

**SECURITY OF SUPPLY IMPROVEMENT IN  
HIGH VOLTAGE DISTRIBUTION SYSTEMS**

**SAODAH BINTI OMAR**

**PhD**

**March 2018**

# **Security of Supply Improvement In High Voltage Distribution Systems**

**By**

**Saodah Omar**

Dissertation submitted to Cardiff University of Engineering  
Cardiff University, in partial fulfilment  
of the requirements for the degree of  
Doctor of Philosophy  
2018

Advisory Committee:  
Professor Huw Griffiths, First Supervisor  
Dr Stephen Robson, Second Supervisor  
Professor Manu Haddad, Third Supervisor

## **DECLARATION**

This work has not been submitted in substance for any other degree or award at this or any other university or place of learning, nor is being submitted concurrently in candidature for any degree or other award.

Signed .....(Candidate)      Date .....

### **STATEMENT 1**

This thesis is being submitted in partial fulfilment of the requirements for the degree of PhD.

Signed .....(Candidate)      Date .....

### **STATEMENT 2**

This thesis is the result of my own independent work/investigation, except where otherwise stated.

Other sources are acknowledged by explicit references. The views expressed are my own.

Signed .....(Candidate)      Date .....

### **STATEMENT 3**

I hereby give consent for my thesis, if accepted, to be available for photocopying and for inter-library loan, and for the title and summary to be made available to outside organisations.

Signed .....(Candidate)      Date .....

## ABSTRACT

In this thesis, algorithms are proposed to improve electricity distribution network supply restoration. The practical implementation of such algorithms relies on the presence of fully automated switches located at a certain number of network substations. The algorithm has the capability to restore a maximum number of customers if an outage occurs on any section of the test network. Since a very high cost is usually involved in the implementation of the fully automated system, a second algorithm was introduced with the aim of reducing the number and location of required switches. Discrete Particle Swarm Optimisation (DPSO) was employed to identify optimal placement of a limited number of remotely operable protective devices as well as the optimal sequence of reconfiguration and restoration of the supply. The reliability of the network was determined by calculating the number of possible post-outage restored customers, considering both upstream and downstream restorations. In the selection of optimal switching sequences, network voltage and current constraints were also considered to ensure that the identified restoration was viable. Further, the proposed algorithm considered the failure rate on each section of the network in arriving at the proposed optimal locations of switches. The developed DPSO-based algorithm and Brute Force is described and applied to real 11kV urban, semi-urban and rural distribution networks each with a different number of feeders and substations. These proposed algorithms have the capability to search for an unlimited number and locations of switches pairs or clusters for all networks (urban, semi-urban and rural) with optimal locations and number of Remotely Operable Switch Pairs (ROS). It was demonstrated that less than half of fully automated switches are needed to restore more than 95% of customers for each case study network. A significant reduction in investment cost of protective devices could be achieved by applying the proposed algorithm and at the same time improving and optimising the reliability of 11kV distribution networks.

## ACKNOWLEDGEMENTS

Firstly, I would like to thank to God for giving me the opportunity to embark on my PhD and completing this long and challenging journey successfully. My gratitude and appreciations go to my supervisors Prof Huw Griffiths, Dr Stephen Robson and Prof Manu Haddad for their continuous helps and guidance and having the vision to perceive the principles in supporting this research. Without them, this thesis would be impossible to be produced.

My appreciation goes to my loving mother Sharifah Binti Anuar for her Do'A and encouragement that has never ended. Special thanks to my husband, Dahalan bin Mat Alin for his understanding and support. Also, superior thanks to my sisters who are Habibah Binti Omar, Siti Hajar Binti Omar and Nurfatim Izati Binti Omar for their strong supports.

Finally, this thesis is dedicated to the loving memory of my very dear late father for the vision and determination in educating me. This piece of victory is dedicated to you. Alhamdulillah.

# CONTENT

<b>DECLARATION</b>	<b>II</b>
<b>ABSTRACT</b>	<b>III</b>
<b>ACKNOWLEDGEMENTS</b>	<b>IV</b>
<b>CONTENT</b>	<b>V</b>
<b>LIST OF TABLES</b>	<b>IX</b>
<b>LIST OF FIGURES</b>	<b>XII</b>
<b>LIST OF APPENDICES</b>	<b>XVIII</b>
<b>LIST OF PUBLICATIONS</b>	<b>XIX</b>
<b>LIST OF ABBREVIATIONS</b>	<b>XX</b>
<b>MATHEMATICAL SYMBOLS</b>	<b>XXI</b>
<b>CHAPTER 1 INTRODUCTION</b>	<b>1</b>
1.1 Challenges to Improving The Reliability of Electricity Distribution Networks	1
1.1.1 Reliability Indices	3
1.1.2 Overview of The UK Electricity Distribution System	4
1.1.3 Regulatory Requirements	6
1.1.4 Electricity Distribution Networks: Types and Topology	7
1.1.5 Failure Rates In Electricity Networks	11
1.1.6 Current State of Network Automation	13
1.1.7 Current Research, New Technologies and Opportunities	14
1.1.8 Economic Considerations	17
1.2 Aims of The Research Work	17
1.3 Contributions of The Thesis	20
1.4 Thesis Structure	22
<b>CHAPTER 2 REVIEW OF AUTOMATIC SUPPLY RESTORATION TECHNIQUES FOR ELECTRICITY DISTRIBUTION NETWORKS</b>	<b>24</b>
2.1 Automated Supply Restoration: A Review	24
2.1.1 Background	24

2.1.2	Historical Technique	27
2.1.3	Automated Supply Restoration In The Era of Smart Grids	28
2.1.4	AURA-NMS Project	36
2.1.5	American FLISR Project	38
2.1.6	Future Trends: Microgrids and Distributed Generation	40
2.2	The Optimisation Problem	41
2.2.1	Possible Locations of Remotely Operable Switch Pairs	42
2.2.2	Brute Force Methods	44
2.2.3	Heuristic Methods	46
2.2.4	Genetic Algorithms	47
2.2.5	Simulated Annealling	48
2.2.6	Mixed Integer Linear Programming	48
2.2.7	Particle Swarm Optimisation Selection	49
2.2.8	Discrete Particle Swarm Optimisation (DPSO)	55
2.3	Review of Current Electrical Network Technology: State of The Art and Future Requirements	57
2.3.1	SCADA Systems	58
2.3.2	Intelligent Devices	58
2.3.3	Communication Requirements	63
2.4	Cost Benefits Analysis	68
2.5	Conclusion	73
<b>CHAPTER 3 OPTIMISATION OF LOCATION AND NUMBER OF PROTECTIVE DEVICES</b>		<b>75</b>
3.1	Introduction	75
3.2	Problem Formulation – Objective Function	76
3.2.1	Customers Restored Assessment For A Single ROS Pair	79
3.2.2	Failure Rate ( $P_{fi}$ )	82
3.2.3	Restoration Assessment For Two ROS Pairs	84
3.2.4	Unlimited Optimal Locations	88
3.2.5	One Branch Objective Function	90
3.2.6	Pre-allocation Matrix	97
3.2.7	Comparison of Feeder Possible Location Options or ROS Pairs	99
3.2.8	Computational Time	102

3.2.9	Discrete Particle Swarm Optimisation and Brute Force Method Selection	105
3.3	The Proposed Algorithm to Determine Optimal Locations and Numbers of The ROS Pairs	106
3.3.1	DPSO Parameter Setting	108
3.3.2	Network Recognition by DPSO and Brute Force	111
3.3.3	Application of Objective Function in DPSO and Brute Force	112
3.4	Software Development	113
3.5	Optimization of Network ULR and DLR For A Given Number and Location of ROS Pairs Using NEPLAN and NPL Software For Fully Automated System	115
3.6	Conclusion	121
<b>CHAPTER 4 DEVELOPMENT OF CASE STUDY NETWORK MODELS AND IMPLEMENTATION OF PROPOSED ALGORITHM</b>		<b>122</b>
4.1	Introduction	122
4.2	DPSO and Brute Force Implementation for Optimal Locations of ROS Pairs– Data Reading	124
4.3	NEPLAN Program Simulations To Obtain Voltage and Current Profiles	129
4.3.1	Fully Automated Case	130
4.3.2	DPSO or Brute Force Implementation For Limited Optimally Placed ROS Pair	135
4.4	Conclusion	138
<b>CHAPTER 5 DPSO AND BRUTE FORCE APPLICATION ON THREE NETWORKS</b>		<b>139</b>
5.1	Introduction	139
5.2	Effect of Remotely Operable Switch Increase	139
5.2.1	Feeder Analysis	140
5.2.2	Overall Feeder Performance	146
5.2.3	Brute Force Performance Analysis	149
5.3	DPSO Compared With Brute Force Method	154
5.4	DPSO Application For Network Wide Studies	159
5.5	Economic Consideration of DPSO	163



5.6	Conclusion	165
<b>CHAPTER 6 VOLTAGE AND CURRENT PROFILES AND LIMITS</b>		<b>166</b>
6.1	Introduction	166
6.2	Pre-Outages	166
6.3	Post-Outage Networks With DLR	171
	6.3.1 Fully Automated System	172
	6.3.2 Application of ROS Pairs by Brute Force	181
6.4	conclusion	186
<b>CHAPTER 7 GENERAL CONCLUSION AND FUTURE WORK</b>		<b>188</b>
7.1	DPSO Algorithm and Brute Force Method For Optimal Locations Of ROS Pairs	188
7.2	Restoration Algorithm	189
7.3	Future Work	190
<b>REFERENCES</b>		<b>191</b>
<b>APPENDICES</b>		<b>201</b>

## LIST OF TABLES

<i>Table 1-1: Distribution network failure rate lines and cables [10][15]</i>	12
<i>Table 1-2: Failure rate for different distribution system plant [15]</i>	12
<i>Table 1-3: Qualitative comparison of GA and PSO applied to power systems optimisation problems [32]</i>	16
<i>Table 2-1: Taxonomy of switch placement literature</i>	30
<i>Table 2-2: Possible locations available if searching for one or two optimal locations of ROS pairs for eight number of substations</i>	46
<i>Table 2-3: Currently available intelligent switch controllers</i>	61
<i>Table 2-4: Summary of communication system development activities for electric utilities [115]</i>	66
<i>Table 2-5: IIS performance [11]</i>	69
<i>Table 2-6: Fault rates including CI and CML values [124]</i>	71
<i>Table 3-1: Summary of load restoration of each section on Feeder A applying ULR and DLR</i>	82
<i>Table 3-2: Probability of failure rate per year for example feeder</i>	84
<i>Table 3-3: Summary of restoration of each section F7 applying ULR and DLR</i>	88
<i>Table 3-4: Cable length for each section</i>	90
<i>Table 3-5: Failure rate per year for each cable section</i>	90
<i>Table 3-6: DPSO Parameters for Different Branches of Feeder</i>	110
<i>Table 4-1: Characteristic of the three real networks chosen for the case studies</i>	124
<i>Table 4-2: NOP termination for Type 1 and 2 feeders</i>	126
<i>Table 4-3: NOP termination for ‘type 3’</i>	127
<i>Table 4-4: Characteristics of Feeder 12 of the urban network (Figure 4-1)</i>	127
<i>Table 4-5: The line data interconnection of Feeder 12</i>	128
<i>Table 4-6: Number of customers at each substation on Feeder 14</i>	131

<i>Table 4-7: Summary of the restored customers of the ULR and DLR</i>	135
<i>Table 4-8: Details of feeder length and number of customers on each substation</i>	137
<i>Table 4-9: Summary of expected customers restored with two optimal locations of the ROS pairs</i>	138
<i>Table 5-1: Characteristic of feeder 1 until 4 for Urban network</i>	141
<i>Table 5-2: Number of optimal locations of ROS pairs restored customers for Feeders 1 – 4 for Urban network (£1000 switch cost)</i>	141
<i>Table 5-3: Number of optimal locations of ROS pairs restored customers for Feeders 3 – 4 for Urban network (£1000 switch cost)</i>	142
<i>Table 5-4: Characteristic of Semi-Urban network for Feeder 1 and 2</i>	143
<i>Table 5-5: Characteristic of Semi-Urban network for Feeder 3 and 4</i>	143
<i>Table 5-6: Number of optimal locations of ROS pairs restored customers for Feeders 1 – 2 for Semi-Urban network (£1000 switch cost)</i>	143
<i>Table 5-7: Number of optimal locations of ROS pairs restored customers for Feeders 3 – 4 for Semi-Urban network (£1000 switch cost)</i>	144
<i>Table 5-8: Characteristic of Rural network for Feeder 1</i>	144
<i>Table 5-9: Characteristic of Rural network for Feeder 2</i>	145
<i>Table 5-10: Characteristic of Rural network for Feeder 3 and 4</i>	145
<i>Table 5-11: Number of optimal locations of ROS pairs restored customers for Feeders 1 – 2 for Rural network (£1000 switch cost)</i>	145
<i>Table 5-12: Number of optimal locations of ROS pairs restored customers for Feeders 3 – 4 for Rural network (£1000 switch cost)</i>	146
<i>Table 5-13: Priority feeder for Urban network with increasing number of ROS pairs</i>	147
<i>Table 5-14: Priority feeder for the Semi-Urban network with increasing number of ROS pairs</i>	148
<i>Table 5-15: Priority feeder for Rural network with increasing number of ROS pairs</i>	148
<i>Table 5-16: Details of the performance of the Urban network with the number of restored customers and simulation time for each feeder</i>	151
<i>Table 5-17: The details of the performance of the Semi-Urban network with the number of restored customers and simulation time for each feeder</i>	152

<i>Table 5-18: Summary of the total number of restored customers by using the Brute Force for each feeder in the Rural network</i>	<i>153</i>
<i>Table 5-19: Optimal locations and number by DPSO and net benefits of adding ROS pairs for multiple feeders (3 feeders with huge number of substations)</i>	<i>159</i>
<i>Table 5-20: Optimal locations and number by DPSO and net benefits of adding ROS pairs for multiple feeders (13 feeders from different networks)</i>	<i>161</i>
<i>Table 5-21: Effect on increment of ROS pair cost on a feeder (sensitivity of analysis)</i>	<i>163</i>
<i>Table 5-22: Net benefits of adding ROS pairs using DPSO on selected feeder (Urban Network)</i>	<i>164</i>
<i>Table 5-23: Net benefits of adding ROS pairs using DPSO on selected feeder (Rural Network)</i>	<i>165</i>
<i>Table 6-1: Summary of restoration of the Feeder 14 loads employing the ULR (via Feeder 14) and DLR (via Feeder 20 and Feeder 26)</i>	<i>180</i>
<i>Table 6-2: Number of customers at each substation on Feeder 14</i>	<i>181</i>
<i>Table 6-3: Overall restoration statistics</i>	<i>181</i>
<i>Table 6-4: Number of customers on each substation for F7</i>	<i>182</i>
<i>Table 6-5: Optimal locations of ROS pairs selected by Brute Force for F7</i>	<i>182</i>
<i>Table 6-6: Summary of restoration of the Feeder 7 loads employing the ULR (via Feeder 14) and DLR (via Feeder 23) with optimal locations and number of ROS pairs</i>	<i>183</i>
<i>Table 6-7: ULR and DLR F7 via F23 by applying the optimal locations of ROS pairs by Brute Force</i>	<i>184</i>

