



**Faculty of Electrical Engineering**

**FUTURE DISTRIBUTION NETWORK PLANNING WITH  
DEMAND RESPONSE APPLICATIONS**

**MEYSAM SHAMSHIRI**

**Doctor of Philosophy**

**2017**

**FUTURE DISTRIBUTION NETWORK PLANNING WITH DEMAND  
RESPONSE APPLICATIONS**

**MEYSAM SHAMSHIRI**

**A thesis submitted**

**in fulfilment of the requirements for the degree of Doctor of Philosophy**

**Faculty of Electrical Engineering**

**UNIVERSITI TEKNIKAL MALAYSIA MELAKA**

**2017**

## DECLARATION

I declare that this thesis entitled “FUTURE DISTRIBUTION NETWORK PLANNING WITH DEMAND RESPONSE APPLICATIONS” 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 : MEYSAM SHAMSHIRI .....

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 : .....

Name : ASSOC. PROF. DR. GAN CHIN KIM.

Date : .....

## **DEDICATION**

This thesis is dedicated to my lovely family.

## ABSTRACT

The philosophy in distribution network planning is continuously evolving to ensure an efficient, reliable and cost-effective network design. This is particularly important with the increasing presence of Distributed Generation (DG) and Demand Response (DR) integration at the distribution network. Thus, there is a need to develop distribution network modelling tool so that the associated impacts and benefits of such integration can be properly assessed and quantified. In light of this, this thesis presents a fractal-based approach to generate a large number of consumer settlements for low voltage distribution networks. Subsequently, branching rate and minimum spanning tree concepts have been applied to connect the load points and create the network for low voltage and medium voltage, respectively. The Particle Swarm Optimization (PSO) technique was then utilized to determine the optimum rating and placement of transformers, DG and capacitors. The developed simulation tool allows the modelling and planning of distribution network to be carried out in a systematic way. In addition, a total of 10,000 network case studies have been performed to assess the network performance under the influence of demand response and solar PV penetration levels. Three different demand response strategies have been considered in this work, namely, consumer response to their own demand profile, consumer response to PV generation profile and the consumer optimized demand response facilitated by smart grid application. Methodology for generating optimum DR pattern for 2,000 individual consumers have also been proposed and implemented with the aim to improve network load factor. These comprehensive analysis of the benefits of DR would enable a more meaningful and robust conclusion to be made. The findings show that DR application at consumer level can greatly facilitate the integration of solar PV systems. The DR benefits include reduced network losses and increased network asset utilization levels. Last but not least, this research work has filed a patent for the invention of Internet-of-Things based remote demand response and energy monitoring system that could be used as an enabler for demand response application in the actual environment.

## ABSTRAK

*Falsafah dalam perancangan rangkaian pengedaran terus berkembang untuk memastikan reka bentuk rangkaian yang cekap, boleh dipercayai, dan kos yang efektif. Hal ini secara khususnya penting kerana peningkatan kehadiran Distributed Generation (DG) dan Demand Response (DR) di rangkaian pengedaran. Oleh itu, menjadi satu keperluan untuk membangunkan alat pemodelan rangkaian pengedaran supaya kesan yang berkaitan dan manfaat integrasi tersebut boleh dinilai dan diukur dengan betul. Sehubungan dengan itu, tesis ini membentangkan pendekatan berasaskan fraktal-asas untuk menjana sejumlah besar penempatan pengguna untuk rangkaian pengagihan voltan rendah. Selepas itu, kadar cawangan dan konsep merangkumi pokok yang minimum telah digunakan untuk menyambung titik beban dan mewujudkan rangkaian untuk voltan rendah dan voltan sederhana. Kemudiannya, teknik Particle Swarm Optimization (PSO) telah digunakan untuk menentukan penarafan optimum dan penempatan transformer, DG dan kapasitor. Alat simulasi yang dibina membolehkan pemodelan dan perancangan rangkaian pengedaran yang akan dijalankan dengan cara yang sistematik. Di samping itu, sejumlah 10,000 kajian kes rangkaian telah dijalankan untuk menilai prestasi rangkaian di bawah pengaruh respon permintaan dan tahap penembusan PV solar. Tiga strategi tindak balas permintaan yang berbeza telah dipertimbangkan dalam kerja-kerja ini, iaitu, respon pengguna ke profil permintaan mereka sendiri, respon pengguna ke profil generasi PV dan tindak balas pengguna dioptimumkan atas permintaan yang difasilitasi oleh grid pintar. Kaedah untuk menjana bentuk DR optimum untuk 2,000 pengguna individu juga telah dicadangkan dan dilaksanakan dengan tujuan untuk meningkatkan rangkaian faktor beban. Analisis komprehensif DR ini akan membuatkan kesimpulan yang lebih bermakna dan mantap. Hasil kajian menunjukkan bahawa aplikasi DR di peringkat pengguna boleh memudahkan integrasi sistem PV solar. Manfaat DR termasuk mengurangkan kehilangan rangkaian dan meningkatkan tahap rangkaian penggunaan aset. Akhir sekali, hasil kajian ini telah memfailkan paten untuk ciptaan Internet-of-Things berdasarkan kawalan respon permintaan dan sistem pemantauan tenaga yang boleh digunakan sebagai pemangkin untuk aplikasi permohonan respon dalam persekitaran sebenar.*

