



**Faculty of Electrical Engineering**

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

**Hayder Salah Mohammed**

**Doctor of Philosophy**

**2021**

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

**HAYDER SALAH MOHAMMED**

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

**Faculty of Electrical Engineering**

**UNIVERSITI TEKNIKAL MALAYSIA MELAKA**

**2021**

## 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 : .....

Name : Hayder Salah Mohammed

Date : .....

## **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.*

## ACKNOWLEDGEMENTS

First of all, I would like to thank all the good people who have helped me in various ways to complete my research studies. My utmost gratitude goes to my main supervisor, Associate Professor Ir. Dr. Gan Chin Kim for continued patience and guidance, and for incredible expertise that he brings to all phases of the research. I highly appreciate his valuable time in giving me useful ideas to complete this thesis.

Very special thanks to, Professor Datuk Dr. Mohd Ruddin bin Ab. Ghani, my Co-Supervisor, and Professor Ir. Dr. Au Mau Teng, my external co-supervisor, who have provided insights into both the topic and technical guidance in this compilation.

Special thanks to the scholarship (ZAMALAH UTeM) from the Ministry of Higher Education Malaysia and UTeM in supporting this research work.

I would like to express my ultimate thanks go to my beloved parents for their moral and outstanding support in completing this thesis. Lastly, I am truly grateful for all the hands and hearts that made this thesis possible. Thank you from the bottom of my heart.

## TABLE OF CONTENTS

<b>DECLARATION</b>	<b>i</b>
<b>APPROVAL</b>	<b>ii</b>
<b>DEDICATION</b>	<b>iii</b>
<b>ABSTRACT</b>	<b>iv</b>
<b>ABSTRAK</b>	<b>vii</b>
<b>ACKNOWLEDGEMENTS</b>	<b>xi</b>
<b>TABLE OF CONTENTS</b>	<b>xvi</b>
<b>LIST OF TABLES</b>	<b>xviii</b>
<b>LIST OF FIGURES</b>	
<b>LIST OF ABBREVIATIONS</b>	
<b>LIST OF PUBLICATIONS</b>	
<b>CHAPTER</b>	
<b>1. INTRODUCTION</b>	<b>1</b>
1.1 Research background	1
1.2 Problem statement	3
1.3 Research objectives	5
1.4 Research scope	5
1.5 Contribution	6
1.6 Thesis outline	7
<b>2. LITERATURE REVIEW</b>	<b>9</b>
2.1 Introduction	9
2.2 Distribution network configurations and components	10
2.2.1 Distribution feeders	11
2.2.2 Distribution transformers	12
2.3 Distribution load characteristics	13
2.3.1 Electrical load behavior and load profile	14
2.3.2 Load factor	16
2.4 Reference Network (RN)	17
2.4.1 Overview of RN development method	19
2.4.2 Research works in RN	21
2.4.3 Development of Malaysian RN	26
2.5 Distribution Network Losses (NL)	26
2.5.1 NL calculation using load flow simulation software	27
2.5.2 Levels of distribution network losses	29
2.5.3 Impact of distribution NL	33
2.6 Distribution network optimization	34
2.6.1 Cable power losses	34
2.6.2 Transformer power losses	35
2.6.3 Interest rate	36