## LIST OF FIGURES

<i>Figure 1-1: Typical reliability investment cost curve [2]</i>	1
<i>Figure 1-2: Evaluation of reliability cost worth [2]</i>	2
<i>Figure 1-3: Example of network with ROS pairs located at each substation on Feeder A</i>	9
<i>Figure 1-4: Optimal number and location of ROS pairs</i>	11
<i>Figure 1-5: Process chart for the fault location, isolation and service restoration [17]</i>	13
<i>Figure 1-6: The proposed algorithm for reliability improvement</i>	18
<i>Figure 1-7: Flow chart showing MATLAB and NEPLAN/NPL software relationship</i>	19
<i>Figure 2-1: Typical 11kV network faulted without ASR</i>	25
<i>Figure 2-2: 11kV typical network with reclosers and sectionalisers [33]</i>	26
<i>Figure 2-3: Improvement in reliability with fully automated for distribution network [33]</i>	27
<i>Figure 2-4: Base case with sectionalising switches on both ends of each primary section [54]</i>	31
<i>Figure 2-5: No sectionalising switches on the primary sections [54]</i>	32
<i>Figure 2-6: 11kV radial test network with connected DG [78]</i>	37
<i>Figure 2-7: 33kV interconnected test network with distributed generation [78]</i>	37
<i>Figure 2-8: FLISR operations [80]</i>	39
<i>Figure 2-9: Possible locations of remotely operable switch pairs</i>	43
<i>Figure 2-10: Possible combinations with increasing number of ROS pairs</i>	44
<i>Figure 2-11: Flow chart for Brute Force method</i>	44
<i>Figure 2-12: Simple Network</i>	45
<i>Figure 2-13: Velocity and position update for a particle in a two-dimensional search space [97]</i>	50

<i>Figure 2-14: Velocity and position update for multi-particle in Gbest PSO [97]</i>	50
<i>Figure 2-15: Representation of each particle in DPSO</i>	55
<i>Figure 2-16: REC615 switch controller by ABB [114]</i>	60
<i>Figure 2-17: Traditional hardwired SCADA architecture [112]</i>	62
<i>Figure 2-18: Transducer in a typical SCADA</i>	62
<i>Figure 2-19: Merger of SCADA and P&amp;C within substation [112]</i>	63
<i>Figure 2-20: Overall communication network architecture for electrical system automation [115]</i>	65
<i>Figure 2-21: Number of customer interruptions per 100 customers on the network [11]</i>	68
<i>Figure 2-22: Durations of customer interruptions [11]</i>	69
<i>Figure 3-1: Single feeder network with 18 substations</i>	77
<i>Figure 3-2: Customers bounded by two switches</i>	77
<i>Figure 3-3: One-line diagram of Feeder A and B of network reconfiguration if single ROS pairs placed at S/S 3</i>	79
<i>Figure 3-4: Number of expected customers restored if an outage occurs at Section (i) or (ii) or (iii)</i>	80
<i>Figure 3-5: Calculate number of expected customers restore if an outage at section (iv) or (v) or (vi) or (vii)</i>	81
<i>Figure 3-6: Feeder with cable section length</i>	83
<i>Figure 3-7: One-line diagram of a feeder of a network reconfiguration during ULR and DLR with an optimal location of two pairs of ROS pairs</i>	85
<i>Figure 3-8: Single line diagram for a feeder with an outage at Section i or ii or iii</i>	86
<i>Figure 3-9: Single line diagram for a feeder with an outage at Section iv or v</i>	87
<i>Figure 3-10: Single line diagram for a feeder with an outage at Section vi or vii</i>	87
<i>Figure 3-11: Single line feeder with one branch and a ROS pair located at S/S2</i>	90
<i>Figure 3-12: Single line diagram for network with feeder plus one branch with two ROS pairs</i>	92

<i>Figure 3-13: Possible combinatorial distributions of ROS pairs on a feeder</i>	95
<i>Figure 3-14: Example of a feeder with two branches</i>	96
<i>Figure 3-15: Example of a feeder with three branches</i>	97
<i>Figure 3-16: Single line feeder</i>	98
<i>Figure 3-17: The number of possible locations for ROS pairs increases exponentially with the number of ROS pairs and feeder length (total number of substations in a feeder)</i>	100
<i>Figure 3-18: Zoom in from Figure 3-17 for possible location with network size 20 and below</i>	101
<i>Figure 3-19: Simulation time increased with increasing the number of ROS pairs and number of substations</i>	103
<i>Figure 3-20: Simulation time increased with increasing the number of ROS pairs and feeder length (with pre-allocation matrix included)</i>	104
<i>Figure 3-21: Simulation time compared between Brute Force method with and without pre-allocation matrix (a) 1 ROS pair (b) 2 ROS pairs (c) 3 ROS pairs (d) 4 ROS pair (e) 5 ROS pairs (f) 6 ROS pairs</i>	105
<i>Figure 3-22: DPSO searching the optimal locations of a pair of ROS pairs</i>	108
<i>Figure 3-23: DPSO algorithm for single feeder network</i>	111
<i>Figure 3-24: The Flow of the Calculation of the ULR and DLR Customers for One Location</i>	113
<i>Figure 3-25: Overall algorithms using MATLAB programming language and NEPLAN/NPL program code</i>	115
<i>Figure 3-26: Example of fully automated urban network</i>	117
<i>Figure 3-27: Flow chart of the supply algorithm</i>	120
<i>Figure 4-1: Case studies real Urban network</i>	123
<i>Figure 4-2: Case studies real Semi-urban network</i>	123
<i>Figure 4-3: Case studies real Rural network</i>	124
<i>Figure 4-4: Normal condition of feeder with one ending (Type 1)</i>	125
<i>Figure 4-5: Feeder with one ending and NOP connected in the middle of feeder (Type 2)</i>	125
<i>Figure 4-6: Feeder with branches and NOP is not available at one of the branch (type 3)</i>	126

<i>Figure 4-7: Topology of single line Feeder 12 (F12) from the urban network</i>	129
<i>Figure 4-8: One-line diagram of 11 kV Urban network</i>	131
<i>Figure 4-9: Post-outage supply restoration for fault occurring on feeder 14 (F14) in section (iii) with fully automated ROS pairs</i>	133
<i>Figure 4-10: Restoration example flow chart</i>	134
<i>Figure 4-11: Post-outage supply restoration for fault occurring on Feeder 14 (F14), section (iii) with two optimal locations of the ROS pairs</i>	136
<i>Figure 5-1: Percentage of restored customers by increasing the optimal location of ROS pair using Brute Force and random selection of location on Urban network and compared with the fully automated system</i>	150
<i>Figure 5-2: Number of restored customer by increasing the number of optimal locations of ROS pairs using Brute Force and random selection of locations, in comparison with the fully automated system on the Semi-Urban network</i>	152
<i>Figure 5-3: Percentage of the restored customers by increasing the optimal locations of ROS pair using Brute Force and random selection locations of ROS pair and it is compared with the fully automated system in the Rural network</i>	153
<i>Figure 5-4: Restoration Performance Comparison the three case study networks of the ROS pair</i>	154
<i>Figure 5-5: Pbest for all particles with 122 substations, outage cost = £44 and switch cost estimated with £6550</i>	155
<i>Figure 5-6: Searching optimal location by Brute Force method</i>	155
<i>Figure 5-7: Comparison between Brute Force method and DPSO achieving same value of cost net benefits (a) Zoomed in view of the Brute Force output (b) gbest by iteration from the DPSO routine</i>	156
<i>Figure 5-8: Pbest for all particles with 122 substations, outage cost = £44 and switch cost estimated with £2450</i>	156
<i>Figure 5-9: Brute Force method searching for 3 ROS pair</i>	157
<i>Figure 5-10: Comparison between Brute Force method and DPSO achieving same value of net benefit (a) Zoomed in view of the Brute Force output (b) gbest by iteration from the DPSO routine</i>	157
<i>Figure 5-11: Pbest for all particles with 122 substations, outage cost = £44 and switch cost estimated with £2450</i>	158



<i>Figure 5-12: Searching all possible combination for 4 ROS pairs using Brute Force method</i>	158
<i>Figure 5-13: Comparison between Brute Force method and DPSO achieving same value of net benefit (a) Zoomed in view of the Brute Force output (b) gbest by iteration from the DPSO routine</i>	158
<i>Figure 5-14: Pbest and Gbest for all particles with 122 substations for each feeder (122 ×3), outage cost = £44 and switch cost estimated with £10000 (a) 100 of particles moving toward optimum location (b) Gbest updated for each iteration</i>	159
<i>Figure 5-15: Multiple feeders from (a) Urban, (b) Semi-urban and (c) Rural network</i>	160
<i>Figure 5-16: Pbest and Gbest for all particles with total of 102 substations and 13 real feeders, outage cost = £44 and switch cost estimated with £10000, 100 of particles moving toward optimum location</i>	161
<i>Figure 5-17: Gbest updated for each iteration</i>	161
<i>Figure 5-18: Selected optimal locations and net benefits of ROS pairs by DPSO on multiple feeders (a) Urban (b) semi-urban and, (c) rural</i>	162
<i>Figure 5-19: Gbest for different ROS pair costs, with outage cost fixed at £44 per customer per outage</i>	163
<i>Figure 6-1: One line diagram for Feeder 14 and 26</i>	167
<i>Figure 6-2: Pre-outage voltage profile along Feeder 26 and 14</i>	168
<i>Figure 6-3: Pre-outage current profiles along Feeder 26 and 14</i>	168
<i>Figure 6-4: Pre-outage voltage profiles for F1-7 and F17</i>	169
<i>Figure 6-5: Pre-outage voltage profiles for F8 – 14 and F16</i>	169
<i>Figure 6-6: Pre-outage voltage profiles for F15 and F18 – 22</i>	169
<i>Figure 6-7: Pre-outage voltage profiles for F21 and F23 – 28</i>	170
<i>Figure 6-8: Pre-outage current profiles for F3, F7, F14, F20 and F22</i>	170
<i>Figure 6-9: Pre-outage current profiles for F5, F8 – 9, F13, F16, F21, F24 and F26</i>	170
<i>Figure 6-10: Pre-outage current profiles for F2, F4, F12, F15, F17, F19, F21, F23 and F28</i>	171
<i>Figure 6-11: Pre-outage current profiles for F1, F6, F10, F11, F18 and F27</i>	171
<i>Figure 6-12: Feeder 7 and 23</i>	172

<i>Figure 6-13: Voltage profiles for Feeder 7 (a) pre-outage and (b) post-Outage with ULR for different fault scenarios</i>	173
<i>Figure 6-14: Voltage profiles for a) pre-outage F7 and b) post-outage for DLR for F7 by F23 with different section of a fault</i>	173
<i>Figure 6-15: Post-outage current profiles for feeder 7 and feeder 23</i>	174
<i>Figure 6-16: Feeder 14 connected with F20 and F26</i>	175
<i>Figure 6-17: Post-outage voltage profile along Feeder 26 supplying 'Feeder 14' lost load at substations B1-B6 via DLR</i>	176
<i>Figure 6-18: Post-outage current profile along Feeder 26 supplying 'Feeder 14' lost load at substations B1-B6 using DLR</i>	176
<i>Figure 6-19: Post-outage voltage profiles along Feeders 14 and 26 with faulted at section (ii) employing the ULR and DLR</i>	177
<i>Figure 6-20: Post-outage current profiles via ULR and DLR</i>	178
<i>Figure 6-21: Post-outage voltage profiles along the feeder using ULR and DLR</i>	178
<i>Figure 6-22: Post-outage current profiles following the strategy of the ULR and DLR along Feeders A and B with faulted at section (iii)</i>	178
<i>Figure 6-23: a) Pre-outage F14 and b) post-outage voltage profile of F14 if an outage occurs at section (ii/iii/iv/v/vi/vii)</i>	179
<i>Figure 6-24: a) pre-outage F26 b) Post-outage voltage profiles F14 DLR restored by F26 for an outage between (i) to (iv)</i>	179
<i>Figure 6-25: a) pre-outage F20 b) post-outage voltage profile F14 for DLR using F20 if an outage occur at section (vi) and (vii)</i>	180
<i>Figure 6-26: Pre and post-outage a) voltage profiles and b) current profiles for one optimal ROS pair by Brute Force (if an outage occurs at section i/ii/iii/iv/v/vi)</i>	185
<i>Figure 6-27: Post-outage a) voltage profiles and b) Current profiles for two ROS pairs located on F7 restored by F23 (outage i/ii and iii/iv/v/vi/vii)</i>	185
<i>Figure 6-28: Pre and post-outage a) Voltage profiles and b) Current profiles for F7 during with two ROS pairs (outage iii/iv/v/vi/vii)</i>	186

## LIST OF APPENDICES

APPENDIX 1: PROBABILITY LOCATION FOR FEEDER WITH DIFFERENT NUMBER OF TOTAL SUBSTATION	201
APPENDIX 2: DATA FOR 122 FEEDERS AND THREE NETWORKS	204
APPENDIX 3: OBJECTIVE FUNCTION FOR ONE BRANCHES	242
APPENDIX 4: URBAN, SEMI-URBAN AND RURAL NETWORK	248
APPENDIX 5: OPTIMAL LOCATIONS FOR CASE STUDY NETWORKS	251

## LIST OF PUBLICATIONS

- [1] S. Omar, H. Griffiths, S. Robson and A. Haddad, “Voltage and Current Transducers for Monitoring and Supply Restoration of HV Distribution Networks,” *8<sup>th</sup> Universities High Voltage Network*, Staffordshire (UK), 14-15 January 2015.
- [2] S. Omar, H. Griffiths, S. Robson, A. Haddad, D. Tuffery, P. Moseley, M. Smith, S. Donnelly, and S. Ali, “HV distribution network supply restoration,” *50<sup>th</sup> International Universities Power Engineering Conference*, pp. 1–6, Staffordshire (UK), 2015.
- [3] S. Omar, H. Griffiths, S. Robson and A. Haddad, “Distribution Network Supply Restoration With Optimal Locations of Ros,” *MEDOW Open Day & Energy Exhibition*, Cardiff University (UK), 8 July 2016.
- [4] S. Omar, H. Griffiths, S. Robson, A. Haddad, N.Harid, “HV Distribution Network Optimum Supply Restoration Algorithm,” *51<sup>th</sup> International Universities Power Engineering Conference*, pp. 1-6, Coimbra (Portugal), 2016.
- [5] S. Omar, H. Griffiths, S. Robson and A. Haddad, “HV Distribution Network Optimum Supply Restoration Algorithm,” *10<sup>th</sup> Universities High Voltage Network*, Glasgow (UK), 18-19 January 2017.