## ACKNOWLEDGEMENTS

Firstly, I would like to express my greatest gratitude to my supervisor, Assoc. Prof. Dr. Gan Chin Kim, for his constant guidance and support during the PhD study, and more especially for his patience and honesty on difficult occasions when nothing seemed to make sense, which kept me motivated to make the most out of my PhD.

Many thanks to my co-supervisor, Assoc. Prof. Ir. Dr. Rosli Bin Omar for his advices and supports during years of study in Malaysia. I would like to acknowledge the support from the UTeM scholarship (Zamalah scheme) and Ministry of Higher Education Malaysia under grant (No. FRGS/1/2015/TK04/FKE/02/F00255) for funding this PhD research. I would also like to express my greatest gratitude to Datuk Prof. Dr. Mohd Ruddin bin Ab. Ghani for his guidance, recommendation and motivation to me in completing this work.

A very special acknowledgment goes to my family, for their endless love, and for giving me all of the encouragement, advice and support I could need. I am grateful to Father, Mother, Mr. Eghbal, Ms. Faranak and also to Hesam, Sara, Hadi and Mina for their continued belief in me.

Finally, and most importantly, thank you to my best friend and beloved wife, Ladan Asadi, for always being for me. Arriving at this point would not have been possible without the stability and love she provided me, and thus, I will be forever grateful to her.



## TABLE OF CONTENTS

	<b>PAGE</b>
<b>DECLARATION</b>	
<b>APPROVAL</b>	
<b>DEDICATION</b>	
<b>ABSTRACT</b>	<b>i</b>
<b>ABSTRAK</b>	<b>ii</b>
<b>ACKNOWLEDGEMENTS</b>	<b>iii</b>
<b>TABLE OF CONTENTS</b>	<b>iv</b>
<b>LIST OF TABLES</b>	<b>viii</b>
<b>LIST OF FIGURES</b>	<b>x</b>
<b>LIST OF APPENDICES</b>	<b>xv</b>
<b>LIST OF ABBREVIATIONS</b>	<b>xvi</b>
<b>LIST OF SYMBOLS</b>	<b>xix</b>
<b>LIST OF PUBLICATIONS</b>	<b>xxi</b>
<b>LIST OF AWARDS</b>	<b>xxiii</b>
<b>LIST OF PATENT</b>	<b>xxiv</b>
<b>CHAPTER</b>	
<b>1. INTRODUCTION</b>	<b>1</b>
1.1 Background	1
1.2 Problem Statements	6
1.3 Objectives of Research	8
1.4 Scope of the Study	9
1.5 Contributions of Research	11
1.6 Structure of the Thesis	12
<b>2. LITERATURE REVIEW</b>	<b>15</b>
2.1 Introduction	15
2.2 Power Distribution Networks in Malaysia	15
2.2.1 Transformer Ratings in Malaysia	16
2.2.2 Conductor Ratings in Malaysia	16
2.2.3 Steady-State Supply Voltage Requirement in Malaysia	18
2.2.4 Demand Estimation	18
2.3 Distribution Network Modelling	20
2.3.1 Allocation of Loads and Consumers	22
2.3.2 Substation Siting and Sizing with Feeder Routing	22
2.3.3 Distributed Generation and Capacitor Allocation	25

