid (VM) construction employing Community Energy Storage (CES) in residential networks with rooftop PV units within Malaysia's energy setting to assist Malaysia in meeting the RE target and addressing the above-mentioned difficulties. Virtual microgrids are virtually islanded systems developed from conventional distribution networks (CDNs) where each partition must contain distributed energy resources to maintain the following electrical characteristics:

self-adequacy, self-sufficiency, and self-healing; and have information and communication technologies (ICTs) between partitions for ideal energy management." Despite VM advantages, until now, there is no such framework being proposed or implemented in Malaysia.

1.3 Problem Statement

Solar photovoltaics (PVs) on rooftops are the most profiled distributed energy resources (DERs). However, if not effectively controlled, an increase of PV penetration in traditional distribution networks may have negative consequences such as voltage fluctuations, reverse power flow, maximum voltage limit violations and poor system stability.

Energy storage systems have significant potential in mitigating concerns with appropriate planning and control strategies. The advantages of the ESS in the power system, particularly those that include renewable energy sources, are undeniable. There are, nevertheless, some obstacles that should not be neglected. The economic justification for integrating the ESS into the electrical grid is one of the primary problems. Even though there was a profit from energy arbitrage, the overall cost, including BESS losses, investment, and operating costs, was greater than the profit made (Xia et al., 2018).

VM can provide an effective solution for the issues of high PV proliferation in the distribution networks. Where a VM can be considered as a group of small-scale prosumers that is perceived as a single controlled entity. It benefits both the utility and the consumer in that it allows more solar energy to be shared among neighbours during peak periods when grid electricity is most expensive, hence enhancing the value of participating houses. CES is an important component of VM. CES may be used to store surplus PV energy throughout the day and feed it back to the community at peak demand periods in the home distribution network. However, there is currently a lack of study on the elements that influence virtual microgrid clustering and construction. In addition, given the present market's high cost of CES, VM design that focuses on maximizing financial returns from CES deployment in Malaysia is required. As a result, this research is being carried out to determine the best VM design for PV residential networks utilizing CES, which would benefit both the utility and the prosumers in Malaysia. Figure 1.1 illustrates the research problem defined in three relative directions specifically, general problem, and specific problem, and the sub-issues. Research problem have derived from the literature review section, which firstly stated that currently, no framework exists that addresses the VM partitioning considering both structure and operational characteristics of DNs. Secondly, it can be observed that CES allocation planning in Malaysia specifically that considers financial standpoint is lacking.

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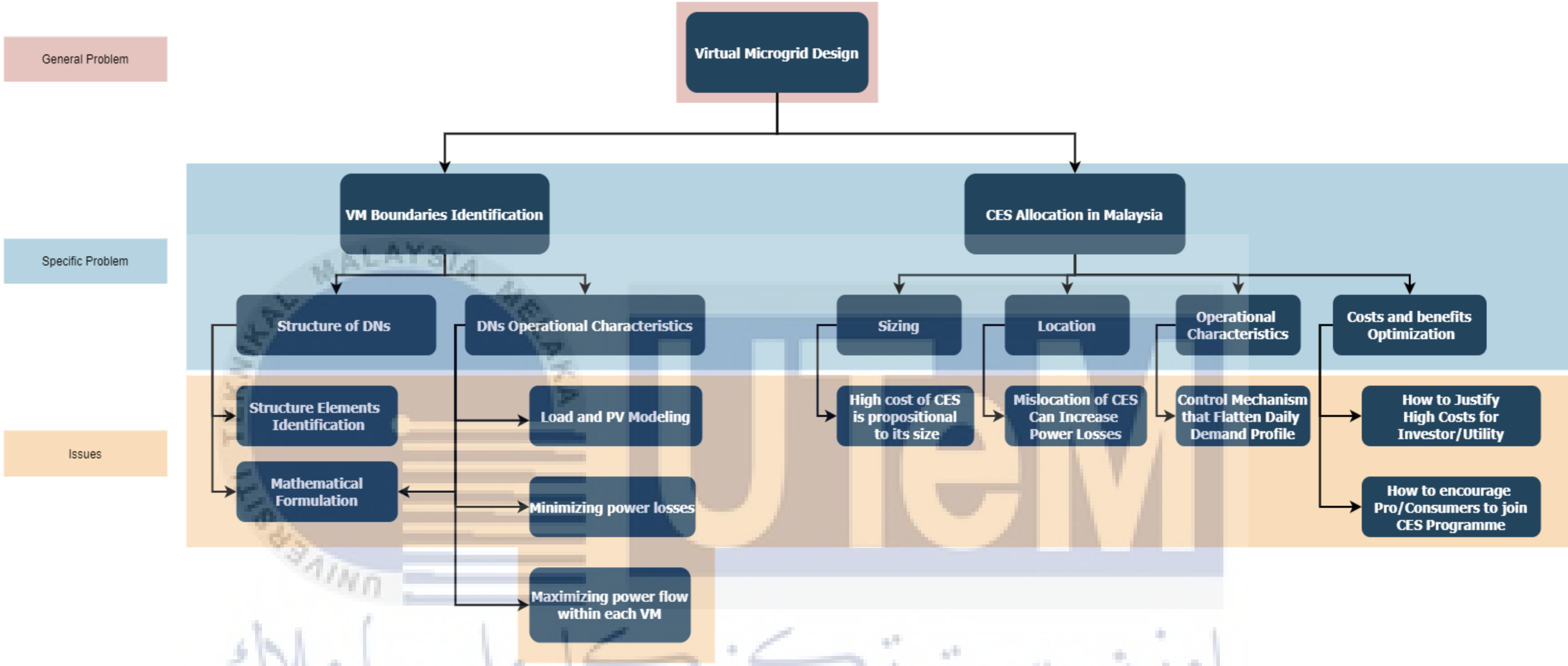

Figure 1.1: Overview of the research problem

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