## LIST OF ABBREVIATIONS

AHP	Analytical Hierarchical Process
ABC	Artificial Bee Colony Optimisation
CB	Circuit Breaker
CI	Customers Interruption
CDF	Cumulative Distribution Function
CML	Customer Minutes Loss
DG	Distribution Generation
DLR	Downstream Load Restoration
DMS	Distribution Management System
DNOs	Distribution Network Operators
DPSO	Discrete Particle Swarm Optimisation
ENS	Energy Not Spplied
ENSI	Energy Not Supplied Index
ECOST	Expected Interruption Cost
EENS	Expected Energy Not Supplied
FLISR	Fault Location, Isolation and Service Restoration
FPI	Fault Passage Indicator
GPRS	General Packet Radio Service
HV	High Voltage
IMNLP	Integer Mixed Non-Linear Programming
MINLP	Mixed Integer Non-Linear Programming
MV	Medium Voltage
NPL	NEPLAN Programming Library
OFGEM	Office of Gas and Electricity Markets
PDF	Probability Distribution Function
PSO	Particle Swarm Optimisation
RBTS	Roy Billinton Test System
ROS	Remotely Operable Switch
SAIFI	System Average Interruption Frequency Index
SAIDI	System Average Interruption Duration Index
SCADA	Supervisory Control and Data Acquisition
ULR	Upstream Load Restoration
UK-REC	United Kingdom Regional Electricity Company
LV	Low Voltage

## MATHEMATICAL SYMBOLS

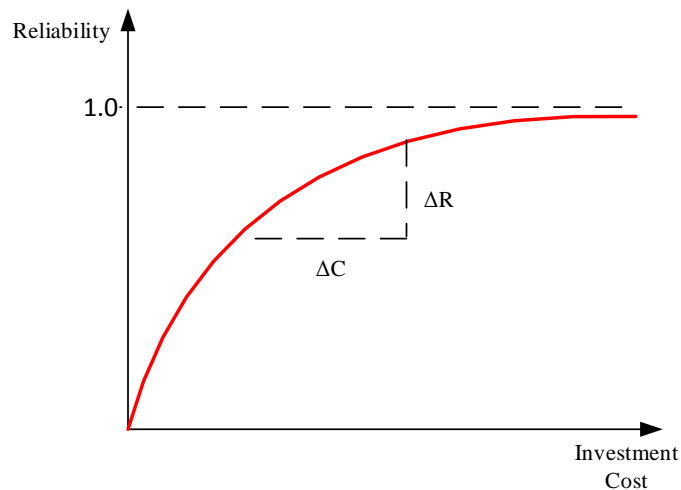
$\Lambda$	Lambda
$\omega$	Weight
$\alpha$	Factor

# CHAPTER 1

## INTRODUCTION

### 1.1 CHALLENGES TO IMPROVING THE RELIABILITY OF ELECTRICITY DISTRIBUTION NETWORKS

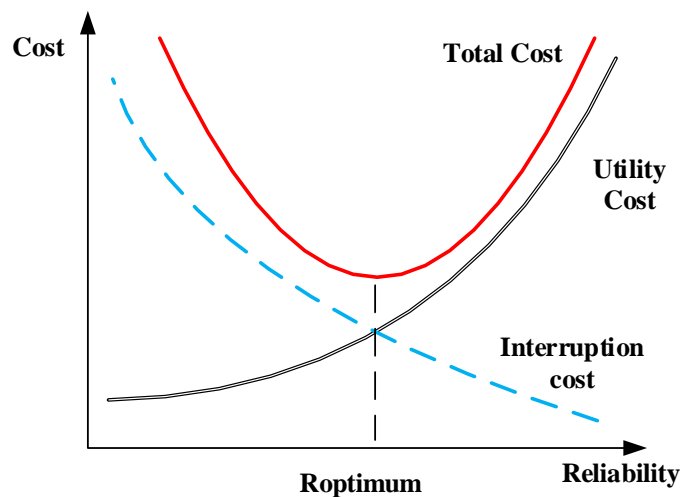
Reliability in electrical power systems refers to quality and continuity of supply [1]. Reliability is the probability that the system will function without failure over a specified period of time. For electrical power systems that require to operate over many decades, investment is required to maintain or improve the reliability of a given network. However, an important question is how much and where should such investment be targeted. *Figure 1-1* shows how the reliability of a system is related to investment. The incremental cost of reliability improvement,  $\Delta C/\Delta R$ , provides a way of deciding whether an investment in a system is economically justifiable [2], as can be seen in *Figure 1-1*, where the law of diminishing returns usually applies.



*Figure 1-1: Typical reliability investment cost curve [2]*

Given that the cost of reliability investment by an electricity utility, in a market-driven electricity industry, is ultimately borne by the customer, reliability evaluation may also be presented as an overall cost versus reliability curve, as shown in *Figure 1-2*.

In *Figure 1-2*, the total cost represents the sum of customer and utility cost. Customer cost is generally defined as the price a customer would be willing to pay to avoid an interruption should one occur. The utility cost is the cost incurred to the utility to achieve a given level of reliability, including the cost of automated switches, regulatory penalties and any other investment which affects reliability.



*Figure 1-2: Evaluation of reliability cost worth [2]*

*Figure 1-2* shows that the optimum reliability is achieved at the crossover point between the utility and customer cost curves. The regulator in the UK, The Office of Gas and Electricity Markets (OFGEM), imposes fines on Distribution Network Operators (DNOs) in the UK for customer interruptions and outages. This places an economic incentive on the DNO to innovate and invest to not only meet future demand, but also to maintain or even improve reliability. However, whether a certain capital investment is economically justifiable is a complex calculation, depending on many probabilistic factors, including the number and location of expected outages, population changes and load growth. Furthermore, as already mentioned, the incremental benefits of investment on reliability tend to diminish, meaning that the first unit of investment will have a greater effect than the second, and so on.



### 1.1.1 Reliability Indices

Several reliability indices have been developed by the electrical industry to measure the reliability of the customers' supply. The most common reliability indices applicable to electrical distribution systems are:(i) the System Average Interruption Duration Index (SAIDI), (ii) the System Average Interruption Frequency Index (SAIFI), (iii) the Customers Average Interruption Duration Index (CAIDI) and the Customer Average Interruption Frequency Index (CAIFI). SAIDI, SAIFI, CAIDI and CAIFI are defined as follows:

$$SAIDI \left( \frac{\text{minutes}}{\text{customer}} \right) = \frac{\sum \text{customers interruption durations}}{\text{total number of customers served}} \quad (1-1)$$

SAIDI is the average duration of interruptions for customers served during a specified time period. It is normally calculated on either a monthly or annual basis. CI is the number of Customers Interrupted per year.

$$SAIFI \left( \frac{\text{interruptions}}{\text{customer}} \right) = \frac{\text{total number of customer interruptions}}{\text{total number of customers served}} \quad (1-2)$$

SAIFI is the average number of interruptions per customer served.

$$CAIDI \left( \frac{\text{minutes}}{\text{interruptions}} \right) = \frac{\sum \text{customer interruption durations}}{\text{total number of interrupted customers}} \quad (1-3)$$

CAIDI measures the average duration of a customer outage within the class of customers that experienced at least one sustained interruption.

$$CAIFI \left( \frac{\text{interruption}}{\text{interrupted customer}} \right) = \frac{\text{total number of customers interruptions}}{\text{total number of interrupted customers}} \quad (1-4)$$

CAIFI defines the conditional average number of interruptions among the class of customers who experience at least one interruption.

In addition to these frequency and time of outage indices, utilities are also interested in ones that are related to energy, as such indices are suitable for an economic assessment of loss of supply. The average energy the customer has not received in the predefined time is known as Energy Not Supplied (ENS). The total cost of interruption or Expected Outage Cost (ECOST) is commonly used by researchers to compare and contrast the performance of candidate reliability improvement techniques. In this work, ECOST will be used as an objective function as it responds to the effect of system topology, interruption duration, load variations and component random failures [3].

### **1.1.2 Overview of The UK Electricity Distribution System**

The electricity distribution system may be of radial, mesh, or radial-mesh topology. The choice of topology will depend on the required quality of service and cost. In the UK, distribution networks, and particularly those operating at 11kV, are generally operated radially. In specific cases, interconnected radial feeders operating as rings offer a method of operation that leads to lower overall voltage drop (due to load sharing), lower losses and higher reliability[4]. Quite often, 11kV distribution feeders are physically constructed as rings fed from different bus sections of the 11kV (primary) substation. In practice, such rings are often operated as two radial systems by establishing a normally open point (NOP) at the position of interconnection.

In this research, three real UK networks have been selected as case studies to investigate the application of automatic post-outage switching to achieve supply restoration: (i) an urban network, (ii) a semi-urban network and (iii) a rural network. These case study networks encompass the same main characteristics as the range of networks found in most UK DNOs. Each type of network has quite different parameters, such as circuit length between each secondary substation, the nature of the circuit

(overhead (OH) or underground (UG)), the number of branches for each feeder, the density of customers etc. These network parameters influence the restoration process both technically and economically.

A typical urban network is mostly made up of UG cables and has a high density of load, where as a typical rural network is predominantly made up of OH lines and has a lower load density. The semi-rural network has a combination of both urban and rural features; viz. some OH lines, some UG cables and an average density of customers between the urban and rural cases. Moreover, loads for urban networks are more diversified with industrial areas characterised by a strong and concentrated power requirement and residential areas characterised by a high service reliability.

Automation systems have been used in distribution networks for many decades with the intended purpose of making the networks function more reliably. Such systems can be described in a hierarchical form:

i) Distribution Management System(DMS)

The DMS is focussed on the control room with a full view of the network. The control room of the distribution network may coordinate all real time operation functions with the nonreal-time information monitored by the operators.

ii) Distribution Automation System (DA)

The DA is system below the DMS and includes all remote devices at the substation and feeder level such as circuit breakers, reclosers and auto sectionalisers. The automation and communication infrastructure at the feeder level is also included in the DA.

The DA gives rise to considerable electrical and economics benefits because it not only improves network reliability, but also has the potential to reduce workforce costs,

as exemplified in [5], where a 40% reduction was reported. Electrical protection equipment such as reclosers in a overhead line feeder will help to detect the fault and interrupt the circuit if the overcurrent persists after a predetermined time and then automatically reclose to re-energise the line. However if the fault still exists, the recloser remains open after a preset number of operations. Normally, reclosers are designed for up to three open-close operations [6]. The second piece of equipment, used in conjunction with the recloser, is the sectionaliser. This device automatically isolates faulted sections of a distribution circuit once the recloser has interrupted the fault current. As such, sectionalisers are usually installed downstream of the recloser.

Deploying an auto-reclosing scheme provides a viable solution where the fault can be cleared without interrupting supply to the customer and in most cases, no further operator assistance or interaction would be required.

### **1.1.3 Regulatory Requirements**

Almost three decades ago, the UK reorganised its electric supply industry which included transferring the distribution role to private ownership, with licenses granted to DNOs. The regulatory role is fulfilled by OFGEM, who require the DNOs to meet certain standards regarding continuity and quality of services for energy supply and restoration [7]. OFGEM is a non-ministerial government department and an independent National Regulatory Authority with the objective to protect the interests of existing and future electricity and gas consumers. DNOs are companies licensed to distribute electricity in UK by OFGEM [8]. CI and CML are used to quantify reliability, as described in Section 1.1.1. The CI index provides an indication of security of supply while a CML is a measure of availability of supply. Referring to statistical analysis by a distribution network company, 25% of faults come from the LV network, 25% from

the HV network and 50 % of faults are derived from MV network [9]. In the UK, transmission substations directly supply distribution systems typically at 132 kV down to 6kV [10]. Referring to a report from OFGEM[11], from 2010 to 2015, a 21% and 36% reduction of CI and CML respectively, was reported. The reduction can be attributed to increased operational support, faster responses to network faults and improved business support, etc. However, the largest single factor attributed to contributing to the index reductions is “replacing and refurbishing equipment”, with 27% of the improvement accounted for by this.

Nowadays, electricity regulators provide financial incentives for DNOs to reduce CI and CML. If a supply interruption lasts less than three minutes in the UK, it is classed as a short interruption that would not incur a penalty under OFGEM regulations[7]. Even though the number of customers off supply and the length of time customers are off supply has fallen in recent years, penalties paid by DNOs to customers are still considered high, with £1.5m in payments in 2015-2016 alone. Achieving the important three minute restoration period has been the main driver for installation of automated switching by DNOs [12], leading to a greater level of investment in automation on the distribution network and improved strategies for post outage restoration.

#### **1.1.4 Electricity Distribution Networks: Types and Topology**

*Figure 1-3* shows a typical section of an 11kV network that will serve to illustrate (i) the impact of faults and their consequential outages and loss of supply and (ii) opportunities for restoration of lost supply. Three 11kV feeders are shown. Feeder A, with 7 substations, is fed from Primary Substation A, while Feeders B (5 substations) and C (3 substations) are fed from Primary Substation B. The network operates radially

with two points of interconnection between feeders with normally open points (NOP): (i) at Point P between secondary substations A7 and B5, and (ii) at Point Q between secondary substations A6 and C3. Feeders A, B and C are controlled by the main circuit breakers under feeder protection at the primary substations; it is also assumed that the switches at NOPs P and Q are remotely operable. In addition, it is assumed that all of the secondary substations on Feeder A have a pair of Normally Closed (NC) split points with Remotely Operable Switch (ROS) pairs. Therefore, Feeder A is observed here to be “fully automated”. It is noted that in urban networks, secondary substations usually comprise a ring main unit (RMU) formed by two load breaking switches in series with the ring and a fused tee-off to the 11kV/415V transformer. Hence, the two switches are part of the same physical RMU unit. In the context of this research, the unit of remotely operable switching is, therefore, taken as the pair of switches inside the RMU, since if retrospective automation is applied to a substation, it is most practicable that it would cover a pair of switches rather than only one of the switches. Henceforth, these will be referred to as ROS pair. The number of customers in the network is given as domestic and non-domestic customers.

Following a fault at Section (iv) of Feeder A, all customers fed from substations (1 – 7) will lose supply due to the tripping of CB A on overcurrent protection. However, the ‘downstream’ customers (S/Ss 4-6) and the ‘upstream’ customers (S/Ss 1-3) could be restored because of the existence of the ROS pairs at all substations on Feeder A. Any of the switches on Feeder A may be operated during the ‘dead time’ following operation of CB A. If the switches on the faulted circuit section at S/S A3 downstream and S/S A4 upstream are opened, the fault will be isolated. Following opening of the two switches, upstream load restoration (ULR) can be applied by closing CB A and this will restore supply to substations 1-3. Downstream load restoration (DLR) of

substations 4 – 7 may be achieved either from Feeder B or C If DLR is provided by Feeder B, NOP ‘P’ would be closed, while if DLR is provided by Feeder C, NOP ‘Q’ would be closed. The merits of using P or Q could be assessed by carrying out a predictive load flow study to examine feeder voltages and currents under the restored configuration.

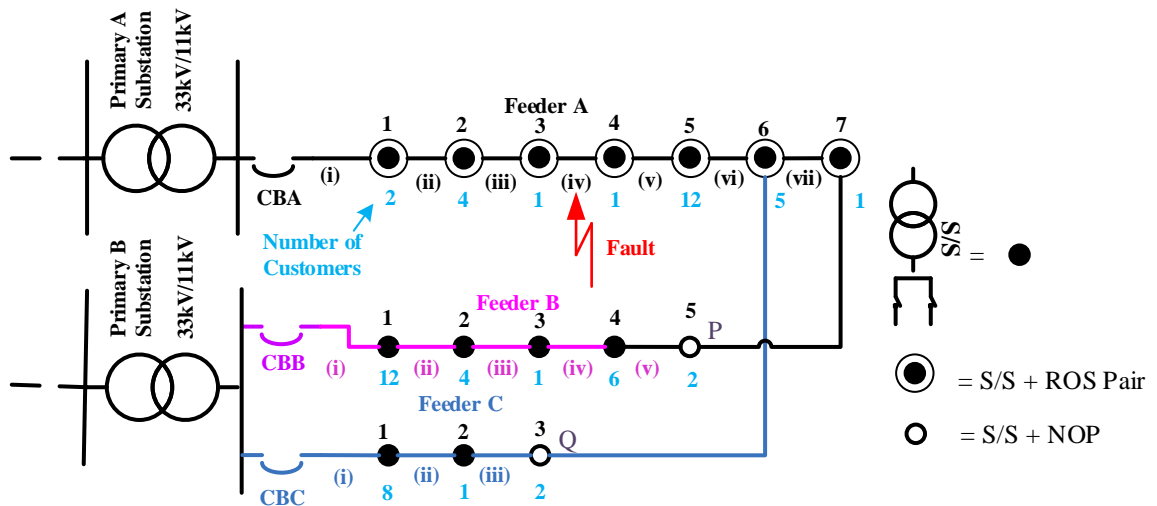


Figure 1-3: Example of network with ROS pairs located at each substation on Feeder A

Generally, the process of ULR following an outage, is quite straightforward as it involves feeding less load than prior to the outage. Therefore, it is unlikely to have any voltage or current violations. All that is required is for the switch (or sectionaliser in the case of a rural network) on the upstream side of the faulted section to be opened. DLR on the other hand, is more challenging. First, it relies on there being an interconnection point (NOP) to another feeder, either from the same primary substation or from an adjacent substation. Second, if a downstream switch is closed to backfeed the lost load on the original feeder, the ‘back feeding’ feeder will supply more power over a greater distance and run the risk of (i) voltage regulation problems towards the end of the newly configured feeder and (ii) current (thermal) violations at the primary

substation end of the feeder. From this example, all 26 customers will be restored by applying ULR and DLR.

Following from this example, it can also be seen that for a fault on any network section of Feeder A (i to vii), a similar process of ULR and DLR could be applied to restore supplies to all customers on the feeder (provided there would be no current or voltage violations). However, this is only possible because ROS pairs are located at all Feeder A substations. Unfortunately, this high level of reliability would come at a high cost. The obvious next step is to consider the benefits of partial automation. This will be considered in the following example.