2.3.4	Challenges and Opportunities of Distributed Generation Integration	29
2.4	Methods of Distribution Network Planning	32
2.4.1	Heuristic and Meta-Heuristic Methods	33
2.5	Demand Response Development	38
2.5.1	Demand Response Applications and Programs in Distribution	40
2.5.2	Demand Side Management Strategies	44
2.5.3	Demand Response Programs	48
2.5.4	Barriers of Demand Response	49
2.5.5	Recent Patents of DR Application and Products	50
2.6	Summary	53
<b>3.</b>	<b>SYSTEM DESIGN</b>	<b>56</b>
3.1	Introduction	56
3.1.1	Distribution Network Modelling	56
3.1.2	Optimum Distribution Network Planning	57
3.1.3	DR Application with Presence of PV Integration	57
3.2	MV and LV Distribution Network Modelling	58
3.2.1	Fractal Network Model Generation	61
3.2.2	Network Branch Connection using Branching Rate (BR) Concept	66
3.2.3	Optimum Feeder Routing for MV Level	67
3.3	Optimum Distribution Transformer Siting and Sizing using PSO and MST	70
3.3.1	Initialization	71
3.3.2	Optimum Distribution Substations Siting and Sizing using PSO	71
3.3.3	OpenDSS File Generation and Power Flow Calculation	78
3.3.4	Optimum Substation Placement	78
3.3.5	Problem Definition and Formulation for Substation Placement	79
3.3.6	Problem Formulation for Optimum Substation Allocation	82
3.4	Optimum Distributed Generations Placement and Sizing	85
3.4.1	Impacts of DGs on Distribution Networks	86
3.4.2	Objective Function and Problem Formulation	87
3.5	Optimum Capacitor Placement and Sizing	89
3.5.1	Problem Definition and Formulation of Capacitor's Allocation	90
3.5.2	Proposed Methodology for Optimum Capacitor Allocation	93
3.6	Parametric PV and DR Assessment	96
3.6.1	Distribution Network Modelling	98

3.6.2	Demand Modelling	100
3.6.3	Solar PV System Modelling	104
3.6.4	Demand Response Modelling and Optimization	106
3.7	Product Development for Demand Monitoring and Load Management	110
3.7.1	Building Demand Response Automated System (Wired Product)	112
3.7.2	Detailed Description of the Invented System	120
3.7.3	My-IoT Powered System (Wireless Product)	128
3.8	Summary	134
<b>4.</b>	<b>RESULTS AND DISCUSSION</b>	<b>137</b>
4.1	Introduction	137
4.1.1	Distribution Network Modelling	137
4.1.2	Optimum Network Planning	137
4.1.3	DR Application with Presence of PV Integration	138
4.2	Results of Network Model Generation using Fractal, PSO and MST	138
4.2.1	Distribution Network Modelling Software Tool (DNMS)	145
4.3	Result of Distribution Substation and Transformer Siting and Sizing	150
4.4	Results of Optimum DGs Allocation	157
4.5	Results of Capacitors Placement and Sizing for Different Case Studies	162
4.5.1	Test system - IEEE 13 node	162
4.5.2	Test system - IEEE 123 node	167
4.5.3	Integrating Optimum Capacitor and DG Allocation with DNMS	172
4.6	Results of Parametric Evaluation of DR with presence of PV	174
4.6.1	The Establishment of Base Case Networks	174
4.6.2	Case study #1 (Consumer response to their own demand profile)	178
4.6.3	Case study #2 (Consumer response to PV generation profile)	181
4.6.4	Case study #3 (Optimized Demand Response)	183
4.7	Results of Prototype Development (Test Field Implementation)	185
4.8	Summary	187
<b>5.</b>	<b>CONCLUSION</b>	<b>189</b>
5.1	Introduction	189
5.2	Summary of Research	189
5.3	Attainment of Research Objectives	191
5.3.1	Modelling the Distribution Network for Both MV and LV Levels	191
5.3.2	Investigating the Impacts of PV and DR on Distribution Network	193

