Faculty of Electrical Engineering

MODELLING OF MALAYSIAN REFERENCE NETWORKS FOR PHOTOVOLTAIC AND BATTERY ENERGY STORAGE SYSTEMS INTEGRATION STUDIES

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DECLARATION

I declare that this thesis entitled "Modelling of Malaysian Reference Networks for Photovoltaic and Battery Energy Storage Systems Integration Studies" 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.

Signature	:	………………………………..
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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 Doctor of Philosophy.

Signature	:	……………………………….
Supervisor Name	:	Associate Professor Ir. Dr. Gan Chin Kim
Date	:	……………………………….

DEDICATION

To my family who has supported me significantly, a special feeling of gratitude to my great parents Mr. Salah Mohammed and Mdm. Ahlam Ahmed who have supported me through my life. I will always appreciate their sacrifices for me. Their encouragement had a main role in achieving my goals and wishes throughout my career. I am extremely proud of them.

To my beloved country, Iraq, which has a special place in my heart.

ABSTRACT

The thesis aims to develop and model six optimal Malaysian Medium Voltage (MV) Reference Networks (RNs) for the investigation of network performance under various future development scenarios. These include the integration of Photovoltaic (PV) system and Battery Energy Storage System (BESS) into the six MV RNs. The integration of PV system into the Malaysian MV distribution network is seen as one of the promising options to reduce carbon footprints for a low-carbon future. However, the integration of PV system into the existing MV distribution networks could cause reverse power flow problem. This reverse power flow may result in the increase of total network losses, voltage rise, and thermal violation of network components. Hence, one of the objectives of this thesis is to quantify the impact of PV integration with different PV locations, PV variability profiles, time resolution of PV profiles, and PV penetration levels on the optimal Malaysian MV RNs. In addition, the integration of PV system comes with other challenges such as PV output fluctuation, mismatch between PV generation and load demand, and network overvoltage. These issues will affect the power quality and the performance of the Malaysian MV distribution network. Therefore, this thesis also aims to identify the possible applications of BESS that could be used together with PV system to mitigate the potential network issues. The results on the optimal MV RNs show that the RNs with 11kV feeders have lower network losses as compared to the RNs with 33 and 11kV feeders. In addition, the losses in the rural RNs are higher than the urban and sub-urban RNs. The results also show that the utilization of optimal cables and transformers can reduce the network losses of between 3.52% to 19.22%. This translates into the increase of profit to the utility company of between RM 29 to RM 59884 per annum for the six RNs. Furthermore, the findings suggest that the total network losses are reduced between 3 to 7 times when the PV system is located at the end of 11kV feeder for the six RNs. The simulation results for PV variability study show that rural RNs with longer feeder need the highest number of voltage step changes (around 7300 annually) to maintain the voltage magnitude within the acceptable range. In addition, the time resolution case study suggests that one-minute interval PV generation profile is the most appropriate time resolution that could be used to analyze the MV total network losses for the urban, sub-urban, and rural RNs. The findings also emphasized the fact that once the PV penetration level threshold was achieved, the total network losses, voltage rise, and thermal violation of transformers will begin to increase. Finally, the BESS simulation results show the ability of lithium-ion BESS models to reduce the network maximum demand of between 4.84% to 52.71%. The BESS also helps to mitigate the issues which are caused by PV system integration through power output smoothening, demand following, and alleviating overvoltage problem.