*Figure 1-4* shows the same network but with two ROS pairs located, for example, only on Substations 2 and 5 of Feeder A. All other NCP points at secondary substations are considered to be only manually operable. For this level of automation, if a fault occurs on Section iv, 24 customers would be restored, only two fewer than for the fully automated system. Therefore, for this example, its performance is similar to the fully automated system which required seven ROS pairs. However, from this quite simple example, two main questions arise: (i) is there an optimum level of automation?, (i.e. optimal or 'economically best' number of ROS pairs), and (ii) if so, where are the optimal positions to locate this certain number of ROS pairs? These two questions may be described as the objective function of this research work. This thesis aims to develop algorithms to determine both aspects (number and optimal location), and this objective is set out in detail in Chapter 2. The fully automated system has the capability to restore 100% of customers if an outage occurs at any section of the network by isolating the fault and transferring the de-energised loads to other neighbouring distribution feeders without violation.



However, a limited number and optimally located of ROS pairs on the feeder could restore an “optimal” number of customers.

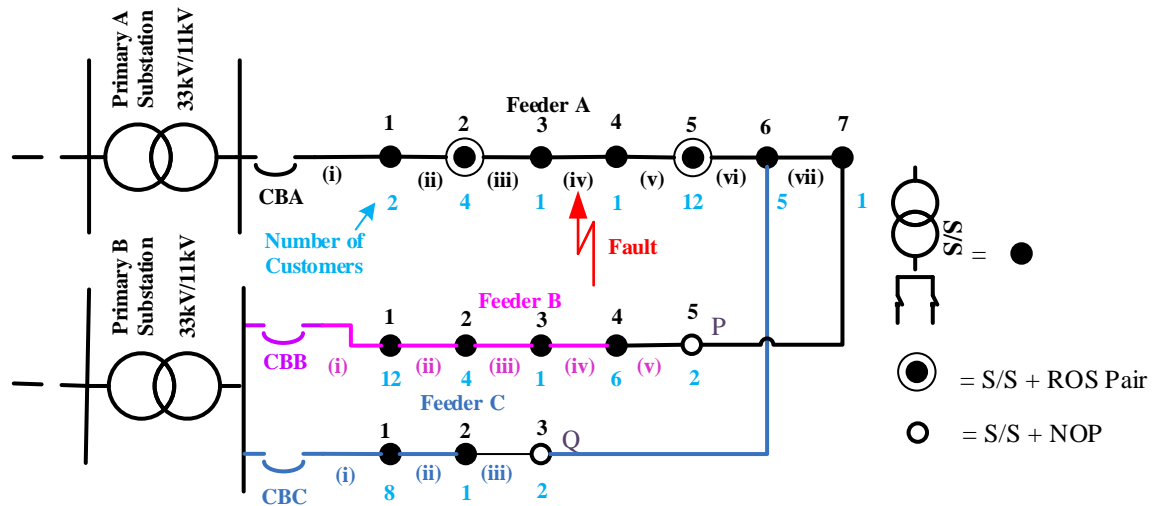


Figure 1-4: Optimal number and location of ROS pairs

As more switches are added to a network, the number of potential customer restorations increases. However, as mentioned already the gains made follow the principle of diminishing marginal returns. That is, adding one more switch will result in a diminished benefit as compared to adding the previous switch. It may be the case, therefore, that the optimum number of switches for a particular network is very small, but this depends also on the marginal cost of a switch, which itself may fall with each additional installed switch.

### 1.1.5 Failure Rates In Electricity Networks

On the distribution system, the fault rate is significantly higher as compared with the transmission system [10]. For example, in the UK, there is a considerably greater total circuit route length in the range 132kV to 6kV with 180,000 km of overhead lines and 133,000 km of underground cables making up the distribution system, compared with only 15,000 km at transmission level. Therefore, it is not surprising that there are

significantly more faults occurring at distribution level compared with the transmission level. It is estimated that there are 25,000 and 200 faults per annum on the HV distribution system and transmission system respectively in the UK [13], greatly affecting DNO performance in terms of the reliability indices.

As well as describing actual fault numbers on the system, fault rates can be quantified for particular items. For example, fault rates for XLPE cable and overhead line and typical plant are shown in *Table 1-1* and *Table 1-2*. From *Table 1-1* it can be seen that the overhead line has a higher failure rate compared to underground cable. The suggested way of reducing the interruption costs and increasing reliability is by reducing the outage time through investments such as the increased usage of remote controlled switches [14]. For this reason, the idea to develop the distribution network with remotely operable switches capable of providing increased reliability is worthy of further investigation. The fault rate for each type of cable influences the reliability of the network and optimal locations of remotely operable switch, as will be shown later in this thesis.

*Table 1-1: Distribution network failure rate lines and cables [10][15]*

Asset	Failure Rate/100km/yr
XLPE Cable	0.1
Overhead Line	0.496

*Table 1-2: Failure rate for different distribution system plant [15]*

Asset	Failure Rate/yr
Switch	0.001
Transformer	0.07
Recloser/Breaker	0.0036
Switchgear/Bus	0.001

### 1.1.6 Current State of Network Automation

In the past, there was relatively little automation and voltage and current measurements beyond the primary substation of the HV distribution network (e.g. 11 kV in the UK) [16]. This means that such networks, which are usually radial, were particularly prone to high CI and CML. Therefore, following a permanent fault-induced outage of a feeder, the process of restoration, which may require manual switching, could take several hours or more to be completed.

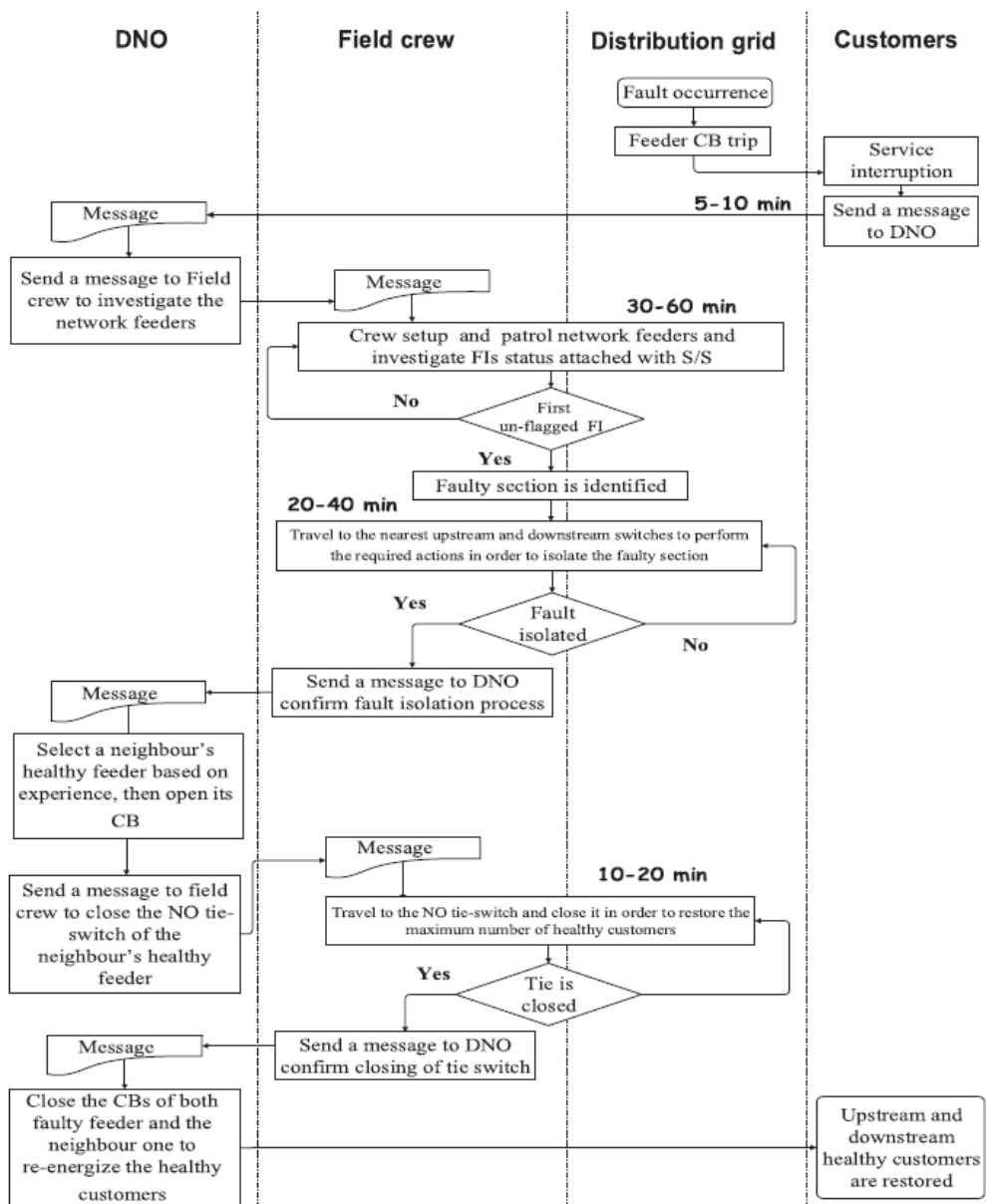


Figure 1-5: Process chart for the fault location, isolation and service restoration [17]

In many existing supply restoration strategies, the DNO deals with post fault system restoration without any interaction with automated systems. A long period of time elapses and intensive efforts are exerted to achieve the processes of Fault Location, Isolation and Service Restoration (FLISR) [17]. For example, an existing or conventional restoration strategy applied by DNOs is shown in *Figure 1-5*. It is estimated that between 65 – 130 minutes are needed to restore the upstream and downstream customers without any violations through manual means [17]. This research focuses on reducing such restoration in less than three minutes [18]. If this can be achieved, the outage would be classified as a short interruption and the network operator would not be subject to financial penalties.

#### **1.1.7 Current Research, New Technologies and Opportunities**

Several studies have been conducted to enhance reliability in HV networks. These include techniques related to priority load restoration [1], [19]–[21], switching sequencing for cost reduction [2], [22], [23], and finding the optimum number of remotely operable protective devices [24], [25]. According to these studies,

- use of automation improves reliability and increases network performance.
- distribution networks benefit by applying automation, as investigated through Cost Benefits Analysis (CBA)
- artificial Intelligence (AI), Genetic Algorithm (GA), Particle Swarm Optimisation (PSO), Ant Colony Optimisation (ACO) and systematic or heuristic techniques were applied for several research objectives such as switch relocation, optimal sizing and location of Distribution Generation (DG), load forecast and DG size.

- developments in circuit breakers (CBs) and switch technology now facilitate easier and more cost effective system automation in HV networks.

A variety of methods have been proposed for the reliability assessment of complex radial distribution systems. However, little research has been carried out which focuses on the determination of the optimal number of protective devices needed on a distribution network to fulfil a given objective (such as minimisation of CI). A number of papers focus on the optimal single switch placement or sectionaliser placement, or the division of the network into sub-sections [26]–[29]. However, in these studies, the considered possible locations of the switch in the network are very limited. In [27], for example, only three sectionalisers are considered on a network with 35 substations. Such coarse granularity may mask potential optimal switch numbers and locations.

There are many potential applications of PSO for reliability purposes, such as finding the optimised reconfiguration of a feeder for restoration or factoring in the uncertainties of optimal automatic switch placement considering future development, i.e. if the number of customers increases or reduces. However, PSO is widely used to determine the optimal placement of electrical components on the distribution network, such as phasor measurement units and switching devices. It is considered by some that, PSO algorithms can generate a high-quality solution within a shorter calculation time and achieve stable convergence compared with other methods [30].

To solve the objective function of this research (optimum customers restored with the optimal locations of switch), a suitable algorithm must be developed. Most of the previous research in this area has been based on the PSO or a Genetic Algorithm (GA) to search for the optimum location of protective devices. Of these two techniques, the PSO has been demonstrated to perform better than GA, as shown in *Table 1-3*. Solution in GA represent as chromosomes and rank from best to worst depend on the

fitness values. However, PSO updated each particles and sending the informations among them to reach the best solution. The number of chromosome or particles for GA and PSO respectively will influence the best solution and also the simulation time of the both algorithm. Simulation time for GA will increase exponentially if the population size increase. Compared to PSO, the simulation time is linearly increase if the population size increase.

However, the population size also influence the algorithms to converge at premature convergence. The way of the fitness ranked or calculated in the algorithms give the ability the algorithms to reach good solution without local search even on high density of search space, especially for PSO. Because of the large search space for the envisaged case study networks to be used in this research (based on actual power networks), PSO is considered to have a higher capability than GA. Moreover, PSO is also able to reach a good solution without local searches (less crowded area) compared with GA, which searches the optimal location as a single group heading towards the optimal area. Particles in PSO update themselves with the internal velocity and keep this information in memory. So, knowledge of a potential good solution is retained by all the particles, while with GA, previous knowledge of the problem is discarded once the population changes [31].

*Table 1-3: Qualitative comparison of GA and PSO applied to power systems optimisation problems [32]*

<b>Criteria of Comparison</b>	<b>GA</b>	<b>PSO</b>
Require ranking of solutions	Yes	No
Influence of population size on solution time	Exponential	Linear
Influence of best solution on population	Medium	Most
Average fitness cannot get worse	False	False
Tendency for premature convergence	medium	High
Continuity (density) of search space	Less	More
Ability to reach good solution without local search	Less	More

Accordingly, discrete PSO has been selected as an algorithm to solve the problem of optimal locations and number of switch respective to customers outage cost (CI and CML) and switch cost together with Brute Force (systematic) method.

### **1.1.8 Economic Considerations**

It has already been established that the maximum possible reliability for a network is achieved if full automation is applied. However, cost is a major barrier to achieving full automation [5]. Moreover, the achievement of the objective requires the highest number of automated protective devices. Therefore, as the number of protective devices increases, the cost to the DNO will also increase. However, the investment cost can be reduced by optimising the number and locations of the ROS pairs. As will be shown later, performance approaching that obtained with full automation can be achieved with only a limited number of switches.

## **1.2 AIMS OF THE RESEARCH WORK**

The main research aim is to develop new algorithms which are capable of finding the optimal locations and number of switches to maximise the number of restored customers and minimise CI and CML.

The analysis includes cost benefit analysis. *Figure 1-6* based on *Figure 1-2*, describes the parameter, 'Costold' (with dotted red curve) which shows the reliability (cost function) of a network before the optimisation process. After installation of optimally placed switches, the curve shifts to the right, with a new red curve labelled as 'costnew'. This shift occurs as a result of the optimum location process and illustrates the benefit of 'smart' investment.

Reducing the total cost of investment from a higher to a lower cost will improve the optimum reliability of a network.