5.3.3	Generating Optimum DR Pattern for Individual Customer	194
5.3.4	Proposal of Method and Development of Product for DR	194
5.4	Significance of Research Findings	195
5.5	Recommendation for Future Works	196
<b>REFERENCES</b>		<b>198</b>
<b>APPENDICES</b>		<b>222</b>

## LIST OF TABLES

<b>TABLE</b>	<b>TITLE</b>	<b>PAGE</b>
1.1	Installed Capacities of Grid-Connected FiT Renewable Energy Projects (MW)	4
2.1	Utilized transformer in Malaysian distribution network	16
2.2	PVC, ABC and Bare Al conductor ratings (TNB, 2013)	17
2.3	XLPE and PILC conductors ratings (TNB, 2013)	17
2.4	Voltage level fluctuation limits under normal conditions	18
2.5	Steady-State voltage fluctuation limits under contingency condition	18
2.6	Maximum demand (M.D) for domestic consumer sub-classes or premises	19
2.7	Range of maximum demand (M.D) for shop houses	20
2.8	Different types of grid-connected PV systems (TNB, 2013b)	30
2.9	Demand side management techniques.	47
2.10	Demand response program types	49
2.11	Summary of the key references and research gaps	55
3.1	The transformers and substations cost	77
3.2	The objective function variables	78
3.3	Possible choice of capacitor size and cost	92
3.4	LV network characteristic	99
3.5	Residential MD for domestic consumer sub-classes in urban area	101
3.6	Commercial maximum demand for types of shop-houses in urban area	102
3.7	Solar PV systems for data collection	105

3.8	The probability of PV system installation in Malaysia, 2012-2016	105
4.1	Comparison between urban and rural network i	141
4.2	Consumer Demand Data	152
4.3	PSO progress in different number of substations	155
4.4	Selected size of MV/LV (11/0.4kV) transformers after optimization	156
4.5	Selected size of secondary transformer (33/11) kV after optimization	157
4.6	Comparison between standard and optimum case	159
4.7	Transformer taps changer comparison	159
4.8	Voltage Profile before Capacitor, Standard Case and Optimum Allocation	164
4.9	Real power losses in IEEE 13 node test system	166
4.10	The results of IEEE 13 node test system in terms of voltages, losses	167
4.11	Load data for new case	169
4.12	The results of IEEE 123 node test system in terms of voltages and losses	172

## LIST OF FIGURES

FIGURE	TITLE	PAGE
1.1	Malaysian Government Green Development Plan (TNB Handbook, 2015)	2
1.2	Primary Energy Supply (Ministry of Natural Resources and Environment Malaysia, 2013)	2
1.3	Primary energy supply and final energy consumption in Malaysia (Ministry of Natural Resources and Environment Malaysia, 2013)	3
1.4	Distribution of received FiA applications based on RE installed capacities as of 2015, for quota offered up to 2018, except for solar PV (SEDA, 2015)	4
1.5	Distribution of cumulative FiA applications that have achieved commercial operation according to installed capacities as of end 2015, for quota offered up to 2018, except for solar PV (SEDA, 2015)	4
2.1	The aggregation network modelling	21
2.2	Proposed smart grid architecture for future distribution network	43
2.3	Demand side management techniques (Logenthiran, Srinivasan, & Shun, 2012)	46
2.4	Intelligent trading/metering/billing system (P. Wang et al., 2010)	48
2.5	The key factors of demand response that featured in proposed prototype	52
3.1	The methodology of network creation using Fractal-Based, BR and MST	61
3.2	New consumer settlement (Gan, 2011)	62
3.3	Example of function $k = \text{function}(l)$ for values $t_1=5$ and $t_2=50$ .	64