PEMODELAN RANGKAIAN RUJUKAN MALAYSIA UNTUK KAJIAN INTEGRASI SISTEM FOTOVOLTA DAN SISTEM SIMPANAN TENAGA BATERI

ABSTRAK

Tesis ini bertujuan untuk membangunkan dan memodelkan enam Rangkaian Rujukan (RNs) Voltan Sederhana (MV) Malaysia yang optimum untuk penyiasatan prestasi rangkaian di bawah pelbagai senario pembangunan masa depan. Ini termasuk penyatuan sistem fotovolta (PV) dan Sistem Penyimpanan Tenaga Bateri (BESS) ke dalam enam MV RNs. Penyatuan sistem PV ke dalam rangkaian pengedaran MV Malaysia dilihat sebagai salah satu pilihan yang menjanjikan untuk mengurangkan jejak karbon untuk masa depan rendah karbon. Namun, penyatuan sistem PV ke dalam rangkaian pengedaran MV yang ada boleh menyebabkan masalah aliran daya terbalik. Aliran daya terbalik ini mungkin mengakibatkan peningkatan jumlah kehilangan rangkaian, kenaikan voltan, dan pelanggaran terma komponen rangkaian. Oleh itu, salah satu objektif tesis ini adalah untuk mengukur kesan penyatuan PV dengan lokasi PV yang berbeza, profil kebolehubahan PV, resolusi masa profil PV, dan tahap penembusan PV pada RNs MV Malaysia yang optimum. Di samping itu, integrasi sistem PV menghadapi dengan cabaran lain seperti turun naik output PV, ketidakpadanan antara penjanaan PV dan permintaan beban, dan voltan berlebihan rangkaian. Masalah-masalah ini akan mempengaruhi kualiti kuasa dan prestasi rangkaian pengedaran MV Malaysia. Oleh itu, tesis ini juga bertujuan untuk mengenal pasti aplikasi BESS yang dapat digunakan bersama-sama dengan sistem PV untuk mengurangkan masalah rangkaian yang mungkin berlaku. Hasil dapatan dari RNs MV yang optimum menunjukkan bahawa RNs dengan feeder 11kV mempunyai kerugian rangkaian yang lebih rendah berbanding RNs dengan feeder 33 dan 11kV. Di samping itu, kehilangan rangkaian di RNs luar bandar adalah lebih tinggi daripada RNs di bandar dan pinggir bandar. Hasil dapatan juga menunjukkan bahawa penggunaan kabel dan transformer yang optimum dapat mengurangkan kehilangan rangkaian antara 3.52% hingga 19.22%. Ini bermaksud peningkatan keuntungan kepada syarikat utiliti antara RM 29 hingga RM 59884 setahun untuk enam RNs. Selanjutnya, penemuan menunjukkan bahawa jumlah kehilangan rangkaian dikurangkan antara 3 hingga 7 kali apabila sistem PV berada di hujung feeder 11kV untuk enam RNs. Hasil simulasi untuk kajian kebolehubahan PV menunjukkan bahawa RNs luar bandar dengan feeder yang lebih panjang memerlukan jumlah perubahan langkah voltan tertinggi (sekitar 7300 setiap tahun) untuk mengekalkan magnitud voltan dalam julat yang boleh diterima. Di samping itu, kajian kes penyelesaian masa menunjukkan bahawa profil penjanaan PV selang satu minit adalah penyelesaian masa yang paling tepat yang dapat digunakan untuk menganalisis jumlah kerugian rangkaian MV untuk RNs bandar, pinggir bandar, dan luar bandar. Penemuan ini juga menekankan fakta bahawa setelah ambang tahap penembusan PV tercapai, jumlah kerugian rangkaian, kenaikan voltan, dan pelanggaran terma transformer akan mulai meningkat. Akhirnya, hasil simulasi BESS menunjukkan kemampuan model BESS lithium-ion untuk mengurangkan permintaan maksimum rangkaian antara 4.84% hingga 52.71%. BESS juga dapat membantu mengurangkan masalah-masalah yang disebabkan oleh penyatuan sistem PV melalui kelancaran output kuasa, penjejakan permintaan, dan mengurangkan masalah voltan berlebihan.

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LIST OF ABBREVIATIONS

ADMD	After Diversity Maximum Demand
BESS	Battery Energy Storage System
BW	Bandwidth
C_C	Capital Cost
C_L	Cost of Losses
DER	Distributed Energy Resources
DG	Distributed Generation
DIgSILENT	DIgital SImuLation of Electrical NeTworks
DNO	Distribution Network Operator
FiT	Feed-in Tariff
FKE	Fakulti Kejuruteraan Elektrik
GHG	Greenhouse Gases
GHI	Global Horizontal Irradiance
GSS	Grid Supply System
K_T	Clearness Index
LF	Load Factor
LL	Load Losses
LV	Low Voltage
MD	Maximum Demand
MV	Medium Voltage
NL	Network Losses

NLL	No-Load Losses
OH	Overhead
OLTC	On-Load Tap Changer
PCC	Point of Common Coupling
PDS	Primary Distribution Substation
PV	Photovoltaic
PVC	Polyvinyl Chloride
PVDG	Photovoltaic Distributed Generation
PVSG	Photovoltaic and Smart Grid
RE	Renewable Energy
RN	Reference Network
SEDA	Sustainable Energy Development Authority Malaysia
SOC	State of Charge
TD	Time Delay
TDIS	Transmission/Distribution Interface Substation
TNB	Tenaga Nasional Berhad
TX	Transformer
UG	Underground
UTeM	Universiti Teknikal Malaysia Melaka
VI	Variability Index
VPI	Voltage Profile Improvement
XLPE	Cross-Linked Polyethylene

LIST OF PUBLICATIONS

Mohammed, H.S., Gan, C.K. and Ghani, M.A., 2020. Technical Impacts of Solar Photovoltaic Systems Integration into Malaysian Medium Voltage Reference Networks. *International Journal of Nonlinear Analysis and Applications*, 11, pp. 265-276.

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CHAPTER 1

INTRODUCTION

1.1 Research background

Power distribution network is the last stage of the power delivery chain, which channel electrical energy from the transmission or Grid Supply System (GSS) network to consumers of electricity. Due to rapid increase in electricity demand, distribution feeders and transformers are getting more extensive, covering wide geographical areas and operating continuously with the expectation of being reliable, safe, and secured.

One of the most cost-effective ways to meet increasing demand, reduce operating cost, and environmental impact is to improve energy efficiency of existing power distribution network by moderating energy demand and reducing wastage of electrical energy (World Bank, 2013). This energy waste degrades the network performance, resulting in higher cost of investment. Thus, reducing energy waste or “reducing losses” is one of the ways to improve network energy and economic efficiency, particularly in power distribution network where the majority of these energy losses occur.

A majority of the electrical distribution cables and transformers currently utilized in the Malaysian distribution network is set up circa 1980s (Energy Commission, 2010), and the equipment would have expired and their substitution are needed. The selection of cables and transformers in substitution should be upgraded and analyzed to achieve better performance. Losses play a prominent role in distribution network which may significantly increase the total cost of distribution network and decreasing the energy efficiency of the network (Ćurčić et al., 2001). At present, the replacement policies for distribution cables and transformers are primarily concerned with the cost of investment while the cost of losses have not been given adequate