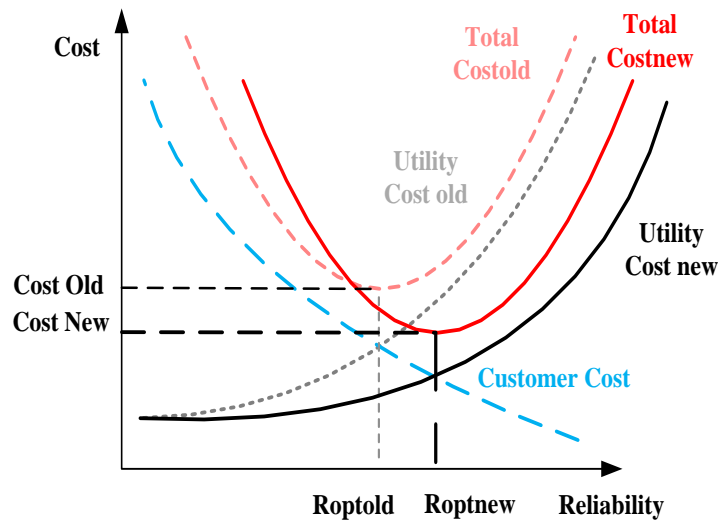
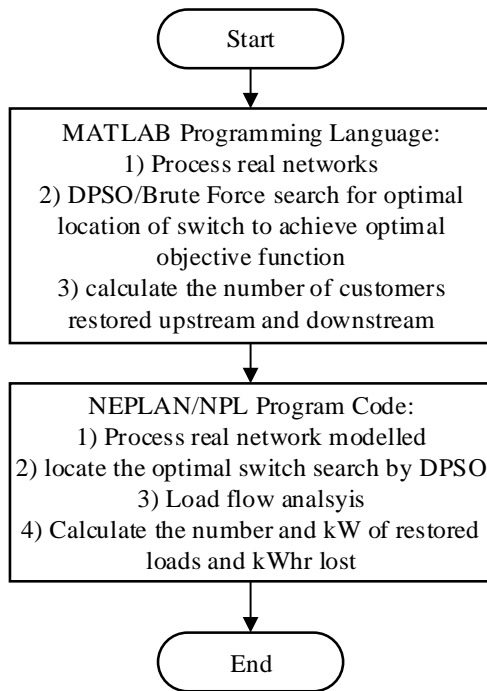


Figure 1-6: The proposed algorithm for reliability improvement

With better algorithms and optimum placement of switches, an increment in optimum reliability from  $R_{optold}$  to  $R_{optnew}$ , as shown in Figure 1-6, could be achieved. It is clearly seen that the utility cost remains almost constant at the early increment of the reliability. After a certain point, the gains of adding more ROS pairs starts to diminish.

The development of the supply restoration algorithms has required two software platforms; MATLAB and NEPLAN. The main function of the code written in MATLAB is to search for the optimal location, number and cost evaluation for having the ROS pairs with suitable number of customers restored. NEPLAN is used to perform the load flow analysis in order to select the optimal sequence of reconfiguration and restoration whilst also ensuring that there are no voltage or current violations. The function of relation for each software is illustrated Figure 1-7.





*Figure 1-7: Flow chart showing MATLAB and NEPLAN/NPL software relationship*

The objectives of this research work are listed below:

- Calculating the number of customers restored in different types of distribution network with automation ranging from zero to full (i.e no remotely operable switches to full automation).
- For each increment of switch automation i.e for each additional switch pair, searching the optimal placement of the switches on the network, starting with an implementation of an automation system on a single substation followed by two substations and so on until full automation.
- Development of a simulation model using DPSO and Brute Force method for a cost effective restoration of upstream and downstream load, consider the customer outage and protective devices cost for optimal number and locations of protective devices.
- Development of the mathematical model for reliability analysis that is suitable for radial networks (used as the objective function in the DPSO and Brute Force Method)

- Search for the optimal location(s) and number of the ROS pairs or clusters using the DPSO algorithm and Brute Force based on a given objective function by considering the failure rate and types of the cable.
- Find the sequence of reconfiguration and restoration of the supply are based on a given deployed set of the ROS pairs and at the same time maintaining the integrity of the network
- Develop capability to select suitable neighbouring feeders to restore as many loads as possible
- Application of the developed optimisation algorithms to three types of network (urban, semi-urban and rural)

Details of the proposed algorithm, using two (MATLAB and NEPLAN) to achieve the main objective of this research is discussed in subsection 4.3 with a detailed flow chart illustrated in *Figure 1-7*.

### **1.3 CONTRIBUTIONS OF THE THESIS**

The main contributions of the present work can be summarised as follows:

- Development of equations used as the objective function of the DPSO and Brute Force to calculate the number of customers restored upstream and downstream at any possible location of protective devices by considering the fault rate for type of cable (OH or UG).
- Embedding of the equations into a DPSO algorithm by using the MATLAB programming language. The system was tested and the results validated by using the Brute Force Method and NEPLAN.
- Novel simulations on the three types of real UK networks were conducted, searching for optimal locations of ROS pairs up to fully

automation. Promising results were obtained, with a high number of customers restored before significant effects of diminishing returns were reached.

- Development of an independent model of the proposed restoration algorithm, using the MATLAB programming language to search the optimal locations of ROS pairs, carry out the load flow analysis and produce the voltage and current profiles. This could lead to a more integrated approach. The system was tested on a simple network and the proposed model was able to perform correctly for outages at any section of network. Results from this model were validated using the NPL.
- The networks were tested probabilistically, including tests on the reliability of the selected optimal locations of ROS pairs. The system demonstrated that the algorithm is likely to be reliable in the future for a large number of future population/load growth scenarios.
- A code written in NPL and implemented in NEPLAN was used to analyse the load flow performance of the networks (Newton Raphson method). The developed system is capable of identifying the best option for DLR if more than one neighboring feeder is available (i.e *Figure 1-3*) two options of DLR via NOP P or Q). In order to choose the best of the ‘back-feeders’ candidates, calculations are required to (i) choose the feeder that could give the highest number of customers/and or load that could be restored, and (ii) to determine possible maximum extent of back feeding without either voltage or current violations. Following the selection of the best or optimal solution, the identified downstream restoration procedure may be operated.

- Results from all networks by using both fully automated and optimal locations of ROS pairs (total customers restored, voltage and current profiles) were compared. The results show considerable promise with no voltage and current violations with optimal locations of ROS pairs.

## **1.4 THESIS STRUCTURE**

The structure of this thesis is as follows:

*Chapter 2 – Review of Automatic Supply Restoration Techniques for Electricity Distribution Networks*

This chapter provides a literature review of the state of the art in the areas of optimum network supply restoration, protective devices, optimisation algorithms, voltage and current constraints and impact of embedded generation.

*Chapter 3 – Optimisation of Location and Number of Protective Devices*

This chapter describes the optimal selection of the location of protective devices using the selected algorithm. Parameters of the networks, such as number of substations, section length, number of branches for the networks and location of the NOP, are also required to select the best parameter of the algorithm. Chapter 3 concludes with a recommendation for an algorithm which is best suited for the application of selecting ROS pairs or clusters in distribution networks.

*Chapter 4 – Development of Case Study Network Models*

This chapter explains the proposed algorithm as applied on the case study networks using MATLAB and NEPLAN, as specified by the methodology shown in *Figure 1-7*.

A new approach to search for the optimal locations of switches and restoration procedure through MATLAB if an outage occurs is proposed.

### *Chapter 5 – DPSO and Brute Force Application*

In Chapter 5, the proposed algorithm is applied to three real UK case study networks representing urban, semi-urban and rural networks. This chapter also discusses the reliability of the proposed algorithm by testing the networks with different probabilistic assumptions of customer numbers at each substation. It provides the conclusion of the work carried out for this PhD thesis and proposes potential project ideas for continuing research work in the future

### *Chapter 6 – Voltage Profiles and Current Limits*

This chapter discusses the simulation results from Chapter 5 on the three types of network, with emphasis on the voltage and current profiles.

### *Chapter 7 – Conclusions and Future Work*

CHAPTER 2  
**REVIEW OF AUTOMATIC SUPPLY RESTORATION  
TECHNIQUES FOR ELECTRICITY DISTRIBUTION  
NETWORKS**

**2.1 AUTOMATED SUPPLY RESTORATION: A REVIEW**

**2.1.1 Background**

Automated Supply Restoration (ASR) is the general term used to describe methods which restore the electrical supply to customers without control room or manual intervention. Since no human intervention is required, ASR is generally regarded as the fastest way to restore load to customers. However, to enable ASR, the network must be monitored in close to real-time. Modern forms of ASR require that the monitored information from various parts of the network are aggregated into a single place. A computer based algorithm then decides the next course of action close to real-time before sending the instructions out to the relevant assets. Therefore, to enable ASR, a two-way communication network is required, and the contributing assets must be able to send information back to a central point (e.g. voltage, current transducers), or receive, and act upon instructions (e.g. the operation of remotely controlled switches). This makes ASR potentially very expensive. It is the responsibility of the network operator to weigh up the benefits of the different forms of ASR against the cost, though such an assessment is extremely complex.

*Figure 2-1* shows a typical 11 kV network with no ASR. It consists of two feeders which are connected at their ends through a NOP. If a fault were to occur on feeder A, in between S/S2 and S/S3, CBA will trip and all customers on this feeder will lose supply. Feeder B is unaffected by the outage on Feeder A. In this scenario,

restoration on Feeder A cannot happen until the fault is located and isolated manually by a crew. This process can last anywhere between several minutes and several hours, often depending on phone calls from customers to alert the DNO of the outage. Once the fault is isolated, S/S3 until S/S N will be separated from their usual supply through CBA, but can be fed through the NOP from feeder B. Meanwhile, CBA can be closed to feed the remaining substations on feeder A (S/S1 and S/S2).

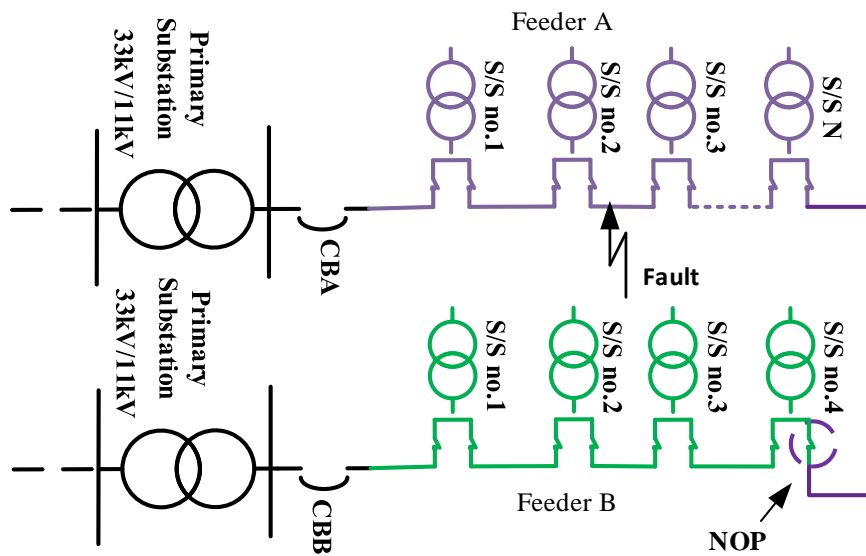


Figure 2-1: Typical 11kV network faulted without ASR

It is clear to see that with no automation, customers are vulnerable to lengthy periods without supply following an outage. An improvement on this scheme is shown in Figure 2-2. Here, there is a recloser 'R' and a sectionaliser 'S', which together provide a degree of automation (it is assumed that the network comprises overhead lines). Now, if a fault should occur just upstream from switch disconnecter 4, the recloser will trip and the sectionaliser will open. After a time delay, the recloser attempts to close, and by this time, the fault has been isolated by the sectionaliser. In this way, a sectionaliser and recloser can cooperate to automatically isolate a portion of the network without the need for manual intervention. In this case, only the load L5 is lost. This

scheme represents a cost-effective form of automated restoration since no communication infrastructure is required.

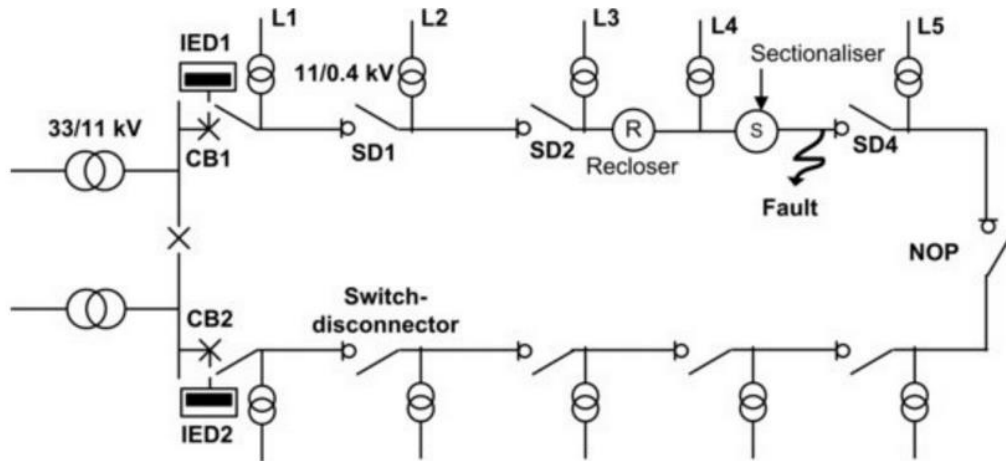


Figure 2-2: 11kV typical network with reclosers and sectionalisers [33]

A vast improvement in reliability is achieved by using the scheme shown in Figure 2-3. Here, Remote Terminal Units (RTUs) are connected to disconnectors either side of every substation. RTUs are assumed here to be intelligent devices which are capable of sending and receiving telemetry data to and from a central point. The RTUs are associated with switches which, upon instruction, operate via actuators. With a suitable sequence of operations, this allows the faulty zone to be isolated, followed soon after by the automatic restoration of the healthy zones within the network. This scheme will be termed *full automation* for the remainder of this thesis.

Full automation represents the most comprehensive form of ASR available to DNOs. However, the infrastructure cost is extremely high, so is usually only deployed in regions with easy access to communication infrastructure and high economic or strategic importance, such as the inner city. It is difficult for DNOs to justify the investment in such systems in rural or semi-rural regions, yet these regions are well placed to benefit from automation. For this reason, a growing area of research is



dedicated to finding more cost-effective alternatives to full automation, with interest in techniques ranging from decentralised approaches to optimisation based methods.

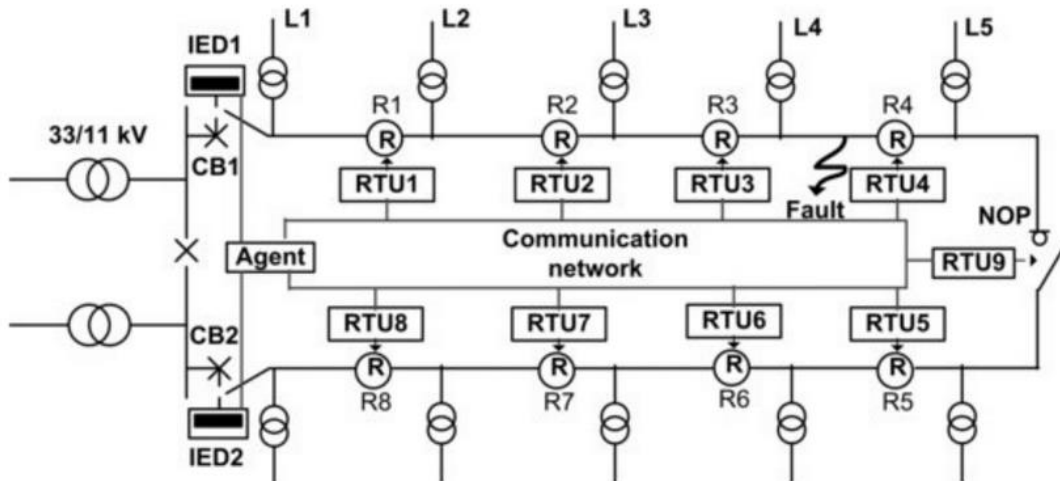


Figure 2-3: Improvement in reliability with fully automated for distribution network [33]

### 2.1.2 Historical Technique

The two primary objectives in power restoration is, firstly, to restore supply to the maximal number of customers in accordance with their importance and, secondly, to accomplish restoration as quickly as possible [27]. A conventional method of reducing the outage time is the use of the recloser as a protective device, and this is generally applied to overhead line networks. If an overcurrent is detected in a section of a network, the circuit breaker will trip and with an electronically controlled reclosing function, the recloser automatically restores power to the affected line if the faults clears itself quickly. Automatic restoration using reclosers is possible around 80% of the time [28], with restoration times in the order of a few seconds because the majority of faults on overhead feeders are transient in nature. However, if the fault does not clear itself, the recloser will, after a pre-determined number of tries (or “shots”), not attempt any further reclosing operations. The circuit breaker will, therefore, remain open until

manual clearance of the fault. A potential improvement on this situation is to incorporate remotely operable switches to automatically isolate the fault and allow reconfiguration of the network for restoration of the upstream and downstream load. Importantly, this process can be very quick, well within the 3 minute time frame.