3.4	LV network creation flowchart	65
3.5	Examples of generated consumers' settlement points: a) urban, and b) rural	66
3.6	Consumer settlement points with high and low branching rate concept	67
3.7	Main flowchart of optimum MV feeder routing using modified MST algorithm	69
3.8	The proposed flowchart of optimum distribution transformer siting and sizing	70
3.9	Particle movement principle in PSO algorithm	72
3.10	Proposed flowchart of optimum substation placement and feeder routing	80
3.11	Flowchart of steps to optimize substation placement using PSO	82
3.12	Two-bus networks	86
3.13	The proposed algorithm for optimum capacitor placement and sizing problem	94
3.14	Example of an urban LV network	100
3.15	Individual and aggregated residential demand profiles	102
3.16	Individual and aggregated commercial demand profiles	103
3.17	Aggregated demand profiles	103
3.18	Actual PV generation profiles for three different PV plants	106
3.19	Proposed algorithm for demand response application	110
3.20	The overall concept of BDRAS and My-IoT Powered systems	111
3.21	Flowchart for BDRAS	112
3.22	The software structure of BDRAS	114
3.23	The controller set box of BDRAS	114
3.24	Hardware prototype of BDRAS	116
3.25	Android application for BDRAS version 1.0	117
3.26	The final prototype of BDRAS	118
3.27	The show case implementation	118
3.28	Android application for BDRAS version 2.0	119



3.29	Diagram of an automated power regulation and management system	120
3.30	The information exchange for plurality of sources	122
3.31	The main diagram of load shifting between flexible and non-flexible loads	124
3.32	The hierarchically flowchart of proposed method and application	126
3.33	The UTeM-IoT Mains	129
3.34	The UTeM-IoT Plugs	129
3.35	The UTeM-IoT Switch	130
3.36	The conceptual diagram of UTeM-IoT Plug in building	131
3.37	The proposed smart demand response of My-IoT Powered System	132
3.38	The snapshot of the web-portal for monitoring/control the UTeM-IoT Plug	133
3.39	The snapshot of the web-portal for monitoring the UTeM-IoT Mains	134
4.1	Percentage of violated voltages based on numbers of substations	140
4.2	The probability of minimum voltages for the case of 15MVA/km <sup>2</sup>	140
4.3	Urban distribution network model (Malaysia context) with 2000 consumers	142
4.4	Power losses for case of 15MVA/km <sup>2</sup> with 52 substations and 100 networks	142
4.5	Rural distribution network model (Malaysia context) with 2000 consumers	143
4.6	Probability of Distribution of power losses for case of 15MVA/km <sup>2</sup>	143
4.7	Examples of urban distribution network model (Malaysia context)	144
4.8	Examples of different rural distribution network model (Malaysia context)	144
4.9	Distribution network modelling software tool	146
4.10	Optimum substation placement after PSO optimization	147
4.11	Voltage drop in distance before applying the PSO optimization	148
4.12	Voltage drop in distance after applying the PSO optimization	148
4.13	Voltage of each buses before applying the PSO optimization	149
4.14	Voltage of each buses after applying the PSO optimization	149

4.15	Power losses per each buses f before applying the PSO optimization	150
4.16	Power losses per each buses after applying the PSO optimization	150
4.17	a) Consumers and candidate substation, and b) Selected MV/LV substations	151
4.18	Obtained network after optimum feeder routing for LV and MV in 500	153
4.19	Voltage drop based on consumer and substations distances	154
4.20	IEEE 34 buses diagram	158
4.21	Voltage comparison before and after DG allocation	160
4.22	Losses minimization	161
4.23	Voltage drop in distance a) before DG, and b) after DG allocation	161
4.24	The IEEE 13 node test case	162
4.25	IEEE 123 Node Test Feeders (Kersting, 1991)	168
4.26	Voltage profile of IEEE 123 node standard case	168
4.27	Voltage profile of 123 test system before capacitor optimization	170
4.28	Voltage profile of new case 123 node test system after capacitor allocation	171
4.29	A snapshot of the distribution network modelling and planning software tool	173
4.30	Minimum network voltage for 100 networks with percentage of violated cases	175
4.31	Single line diagram of the selected network (42 distribution substations)	176
4.32	Breakdown of cable sizes for 100 networks	177
4.33	Breakdown of transformer ratings for 100 networks	177
4.34	Aggregated demand and PV generation profiles	179
4.35	Total network losses for Case #1	179
4.36	Network load factor for Case #1	180
4.37	Total network losses for Case #2	182
4.38	Network load factor for Case #2	182
4.39	Total network losses for Case #3	184