2.6.4	Review of previous works	37
2.7	PV system on distribution network	38
2.7.1	Requirement of PV connection in Malaysia	39
2.7.2	Challenges of PV system on distribution network	40
2.8	Battery Energy Storage System (BESS)	47
2.8.1	Energy storage system research history	48
2.8.2	Lithium ion batteries	49
2.8.3	Coulomb counting method for SOC estimation	50
2.8.4	BESS applications	51
2.9	Summary	55
<b>3.</b>	<b>METHODOLOGY</b>	<b>57</b>
3.1	Introduction	57
3.2	DIgital SIMuLation of Electrical NeTworks (DIgSILENT)	57
3.2.1	Time-series load flow analysis	58
3.2.2	Validation of DIgSILENT with IEEE 34 node test feeder	58
3.3	MV Reference Network (RN) model	60
3.3.1	Data collection and filtering	61
3.3.2	Distribution feeder datasets classification	66
3.3.3	Develop reference network model	75
3.4	Base case modelling and simulation	78
3.4.1	Reference Networks (RNs) modelling	78
3.4.2	Cable modelling	87
3.4.3	Transformer modelling	88
3.4.4	Network demand modelling	89
3.4.5	Base case simulation	93
3.5	Optimal selection of distribution cables and distribution transformers	94
3.5.1	Life-cycle cost of equipment	94
3.5.2	Optimal selection of distribution cables	95
3.5.3	Optimal selection of distribution transformers	100
3.6	PV system integration	102
3.6.1	PV system modelling and generation profile data collection	103
3.6.2	Impact of PV integration on the optimal Malaysian MV reference networks	103
3.7	Battery Energy Storage System (BESS) integration	114
3.7.1	BESS modelling	114
3.7.2	PV power smoothing techniques using BESS	116
3.7.3	PV energy time shift using BESS power model	118
3.7.4	Voltage support using BESS voltage model	119
3.8	Summary	120
<b>4.</b>	<b>RESULT AND DISCUSSION</b>	<b>121</b>
4.1	Introduction	121
4.2	Evaluation of network losses and voltage profile based on base case simulation	121
4.2.1	Network losses	121
4.2.2	Voltage profile	125
4.3	Optimal cable and transformer selection based on minimum life-cycle cost methodology	127
4.3.1	Optimal cable selection	127
4.3.2	Sensitivity analysis	131
4.3.3	Optimal transformer selection	133

4.4	Network impact quantification	136
4.4.1	Case study 1- impact of PV integration with different locations on the 11kV feeder on total network losses	137
4.4.2	Case study 2- impact of PV integration with different PV variability profiles on voltage profile improvement and 33/11kV transformer tap changer	140
4.4.3	Case study 3- impact of PV integration with different time resolution of PV generation profiles on total network losses	144
4.4.4	Case study 4- impact of PV integration with different PV penetration levels on total network losses and transformer thermal loading	145
4.5	PV power smoothing, PV energy time shift, and voltage support applications of BESS	152
4.5.1	PV power smoothing	152
4.5.2	PV energy time shift	161
4.5.3	Voltage support	165
4.6	Summary	168
<b>5.</b>	<b>CONCLUSION AND RECOMMENDATIONS FOR FUTURE RESEARCH</b>	<b>171</b>
5.1	Introduction	171
5.2	Research contribution	171
5.2.1	Developing and modelling six optimal MV reference networks	171
5.2.2	Quantifying the impact of PV system integration on the optimal Malaysian MV RNs	172
5.2.3	Identifying the possible applications of battery energy storage system with PV system in the optimal Malaysian MV RNs	173
5.3	Significant of results	173
5.4	Suggestion for future work	176
	<b>REFERENCES</b>	<b>177</b>
	<b>APPENDICES</b>	<b>206</b>

## LIST OF TABLES

<b>TABLE</b>	<b>TITLE</b>	<b>PAGE</b>
2.1	Example of parameters of Malaysian RNs (Ibrahim et al., 2015)	22
2.2	Estimated distribution NL in different network types in UK (Sohn Associates and Imperial College London, 2014)	32
2.3	Normal operating at point of common coupling (MV) (TNB, 2013)	39
3.1	Validation of DIgSILENT 34-bus system results with IEEE test results	60
3.2	Sample of distribution feeder datasets	63
3.3	Samples of selected network location areas representing urban network	68
3.4	Samples of selected network location areas representing rural network	70
3.5	Estimated stratum boundary based on geographic location	72
3.6	Parameters for the development of urban RN with 33 & 11kV feeders	79
3.7	Parameters for the development of sub-urban RN with 33 & 11kV feeders	81
3.8	Parameters for the development of rural RN with 33 & 11kV feeders	82
3.9	Parameters for the development of urban RN with 11kV feeders	83
3.10	Parameters for the development of sub-urban RN with 11kV feeders	85
3.11	Parameters for the development of rural RN with 11kV feeders	87
3.12	Technical data of TNB cables (Tenaga Nasional Berhad, 2020)	88
3.13	Technical data of TNB transformers (Tenaga Nasional Berhad, 2019)	88
3.14	Range of Maximum Demand (MD) for domestic consumer sub-classes or premises (TNB, 2007)	90
3.15	Range of Maximum Demand (MD) for types of shop-houses (TNB, 2007)	90