### **2.1.3 Automated Supply Restoration In The Era of Smart Grids**

#### ***2.1.3.1 Full Automation***

A number of publications have been devoted to the topic of distribution network supply restoration. However, they normally discuss only the centralised system automation rather than full switch automation. Centralised system is process of gather a data from a larger network and enable the process of restoration from the control center depend on the location of the switching devices [34] and full switch automation located with automated switch at the substations and has capability to restored an outage at without operator intervention. A few notable papers focus on minimising the number of switching operations [35]–[41], while other researchers focus on maximising the load restoration [42]–[45]. In [46], a restoration guidance simulator is outlined to allow a system operator or planner to simulate and plan restoration events in an interactive mode. A multi-objective optimisation approach, in [36], which takes operational constraints of the network into account, is proposed. In [47]–[49], the optimal network reconfiguration of load balancing is searched for, and the status of sectionalising and tie switches are determined while the constraints for voltage magnitudes and line flows are satisfied. The process of modifying the radial structure of distribution feeder by transferring heavily loaded feeder to lightly loaded feeder known as load balancing index. The network with the least load balancing index value is selected as the optimal

solution. The load balancing index is used to determine the loading conditions of the system and maximum system loading capacity.

A proposal for investigating the technical feasibility of connecting feeders in parallel was studied in [37][50][51] and indicated that there could be possibilities of a reduction of energy losses and the number of CIs. Feeders is routed from main substation to secondary substations using different route is known as parallel feeders. Feeders connecting in parallel normally applied on feeder with higher number of customers, especially on urban network. Optimal placement of fault indicators [52] on networks is investigated to reduce the supply restoration time and avoid the high cost in locating such devices at every point in the network.

### ***2.1.3.2 Optimization Automation***

A summary of recent research focusing on optimisation of single automated switches is shown in *Table 2-1* with most researchers focusing on multiples of single switch units a rather than switch pairs. The research classified with different characteristics, including the types of protections devices, algorithms, size of networks, progress stage either simulation or real application network and others which related with the analysis. From 23 of the research since 1996 until 2016, only two research discussed on the ROS pairs [42], [53]. In [42], eight ROS pairs are search on 29 possible locations and for [53] only one ROS pair on five possible locations are analyse. Both research also lack of comparison with fully automated system. Optimal number and locations of each single sectionalising switch in considering minimum outage, maintenance and investment cost were sought in [54].

Table 2-1: Taxonomy of switch placement literature

Paper	[54]	[57]	[58]	[59]	[14]	[60]	[61]	[62]	[56]	[63]	[64]	[65]	[66]	[3]	[53]	[67]	[68]	[69]	[70]	[71]	[29]	[42]	[17]	
No of ROS	Single	14	x	x	6	x	x	x	16	12	x	x	x	12	12	x	12 and 14	12	10	22	1 until 7	6	x	x
	Pair	x	x	x	x	x	x	x	x	x	x	x	x	x	x	1	x	x	x	x	x	x	8	x
Recloser	x	2	x	x	x	2	2	x	x	16	0 up to 4	1 until 4	x	x	x	x	x	x	4	x	x	x	x	x
Tie-line	x	x	√	x	1 until 11	x	x	6	x	x	x	x	x	x	x	x	x	x	x	x	x	√	x	
Possible locations	67	3	16	37	11	NI	4	40	67	NI	11	NI	15	67	5	67	183	51	67	7	25% of S/S	29	35	
Compare with Fully Automatic	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	√	x	x	√	
CBA	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	x	√	√	√	√	√	x	√
Optimisation	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	x	x
Optimisation Technique	SA	HM	AL	HM	DEC	MILP	VB	IA	PSO	RTS	MILP	NLBP	ACO	PSO+GA	AHP	MILP	GA	ABC	MILP	SA	MILP	GR	AT	
Network Size	RBTS	S	L	M	L	L	RBTS	M	RBTS	L	L	L	L	RBTS	L	RBTS	L	RBTS	RBTS	S	L	L	M	
Network Type	SN	7	576	SN	RN	RN	SN	RN	SN	RN	SN and RN	RN	RN	SN	RN	SN	RN	SN	SN	SN	SN	IEEE 123 BUS	RN (160 S/S)	SN(35 S/S)
Progress Stage	SI	SI	SI	SI	SI	SI	SI	SI	SI	SI	SI	SI	SI	SI	SI	SI	SI	SI	SI	SI	SI	SI	SI	SI
Year	96	98	01	02	05	05	06	06	08	08	09	09	09	09	11	11	12	12	14	15	15	15	15	16

**Algorithms:** ACO = Ant Colony Optimization; IA = Immune Algorithm; SA = Simulated Annealing; GA = Genetic Algorithm; PSO = Particle Swarm Optimization; MILP = Mixed Integer Linear Programming; HM = Heuristic Method; AT = Analytical Technique; GR = Greedy Rule Based Strategy; VB = Value Based Optimisation; DEC = Decomposition and Convex Analysis; RTS = Reactive Tabu Search Algorithm; ABC = Artificial Bee Colony Optimisation; AHP = Artificial Hierarchical Process; NLBP = Nonlinear Binary Programming; AL = Anneal Local Search.

**Progress Stage:** SI = Simulation; RA = Real Application

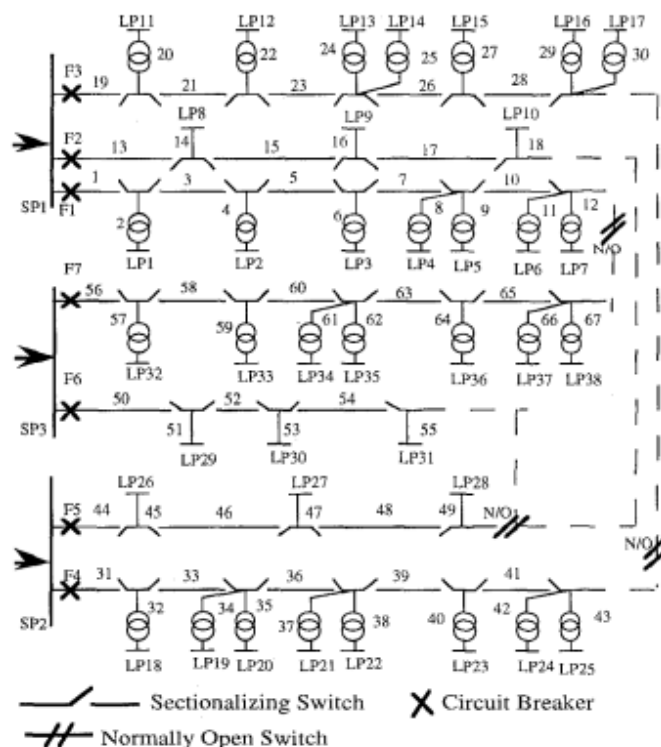
**Network Size:** Small (S) =  $S/S \leq 20$ ; Medium =  $21 \leq S/S \leq 40$ ; Large (L) =  $S/S \geq 41$

**Types of Network:** RN = Real Network; SN = Typical Study Network

Others: NI = No Information; RBTS = Roy Billinton Test System

In [54], a simulated annealing technique was used to search for optimal locations, where the test network presenting of 51 possible switch locations. Two cases were considered in the research; i) a base case with sectionalising switches on both ends of each primary section feeding the secondary substation

*Figure 2-4*, and ii) no sectionalising switches on the primary sections (*Figure 2-5*). It is shown that a reduction of about 20% the Expected Interruption Cost (ECOST) was achieved by [55]. A further study was carried out [56], using the same case study network used in [54]. In this study, discrete Particle Swarm Optimisation was used in the optimisation process; the same objective as [54] but the total number of switches was 12 instead of 14 [54] and the ECOST was reduced by 32%. Because the number of switches applied in both these studies are different, a direct comparison is not possible because the number of protective devices employed is different.



*Figure 2-4: Base case with sectionalising switches on both ends of each primary section [54]*

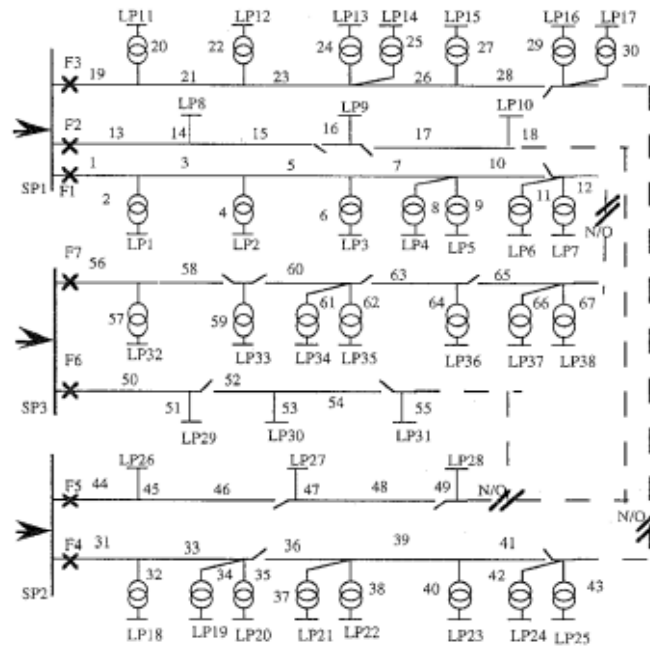


Figure 2-5: No sectionalising switches on the primary sections [54]

In [3], PSO and GA algorithms were implemented by introducing a new linear method for velocities and states limitation. In the proposed scheme, a genetic preprocessing or modification algorithm is used to generate a suitable first population in the PSO and summarise the search space for the enhancement of the main PSO algorithm operation in escaping from local minima and decreased time of optimisation. The value of ECOST for the study was for optimal locations of twelve switches [56]. The analysis also considered the effect of Distributed Generation (DG) that might be embedded in the distribution power system and it was found that the results were unaffected.

A Mixed Integer Linear Programming (MILP) was used in [67]. In this study, the ECOST associated with the optimal location of protective devices was recalculated using the customers damage functions (interruption cost estimates are expressed as \$ per kW of annual peak load). It was shown that ECOST was reduced by 10.35% by using a simulated annealing but this increased to 17.26% when using MILP with the

same number of switches. A further study [70] emerged with better results with the same objective and different number of protective devices by using the same network (RBTS network). Here, the sectionalising switch and recloser were considered. Applying MILP for optimisation, a similar ECOST was obtained as [67]. Cost benefit analysis was employed by [72] to solve the optimisation problem. The objective function of the study was to reduce Energy Not Supplied (ENS) by determining the locations of the reclosers, sectionalisers, fuses and isolators. The results presented the number of each type of protective device and the total cost as optimised values, however, location details of the proposed protective devices were not provided. With the same objective as [72], the proposed algorithm in [73] searches for an optimal sequence of switching operations that minimises ENS for each configuration.

Optimal number and locations of protective devices were investigated using a Simulated Annealing Algorithm [74] to meet the reliability and economic requirements of an LV distribution system [74]. The test system consisted of seven possible locations of protective devices and three protective devices at essential locations (main unit, DG unit and energy storage unit). Three objective functions (SAIDI, EENS and ECOST) were used to measure the reliability of the proposed system. In this study, different weights were set for each index with the highest weight belonging to SAIDI (0.4) and the other two indices carrying the same weight (0.3). Economic and reliability analysis was carried out with several stages of simulation until a fully automated condition was achieved. However, the test network required the NOP to be operated manually.

#### ***2.1.3.2.1 Optimisation Technique***

Determination of the optimal level of automation is complex, nonlinear and discrete and the optimisation problem is of an enormous dimension. It is not possible to apply directly any optimisation procedures on it [51]. Certain optimisation techniques

are only suitable with particular objective functions, such as searching for optimal locations of protective devices, optimal size of capacitor placement to correct power factor, optimal size of distributed generation connected to the load for back up purposes and optimal location of tie switches to reduce voltage drops along a feeder. Each of these objective functions need different optimization techniques.

#### ***2.1.3.2.2 Optimal Location and Number of Remotely Operable Switches***

Many published papers propose methods of searching for the optimal number and locations of protective devices but the constraints in this study normally limit considerably the number and locations of the protective device, as tabulated in *Table 2-1*. Only two published studies, [42] and [64], focus on optimisation of a pair of ROS while the others all focus on single switches. So, relatively few protective devices have been considered that can be freely allocated to a limited possible number of locations for those analyses. For example in [42], searches for 8 ROS pairs on 29 possible locations while in [53], searches for one optimal location of ROS pairs on 5 possible locations. In [42] and [53], large networks were used with the number of secondary substations exceeding 41. Hence, in these reported studies, as only a few substations were selected to be candidates for switch placement it constrains the possibilities for optimisation of network reliability. The literature review in *Table 2-1* also shows different algorithms are used to search type, number and locations of protective devices.

#### ***2.1.3.3 Voltage and Current constraint***

In [75], the search for reliability improvement was sought by applying optimisation in the restoration process. The proposed method selected the best configuration, and it was obtained with the closing of the NOP and switches to restore



interrupted customers through load transfers to adjacent feeders. The best restoration strategy was obtained considering the network constraints (voltage drop and feeder loading) and the number of interrupted customers. However, computational time of this study was high. A technique was proposed by [76] that included the same constraint as in [75] but to maintain the bus voltages to acceptable levels, a voltage regulator was applied.

Considering restoration sequence and network constraints [21], a technique was proposed to respond dynamically to the change of network topology. The method divided the affected load point into six classes based on restoration times. From the results, the network constraint has significant impact on the EENS, load point failure rate and unavailability. A similar method was applied by the same author but the study was updated dynamically [77].

The function of the voltage and current profiles are important observations since they reveal whether the reconfigured network may operate acceptably or not. The restoration strategy should be able to restore the maximum number of customers while maintaining the integrity of the network. In order for automatic systems to operate, voltage and current measurements may be obtained from various points of the network for analysis. The existing and currently developed technologies for voltage and current measurements on the HV distribution networks together with circuit interruption, isolation and reclosing devices will be discussed in detail in the next section.

#### ***2.1.3.4 Limitation of Current Approaches***

There are many aspects to consider during and after searching the optimal location of the protective devices. During the search for optimal locations of the protective devices, network topology, network size, capacity of customers, cable length,

cable types, and more, have to taken into consideration. The topology of the network will also have a considerable effect on optimal locations of protective device. During restoration or reconfiguration, voltage and current limits are also vital to account for. The capability of neighboring feeders to restore load through back-feeding must be achieved without voltage and current violation.

When the optimal location of a switch is selected, the uncertainty of this result has to be analysed to account for further load or network changes. However, current approaches do not consider these points, especially on the uncertainty of the optimal location. None of the approaches discussed consider the full range of optimal locations of switches, either single or in pairs of switches, as illustrated in *Table 2-1*.

#### **2.1.4 AURA-NMS Project**

The project known as ‘Autonomous Regional Active Network Management System’ (AuRA-NMS) is a £2.5m, EPSRC funded project comprising 7 universities and 3 major companies in the power industry. The three major areas of the project development are; i) measurement of distributed generation and demand side management to facilitate the connection of DG to the network ii) develop a controller that will monitor electricity networks, isolate faults quickly and allow distributed generation to remain connected and operating and iii) optimise the network with respect to losses, where distributed generation is concerned [78]. Two test networks were selected, as illustrated in *Figure 2-6* and *Figure 2-7*. The networks have different topologies, specifically, the 11kV network has distributed generation and the 33kV network is interconnected with a large amount of connected DG.