4.40	Network load factor for Case #3	184
4.41	Test field in building that installed with grid-connected solar system (3.5kW)	185
4.42	The load profile of 10 days residential consumer	186
4.43	The PV generation profile of 10 days residential consumer	186

## LIST OF APPENDICES

APPENDIX	TITLE	PAGE
A	TEST FIELDS	222
B	SCRIPTS	239
C	PUBLICATIONS	260
D	AWARDS	269

## LIST OF ABBREVIATIONS

AC	Alternating Current
ACO	Ant Colony Optimization
AVR	Automatic Voltage Regulator
ABC	Aerial Bundled Cable
AI	Artificial Intelligence
ADMD	After Diversity Maximum Demand
BDRAS	Building Demand Response Automated System
BR	Branching Rate
BESS	Battery Energy Storage System
CLs	controllable loads
CPP	Critical-Peak Pricing
CREST	Centre for Renewable Energy Systems Technology
DC	Direct Current
DR	Demand Response
DG	Distributed Generation
DSOs	Distribution System Operators
DRMS	Demand Response Management System
DERs	Distributed Energy Resources
DMS	Demand Management System
DSM	Demand Side Management

DSO	Distribution System Operator
DLC	Direct Load Control
DNMS	Distribution Network Modelling Software Tool
EMS	Energy Management System
FiT	Feed-in Tariff
GA	Genetic Algorithm
GIS	Geographical Information System
HIT	Heterojunction with Intrinsic Thin-layer
IEEE	Institute of Electrical and Electronic Engineering
IoT	Internet of Things
HIS	Improved Harmony Search
ILC	Interruptible Load Contract
ITMBS	Intelligent Trading/Metering/Billing System
LV	Low Voltage
MST	Minimum Spanning Tree
MV	Medium Voltage
MD	Maximum demand
MGO	Micro-Grid Operator
MG	Micro-Grid
NFE	Number of Function Evaluation
OpenDSS	Open Source Distribution System Simulation
PSO	Particle Swarm Optimization
PV	Photovoltaic
PVC	Ploy Vinyl Chloride
PILC	Paper Insulated Lead Covered

PDF	Probability Distribution Function
PMCB	Power Management Controller Box
RNM	Reference Network Model
RTP	Real-Time Pricing
SA	Simulated Annealing
SEDA	Sustainable Energy Development Authority of Malaysia
TNB	Malaysian utility service (Tenaga Nasional Berhad)
TS	Tabu Search
TOU	Time-Of-use
UKGDS	UK Generic Distribution System
XLPE	Cross-Linked Polyethylene

## LIST OF SYMBOLS

$OF$	Objective Function
$NLF$	New load factor
$DLF$	Desired load factor
$P_{losses}$	Total power losses in $kWh$ per day
$nV_{violated}$	Number of buses that violate the statutory voltage
$NLP$	New load factor
$LP$	Load profile for a day
$\alpha$	Load factor coefficient
$\beta$	Total power losses coefficient
$\gamma$	Voltages violation coefficient
$npc$	Number of the non-participating consumers in the DR program
$pc$	Number of participating consumers in the DR program
$LF$	Load Factor
$LP'_j$	Load profile before DR participation for consumer $j$
$LP_{t+1j}$	Load profile after DR participation for consumer $j$
$Cu$	Copper
$Al$	Aluminium
$kWp$	Kilo watt
ktoe	kilotonne of oil equivalent
$CL$	Total losses cost for a study year