3.16	Load composition and LF for urban RN with 33 & 11kV feeders	91
3.17	Load composition and LF for sub-urban RN with 33 & 11kV feeders	91
3.18	Load composition and LF for rural RN with 33 & 11kV feeders	92
3.19	Load composition and LF for urban RN with 11kV feeders	92
3.20	Load composition and LF for sub-urban RN with 11kV feeders	92
3.21	Load composition and LF for rural RN with 11kV feeders	93
3.22	Standard 11kV (Al/XLPE/PVC) cable data from local vendors	100
3.23	Technical data of distribution transformers obtained from the local vendors	101
3.24	Number of days for each PV variability type in Melaka	107
3.25	Cost and performance of lithium ion battery (Schoenung, 2011)	115
3.26	Sample of parameters used in the BESS power model	115
3.27	Sample of parameters used in the BESS voltage model	116
4.1	Proportion of network losses breakdown	124
4.2	Cable utilization and annual saving for urban RN with 33 & 11kV feeders	129
4.3	Cable utilization and annual saving for sub-urban RN with 33 & 11kV feeders	129
4.4	Cable utilization and annual saving for rural RN with 33 & 11kV feeders	129
4.5	Cable utilization and annual saving for urban RN with 11kV feeders	130
4.6	Cable utilization and annual saving for sub-urban RN with 11kV feeders	130
4.7	Cable utilization and annual saving for rural RN with 11kV feeders	130
4.8	Sensitivity analysis on energy price change for urban RN with 33 & 11kV feeders	131
4.9	Sensitivity analysis on cable cost change for urban RN with 33 & 11kV feeders	132
4.10	Sensitivity analysis on interest rate change for urban RN with 33 & 11kV feeders	133

4.11	Average value and optimal transformer capacity selection for urban RN with 33 & 11kV feeders	133
4.12	Average value and optimal transformer capacity selection for sub-urban RN with 33 & 11kV feeders	134
4.13	Average value and optimal transformer capacity selection for rural RN with 33 & 11kV feeders	134
4.14	Average value and optimal transformer capacity selection for urban RN with 11kV feeders	134
4.15	Average value and optimal transformer capacity selection for sub-urban RN with 11kV feeders	135
4.16	Average value and optimal transformer capacity selection for rural RN with 11kV feeders	135
4.17	Total network losses with different locations of PV system	138
4.18	Losses reduction across the 11kV feeder	140
4.19	Number of voltage step changes for urban, sub-urban, and rural RNs with 33 & 11kV feeders	142
4.20	Error ratio based on different time resolutions	145
4.21	Summary of safe PV maximum penetration level respect to different network impact quantification criteria	150
4.22	PV penetration level and maximum allowable TNB and proposed PV system capacity	151
4.23	Maximum power and capacity of battery for each PV variability type	156
4.24	Comparison of two smoothing techniques based on various criteria for urban RN with 33 & 11kV feeders	158
4.25	Comparison of two smoothing techniques based on various criteria for sub-urban RN with 33 & 11kV feeders	158

4.26	Comparison of two smoothing techniques based on various criteria for rural RN with 33 & 11kV feeders	159
4.27	Comparison of two smoothing techniques based on various criteria for urban RN with 11kV feeders	159
4.28	Comparison of two smoothing techniques based on various criteria for sub-urban RN with 11kV feeders	160
4.29	Comparison of two smoothing techniques based on various criteria for rural RN with 11kV feeders	160
4.30	Maximum battery power and capacity for each feeder of urban RN with 33 & 11kV feeders	161
4.31	Maximum demand reduction for each feeder of urban RN with 33 & 11kV feeders	162
4.32	Maximum battery power and capacity for each feeder of rural RN with 33 & 11kV feeders	165
4.33	Maximum demand reduction for each feeder of rural RN with 33 & 11kV feeders	166