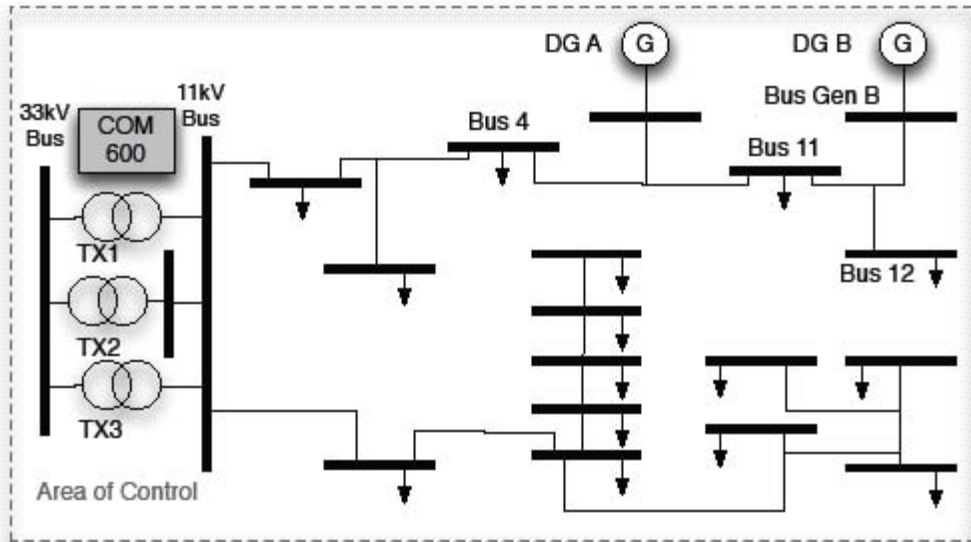


Figure 2-6: 11kV radial test network with connected DG [78]

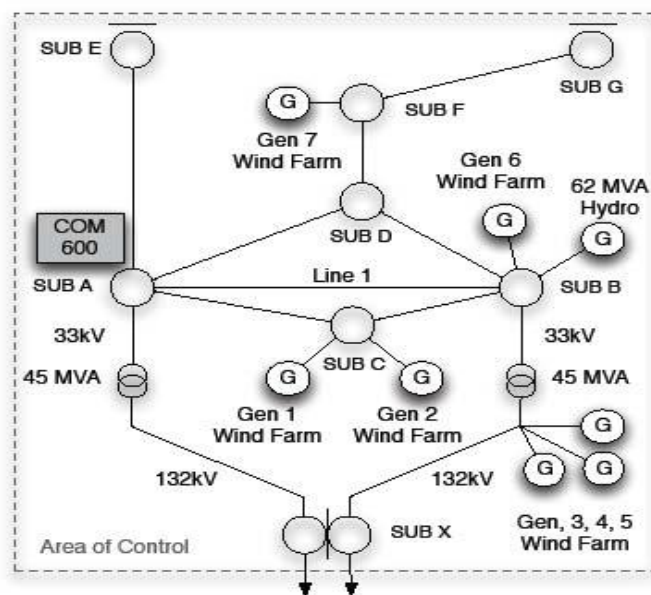


Figure 2-7: 33kV interconnected test network with distributed generation [78]

The project has developed a distributed control system to deliver; i) real-time automated reconfiguration, initially to a regional network of up to four primary substations, ii) methods to economically, efficiently and effectively integrate large amount legacy infrastructure and renewal programmes and iii) network optimisation taking into account DG and electrical energy storage [79]. Algorithmic automation was applied on this project with faults detected by Fault Passage Indicator (FPI). The process continues

to isolate the fault by using pre-programmed remote control switches along feeders and to restore the customers upstream or downstream. However, only switches declared in the pre-programmed can be controlled by system and if the feeder is running abnormally, the automation has to be disabled.

### **2.1.5 American FLISR Project**

The US Department of Energy (DOE) and the electricity industry in the US has recently invested over \$7.9 billion to modernise the grid, strengthen cyber security, improve interoperability and collect an unprecedented level of data on smart grid and customer operations. Ten utilities are involved in the applications of fault location, isolation, and service restoration (FLISR) project. The investment of the Smart Grid Investment Grant (SGIG) funding focused on the FLISR. The FLISR technologies involve automated feeder switches and reclosers, line monitor, communication networks, distribution management system (DMS), outage management system (OMS), supervisory control and data acquisition (SCADA) system [80].

Figure 2-8 illustrates FLISR operations. Figure 2-8 A shows a fault which occurs at a line section on feeder B. For the first stage, FLISR locates the fault by using line sensors that monitor the electrical components in the system, communicates conditions to other devices and grid operator. Once the location of the fault is known, the second stage of FLISR opens upstream and downstream switches to isolate the fault, as shown in Figure 2-8 (B-C). For the last stage, as shown in Figure 2-8 D, the FLISR closes the normally open-tie switches at a neighbouring feeder to restore healthy sections (downstream restoration). The fault isolation location feature of the technology can help operators repair the faulted area and reduce the customer interruption time. From the findings, the FLISR application can reduce the number of customers impacted by a fault

by automatically isolating the faulted area and restoring service to remaining customers by transferring them to adjacent circuits. The FLISR is categorised into 2 parts, first, the fully automated FLISR and second, manually validated FLISR. The fully automated FLISR automatically restores services to un-faulted sections without human intervention, whilst the manually validated FLISR requires validation from a control room operator before restoration.

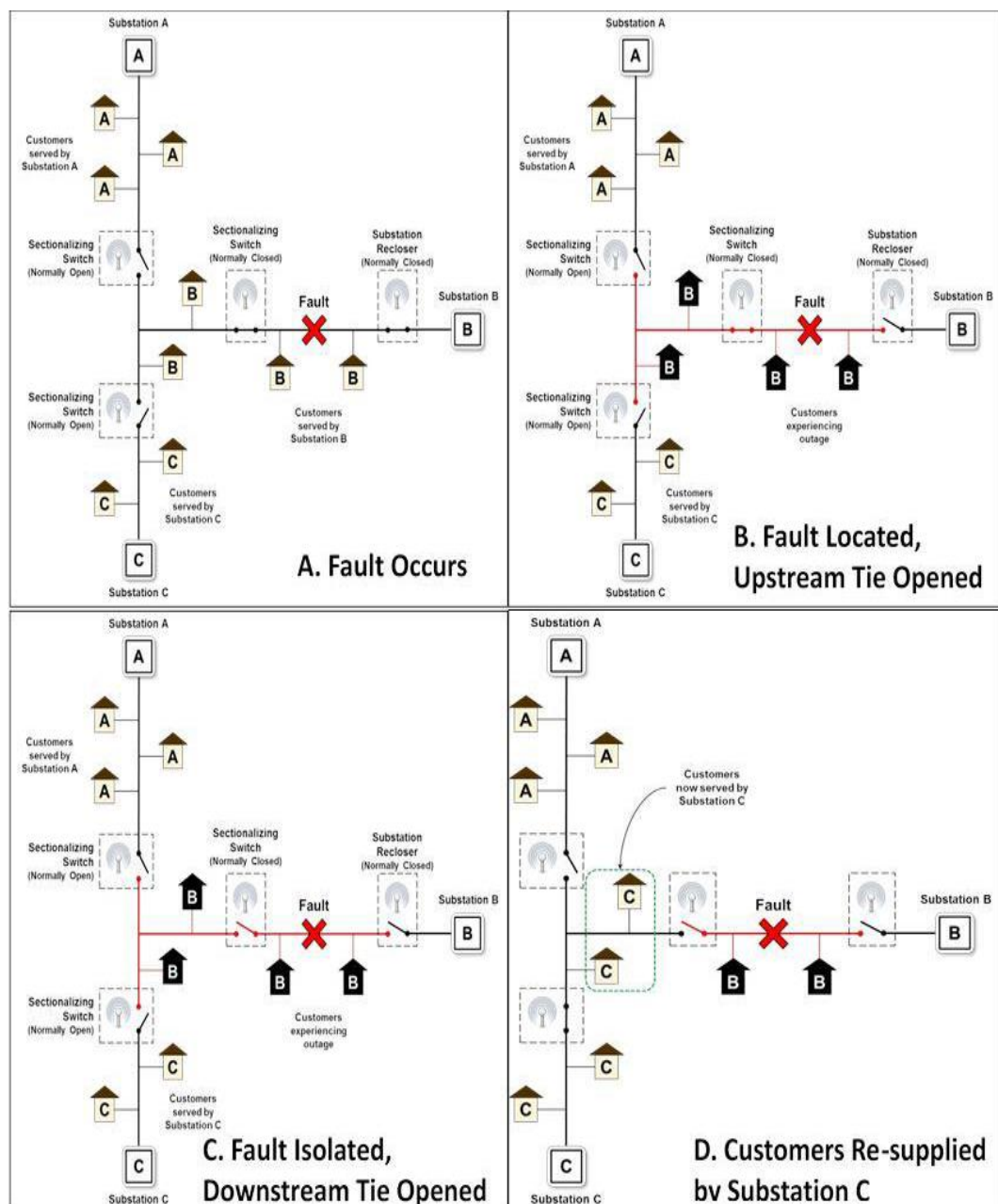


Figure 2-8: FLISR operations [80]

However, fully automated systems require extensive pre-validation and calibration processes to ensure effective and reliable operations. The fully automated FLISR takes less than one minute for restoration while the manually validated FLISR actions can take five minutes or more. From the finding, the fully automated FLISR system was more successful in reducing the number of customers interrupted for automated switching operations compared to manually validated FLISR, with 55% and 35% respectively. This finding proved that the automated switching operation has a high impact on reducing the restoration time.

#### **2.1.6 Future Trends: Microgrids and Distributed Generation**

Installation of embedded generation may improve power reliability and reduce the cost of electricity by using renewable energy technologies such as Photovoltaic (PV) solar and wind farms. Following the growing trend of the embedded generation as projected by Western Power Distribution from 2015-2020 on 33 kV substations [81], a study took into consideration the effect of the protective devices installed at substations that have to be secured in future developments. An algorithm, presented in [82] determined an optimal placement of protective devices (circuit breaker) in a micro-grid systems for improving reliability indices by considering three different operation mode depend on the fault location on a network. The network was divided into different zones depending on the location of the fault. The system was tested for three cases. Case 1 located the optimal locations of 2 circuit breakers on different zones, followed by 3 circuit breakers for the second case and 4 circuit breakers in the third case. However, the outcome did not meet the expectation to improve its reliability by increasing the number of circuit breakers in different cases. Similar studies were done by [83] and [82] and published in the same year. These compared a network with and without the

presence of Distributed Generation (DG). The analysis searched for optimal sizing of a protection system (recloser) on a DG enhanced distribution feeder. The algorithm found the optimal location for five reclosers on a 70 node test feeder. However, there was only a limited reduction in ENS with the presence of DG.

One of the well-known effects of the addition of embedded generation into the system is the change in the fault current. This has the potential to interfere with the synchronization and coordination of protective devices in a distribution system [84], [85]. Also, a high level of embedded generation penetration may cause interaction with relays of automatic tap changers [86].

In a secured condition, the existing system needs to be tested under various steady state and fault conditions and reconfigured to operate with the inclusion of embedded generation [87]. In [88], a distribution system with a micro-grid was used as a case study to test the impact of DG and distributed energy resources if an outage occurs in the network.

## **2.2 THE OPTIMISATION PROBLEM**

A considerable amount of research has been done aimed to increase the reliability of networks and by using different algorithms. Some of the proposed algorithms predict hazards and analyse the reliability of a network based on their topology and pre-post fault outage measurements [89]. One algorithm used a bootstrapping method to estimate lightning storm parameters and a Monte Carlo approach was used by [90] to assess the distribution of reliability indices. Another algorithm uses a two-stage prediction method to classify and track various types of storms so that the grid operator can be proactive based on the errors between predicted storm outages and actual outages proposed by [91]. From such work, it can be seen that different algorithms can be used for different

objective functions. As already mentioned, certain algorithms may be more suitable for particular problem statements. For example, the selection of the optimal reconfiguration of a feeder depends on distance and voltage drop at the end of the substation for the feeder. However, optimal locations of switches depends on the number of customers that could be restored if the locations are selected. Therefore, it is important to select most suitable algorithm to achieve a particular objective functions to find the optimal solution most efficiently and in minimum time.

Three types of algorithm are normally used to search for optimal locations of protective devices. These are: (i) Mixed Integer Linear Programming (MILP), (ii) Particle Swarm Optimization (PSO) and (iii) Genetic Algorithm (GA) as seen in *Table 2-1*. However, other algorithms also used and these are described briefly in the Subsections 2.2.3 to 2.2.6.

### 2.2.1 Possible Locations of Remotely Operable Switch Pairs

The possible locations of ROS pairs available in a network is dependent on the number of substations in the network. For example, if a network consists of 8 secondary substations, as illustrated in *Figure 2-9*, the total number of possible locations of ROS pairs for Feeder L is 8. Pairs of NCP and a single NOP are labelled in the network. The number of possible combinations of locations available in a network can be calculated using Equation (2-1).

$$N_p = \frac{N_t!}{k_{ros}! \times (N_t - k_{ros})!} \quad (2-1)$$

Where;

$N_t$  = total number of substations

$k_{ros}$  = number of ROS pairs considered as possible 'ROS' locations



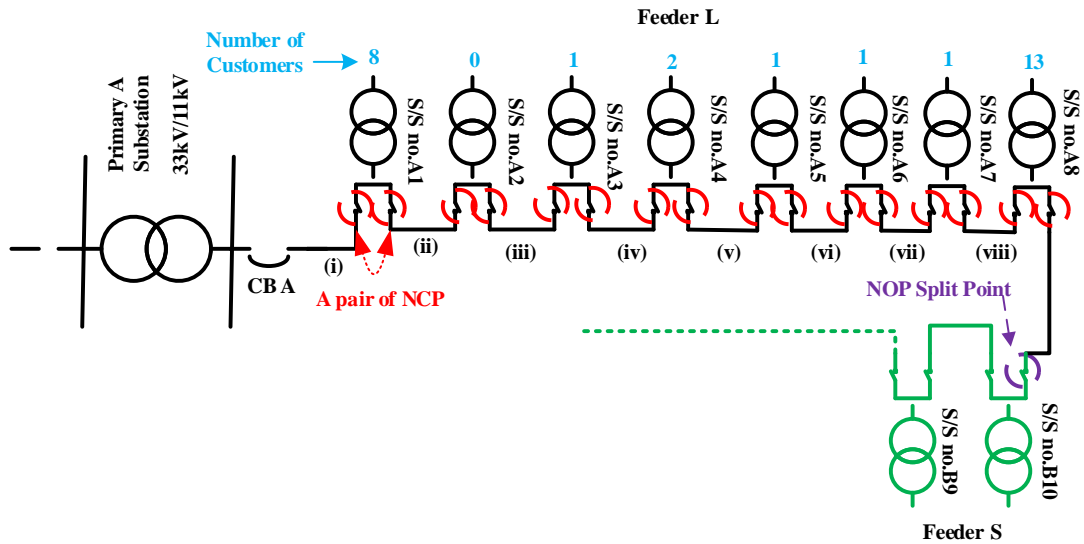


Figure 2-9: Possible locations of remotely operable switch pairs

As an example, optimal locations for two ROS pairs are searched for in a network, the total number of possible combinations options is:

$$N_p = \frac{8!}{2! \times (8 - 2)!} = 28 \text{ possible combinations} \quad (2-2)$$

The number of possible combinations of ROS pairs are presented in *Figure 2-10*, in a more general sense, by plotting the number of possible combination as a function of required ROS pairs for different network sizes. As a general rule, the number of possible ROS pair combinations increases until ROS pairs occupy half of the possible combinations. After this point, the total number of possible ROS pair combinations decreases. An important consequence of this result is that, as the network size grows, the total number of possibilities also grows. For example, adding 10 nodes to the network increases the maximum number of possibilities (reached when half of the locations have ROS pairs) increases the total number of locations by approximately 3 orders of magnitude.