## LIST OF FIGURES

FIGURE	TITLE	PAGE
2.1	Example of power distribution network layout (Kersting, 2012)	10
2.2	MV feeder numbers in Malaysia	11
2.3	Malaysian distribution network capacity from 2014 to 2017 (Energy Commission, 2018)	11
2.4	Example of load curve of a residential consumer (Dickert and Schegner, 2010)	14
2.5	Aggregated load profiles in Malaysia (Busrah et al., 2011)	15
2.6	Examples of load profiles (Short, 2006)	16
2.7	Process of developing RN	19
2.8	Representative network development framework (Kawahara et al., 2004)	20
2.9	Examples of UKGDS RN model (SEDG, 2015)	23
2.10	Examples of RN for Italian distribution network (Celli et al., 2014)	25
2.11	Feeder disaggregation process to develop Indian RN (Bhakar et al., 2010b)	25
2.12	Examples of RN for Indian distribution network (Bhakar et al., 2010b)	25
2.13	Distribution network losses percentage in selected countries (Dortolina and Nadira, 2005)	30
2.14	Distribution losses in Malaysia (TNB, 2019)	30
2.15	T&D losses breakdown in Malaysia (TNB, 2019)	30
2.16	Breakdown of distribution losses in several Brazilian DNO (Lange et al., 2015)	31

2.17	Breakdown of distribution losses in Albanian DNO (Coopers, 2010)	31
2.18	Breakdown of distribution NL in US in 2014 (Aman et al., 2014)	32
2.19	Total PVDG size vs. $\Delta$ PL with single PVDG unit (Al-Sabounchi et al., 2015)	41
2.20	PV variability in Melaka, Malaysia	42
2.21	Loss ratio (Urquhart and Thomson, 2015)	44
2.22	Network losses for three different networks (Annathurai, 2017)	46
2.23	Percentage of case violation in Malaysian and UK networks (Annathurai, 2017)	47
2.24	Lithium ion battery schematic (Carnegie et al., 2013)	50
2.25	General structure of PV with battery energy storage system (Nikolov, 2017)	51
3.1	IEEE 34 node test feeder system (modified from (IEEE, 2010))	59
3.2	Stratification concept	67
3.3	Histogram analysis of the average 11kV feeder length (km) and peak load density (MW/km) of selected urban areas and compared with sub-urban and rural areas	69
3.4	Histogram analysis of the average 11kV feeder length (km) and peak load density (MW/km) of selected rural areas and compared with urban and sub-urban areas	71
3.5	Data stratification for the Malaysian distribution MV feeders	73
3.6	K-means algorithm for 3 clusters	74
3.7	Overall process to develop RN model	76
3.8	Single line diagram for medium voltage reference network with 33 & 11kV feeders	77
3.9	Single line diagram for medium voltage reference network with 11kV feeders	77

3.10	DIgSILENT model for urban RN with 33 & 11kV feeders	79
3.11	DIgSILENT model for sub-urban RN with 33 & 11kV feeders	80
3.12	DIgSILENT model for rural RN with 33 & 11kV feeders	82
3.13	DIgSILENT model for urban RN with 11kV feeders	83
3.14	DIgSILENT model for sub-urban RN with 11kV feeders	85
3.15	DIgSILENT model for rural RN with 11kV feeders	86
3.16	Sample of distribution feeder datasets with type of load	89
3.17	Samples of normalized load composition utilized in time-series simulation for different load types	91
3.18	Flowchart of base case simulation using DIgSILENT power factory	94
3.19	Correlation between current rating and cable size	97
3.20	Correlation between annuitized capital cost and current rating	97
3.21	Flowchart of optimal cable selection operation	99
3.22	Flowchart of optimal transformer selection operation	102
3.23	Inverter room with a monitoring system in UTeM	103
3.24	Location of PV system on the 11kV feeder	104
3.25	Probability of occurrence of PV variability in Melaka	107
3.26	PV generation profile on clear sky day	108
3.27	PV generation profile on overcast day	108
3.28	PV generation profile on mild variability day	109
3.29	PV generation profile on moderate variability day	109
3.30	PV generation profile on high variability day	109
3.31	Solar irradiance versus time for a moderate variability day	111
3.32	Installation location of BESS and PV system	115
3.33	Flowchart of BESS power model operation	119
4.1	Detailed network losses for urban, sub-urban, and rural RNs with 33 & 11kV feeders	122

4.2	Detailed network losses for urban, sub-urban, and rural RNs with 11kV feeders	123
4.3	Samples of NL estimation results obtained from TNB loss estimation database (Ibrahim, 2017)	124
4.4	Voltage level at bus bars and nodes	125
4.5	Maximum and minimum voltage histogram for the six RNs based on base case simulation	126
4.6	Peak driven and optimal cable size for the six RNs	128
4.7	Loss reduction for the six RNs after network optimization	136
4.8	Total loss reduction with the position of PV system	139
4.9	Maximum voltage profile improvement for urban RN with 33 & 11kV feeders from five different PV variabilities	141
4.10	Maximum voltage profile improvement for sub-urban RN with 33 & 11kV feeders from five different PV variabilities	141
4.11	Maximum voltage profile improvement for rural RN with 33 & 11kV feeders from five different PV variabilities	141
4.12	OLTC step changes and voltage profile at low voltage side of 33/11kV TX for urban RN with 33 & 11kV feeders	143
4.13	OLTC step changes and voltage profile at low voltage side of 33/11kV TX for sub-urban RN with 33 & 11kV feeders	143
4.14	OLTC step changes and voltage profile at low voltage side of 33/11kV TX for rural RN with 33 & 11kV feeders	143
4.15	Loss ratio for urban, sub-urban, and rural RNs with 33 & 11kV feeders based on different time resolutions	144
4.16	Percentage of total network losses at different PV penetration levels for urban RNs	147

4.17	Percentage of total network losses at different PV penetration levels for sub-urban RNs	147
4.18	Percentage of total network losses at different PV penetration levels for rural RNs	148
4.19	Transformer thermal loading versus PV penetration level for the six optimal RNs	149
4.20	Total loss reduction for the six optimal RNs based on TNB and proposed PV capacity	152
4.21	PV power smoothing simulation results for overcast and mild variability days	154
4.22	PV power smoothing simulation results for moderate variability and high variability days	155
4.23	PV energy time shift simulation results for urban RN with 33 & 11kV feeders	164
4.24	Voltage support simulation results for rural RN with 33 & 11kV feeders	167

## 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.

Mohammed, H.S., Gan, C.K. and Ghani, M.A., 2020. Integrating PV Systems with Battery Energy Storage Systems into Malaysian Medium Voltage Reference Networks for the Applications of PV Power Smoothing and Energy Time Shift. *International Journal of Advanced Science and Technology*, 29 (9s), pp. 1383-1402.

Mohammed, H.S., Gan, C.K. and Ghani, M.A., 2021. Time-Series Load Flow Simulations for The Estimation of Network Losses in Malaysian Medium Voltage Reference Networks. *Gazi University Journal of Science*. (Accepted).

Mohammed, H.S., Gan, C.K. and Ghani, M.A., 2020. The Impact of Losses on The Selection of Distribution Cables and Transformers of Malaysian Medium Voltage Reference Networks. *Gazi University Journal of Science*, 33 (12), pp. 322-338.

Mohammed, H.S., Gan, C.K. and Baharin, K.A., 2019. Performance Evaluation of Various Solar Photovoltaic Module Technologies under Tropical Climate Conditions at Melaka, Malaysia. *Journal of Engineering and Applied Sciences*, 14 (2), pp. 336-341.

# 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