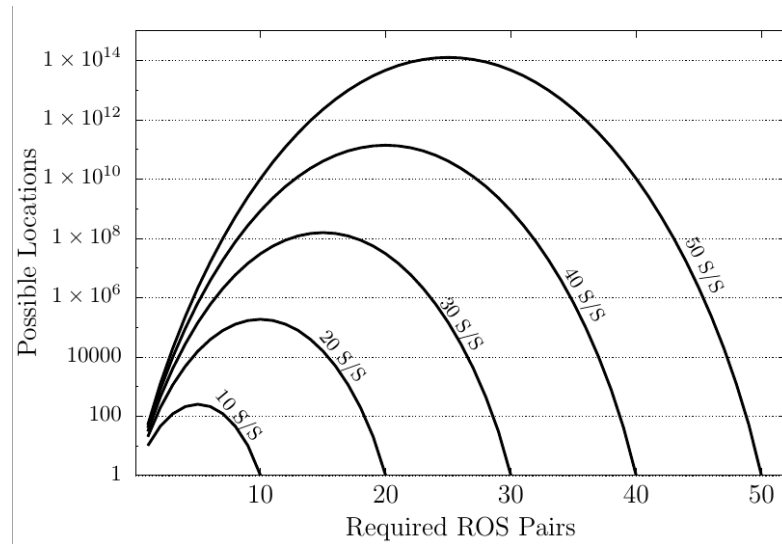


Figure 2-10: Possible combinations with increasing number of ROS pairs

### 2.2.2 Brute Force Methods

‘Brute force’ method is a systematic method that investigates every possible combinations to search for a solution or optimal solution. Here, the method will calculate the number of customers restored by considering all possible switch locations available in a network. The set of locations that produce the highest number of customers restored will be selected as the optimal location set. The process of searching for optimal locations of ROS pair by the Brute force method is illustrated in *Figure 2-11*.

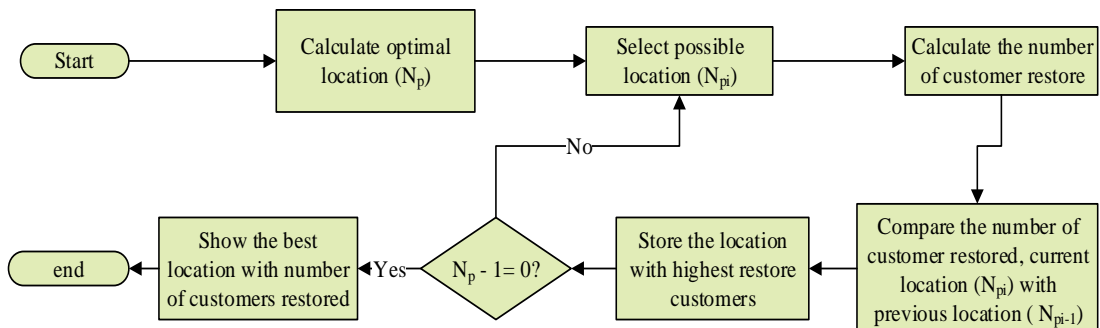
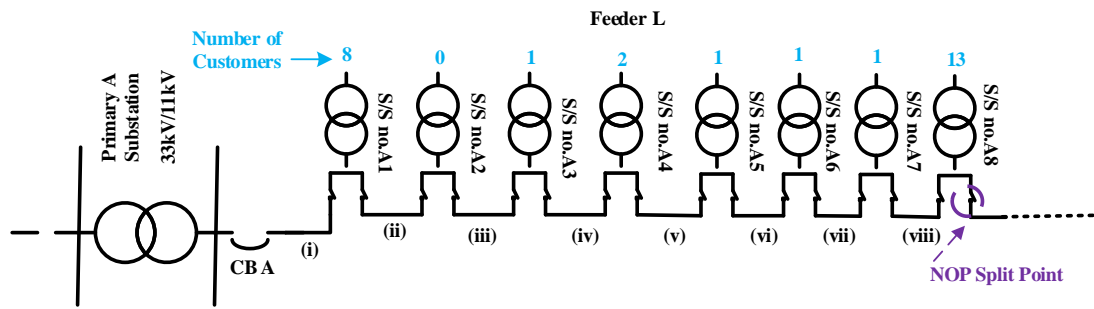


Figure 2-11: Flow chart for Brute Force method

The process begins by calculating the number of possible combinations available using Equation (2-1). The Brute Force systematically selects locations in a

network and calculates the number of customers restored if an outage occurs in the network. The number of customers restored will be compared with the result of the previous location set, if any. The location set with higher number of customers restored will be stored and the process of testing continues until all of the possible sets of locations are tested. The final output will represent the best location set with the highest number of customers restored. For example, if a network consists of 8 secondary substations, as illustrated in *Figure 2-12*, and searching for two optimal locations of ROS pairs, the possibilities of locations available by applying Equation (2-1) is given as:

$$N_p = \frac{8!}{2! \times (8 - 2)!} = 28$$



*Figure 2-12: Simple Network*

The Brute Force method will search for all 28 possible combinations of two ROS positions in a network. The results from this analysis, i.e. the location set with the highest number of customers restored will be selected as the optimal location set. *Table 2-2* tabulates all the possible locations of ROS pairs available, searching for one or two optimal locations of ROS pairs. Brute Force method is used in this study to search unlimited and increment numbers of ROS pairs.

This method is suitable to search optimal locations of ROS pair if the number of location combinations is of limited size and in such case relatively fast simulation time can be achieved. A detailed discussion of how to overcome the problem of simulation time using Brute Force is given in Section 3.2.8.

Table 2-2: Possible locations available if searching for one or two optimal locations of ROS pairs for eight number of substations

Number of ROS pairs	Possible Location							
	1	2	3	4	5	6	7	8
1	1,2	1,3	1,4	1,5	1,6	1,7	1,8	
	2,3	2,4	2,5	2,6	2,7	2,8		
	3,4	3,5	3,6	3,7	3,8			
	4,5	4,6	4,7	4,8				
	5,6	5,7	5,8					
	6,7	6,8						
	7,8							

### 2.2.3 Heuristic Methods

Heuristic comes from Greek word *heuriskein*, meaning to find or discover. Heuristic methods are used for solving optimisation problems and can be applied to a variety of difficult problems that have to be solved efficiently in a short or reasonable time. These methods only attempt to produce good results and not necessarily provide an optimum solution, and are also known as ‘approximate’ algorithms. A good heuristic algorithm should search a good solution in a reasonable time and with commensurable computational effort, and the solution should be near-optimal with high probability [92]. Most of the heuristic methods are designed to solve specific problems with the possibility of generalisation or application to other similar problems [93].

Heuristics method are divided into five categories [94]:

- i) Decomposition method – the problem is divided into sub problems for easy solving, and the sub problem belongs to the same problem class
- ii) Inductive method – the problem generalises to a simpler version and can be applied to the whole problem
- iii) Reduction methods – identifying properties that are mainly fulfilled by the good solutions and introduced as boundaries to the problem.

However, the objective is to restrict the space of the solutions by simplifying the problem. The risk is that the optimal solution of the original problem may be left out.

- iv) Constructive methods – building a solution to the problem using a step by step process from scratch. Usually, they are deterministic methods and tend to be based on the best choice in each iteration. These methods are widely used in classic combinatorial optimisation problems.

#### **2.2.4 Genetic Algorithms**

In nature, the individuals of a population adapt to the environment which they live in. The fittest individuals have the highest probability of survival and tend to increase in numbers, since their reproduction rate is high. The less fit individuals tend to die out if unsuitable with the environment. This principle is known as “survival of the fittest” and can be used in optimization. This concept of biological evolution in a search space or environment of a coded population of potential solution is known as a Genetic Algorithm or GA [95]. The principle producing the survival of the fittest or potential solution is to produce a better approximation to a solution or objective function. For each generation, a new set of approximations is created by the process of selecting individuals according to their level of fitness in the problem domain and breeding them together using operators taken from natural genetics [95]. The produced population of individuals suited to their environment or objective function are better than the individuals they are created from. For comparison purposes, it is considered that GA has a computational time advantage compared with Artificial Bee Colony (ABC) and PSO algorithms [69].

### **2.2.5 Simulated Annealing**

The word annealing refers to a physical process in metallurgy, heating it above melting point and cooling it slowly until it solidifies into a perfect crystalline structure. Physically, the process will produce high quality material. The simulation of this process is known as Simulated Annealing (SA). SA is composed of two stochastic processes; i) the process for generation of a solution, and ii) the acceptance of solution. The SA is designed to search for a global minimum among many local minima. The process of the algorithm is like searching for the best or shortest path to reach given locations. However, the time taken for this type of algorithm is very slow if repeated processes are needed; for example when searching for optimal locations of ROS pairs, a high number of iterations would be needed [96]. The method is also able to identify an optimal solution.

### **2.2.6 Mixed Integer Linear Programming**

Linear programming involves linear objective functions and linear constraints. For example, searching for a quantity or amount of two constraints by giving limits for each variable and the result produced should be optimal or the cost should be minimum. However, mixed integer linear programming involves problems in which only some of the variables are constrained to be integers and the other variables are allowed to be non-integers. For a problem involving protective devices placement, the constraints are mixed with locations of protective devices, outage cost, switch investment, operation and maintenance cost, customer types and load density. Protective device placement requires a set of binary variables. The constraint refers to the number of protective devices available for installation in case of budget inadequacy. However, MILP encounters difficulties when functions do not satisfy convexity conditions, for systems

having large combinatorial explosion or when the solution space is discontinuous. It is considered that this would be a problem during searching for optimal locations of protective devices in a large network.

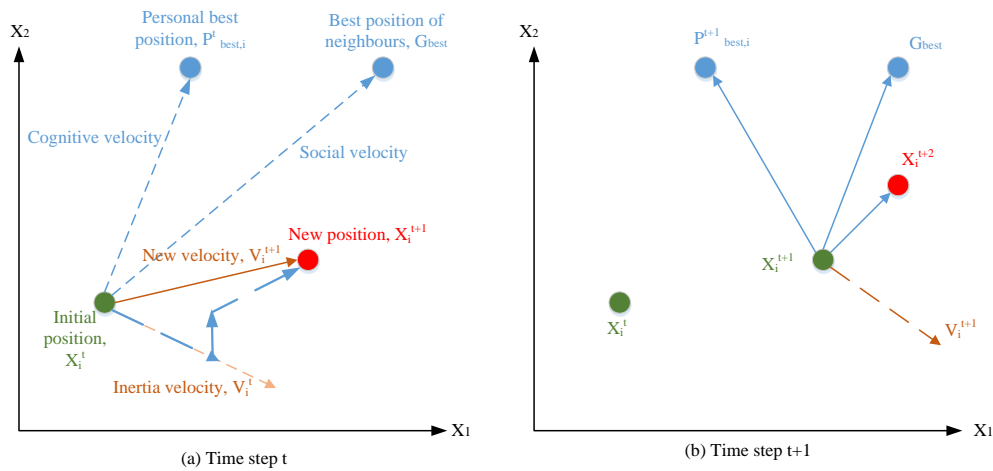
## **2.2.7 Particle Swarm Optimisation Selection**

A general overview of PSO and its application in system restoration are provided in the next subsections.

### ***2.2.7.1 General overview and concept of PSO***

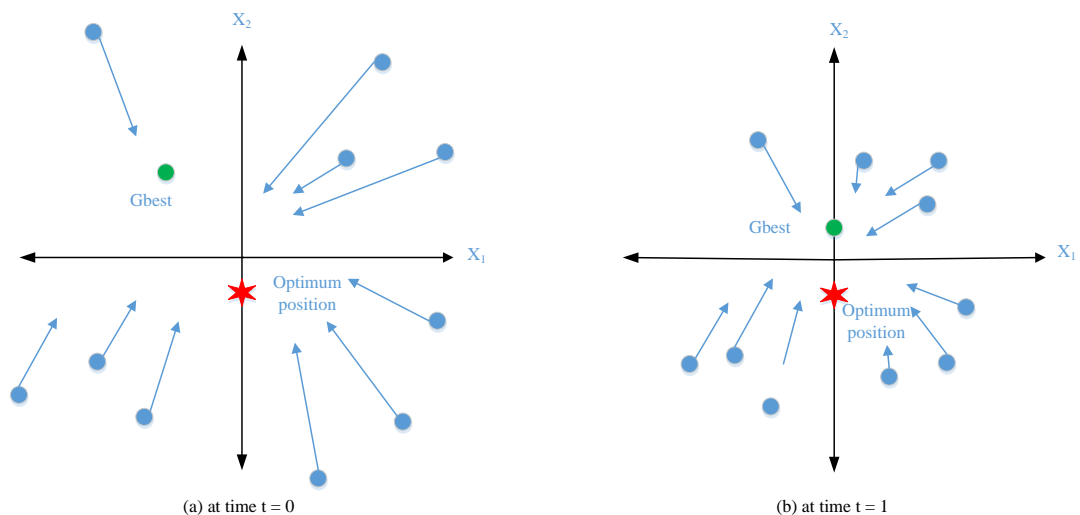
The PSO is a population-based optimisation randomized search technique introduced in 1995 [54]. This optimisation method is inspired by social interaction principles. It updates the population of candidate solutions called a swarm. Each candidate solution is called a particle or agent that is used in a search space to achieve an objective function (e.g. searching for optimal locations of protective devices). The PSO algorithm begins with a randomly generated population and each point in the population has a velocity vector as shown in *Figure 2-13*. Consider a movement of a single particle in a two dimensional search space. Three velocity components contribute to move the particle towards the global best position at time steps  $t$  and  $t+1$  respectively. Each particle is moving with an associated velocity to each possible point in space. The objective function at each point in the population is evaluated. Referring to the evaluated population, the new population of points is created together with a new set of velocities. Each particle keeps track of the best position based on the objective function. Under this condition, the best position of an individual particle is called “personal best” (pbest) and the overall best position among all positions encountered by the entire population is named as a “global best” (gbest). The particles keep interacting with each other and updating their velocities according to their pbest as well as gbest. The velocity of each

particle is changed at each time step towards a combination of its pbest and gbest locations as shown in *Figure 2-13* (b).



*Figure 2-13: Velocity and position update for a particle in a two-dimensional search space [97]*

Inertia velocity for (t+1) illustrated in *Figure 2-13*(b) calculated depend on inertia velocity at t and change upon each iteration. The velocity is weighted by a random term, with separate random numbers being generated for velocities towards pbest and gbest locations. Thus, the particles are drawn both to their own personal best positions as well as to the best position of the entire swarm as shown in *Figure 2-14*.



*Figure 2-14: Velocity and position update for multi-particle in Gbest PSO [97]*



The optimum position is denoted as “star” and given Gbest for more than one particle. At  $t = 0$  in *Figure 2-14 (a)*, the velocity and direction of component for all of particles is zero, and the particles are only attracted towards the best position by the social component. After the first iteration, all the particles move to new positions with a new global best positions as shown in *Figure 2-14(b)*. The stopping criterion is met when the algorithm reaches a certain number of iterations or by achieving a certain objective function value. The values of velocities and locations updated for each particles by using Equations (2-3) and (2-4) respectively.

$$V_{i(it+1)} = \left[ W_{(it)} + \left( C_1 \times R_{nd(0,1)} \times (pbest_{(it)} - X_{i(it)}) \right) + \left( C_2 \times R_{nd(0,1)} \times (gbest_{(it)} - X_{i(it)}) \right) \right] \quad (2-3)$$

$$X_{i(it+1)} = X_{i(it)} + V_{i(it+1)} \quad (2-4)$$

where:

- *it is the iteration number*
- *W is the inertia weight*
- *i is the particle's index*
- *X<sub>i</sub> is the position of particle i*
- *V<sub>i</sub> is the velocity of particle i*
- *C<sub>1</sub> is the acceleration constant for the cognitive component*
- *R<sub>nd</sub> is a random value between 0 and 1*
- *C<sub>2</sub> is the acceleration constant for the social component*
- *pbest is the best fitness of all visited locations of particle i*
- *gbest is the global optimum location of the particle i through iteration*

The weighting function (W), is a weighting factor related to the velocity of the particle during the previous iteration. It controls the amount of the previous velocity that particles take in the next iteration. This weighting function is obtained as:

$$W(it) = W_{max} - \frac{(W_{max} - W_{min}) \times it}{it_{max}} \quad (2-5)$$

- *it is the current iteration number*
- *it<sub>max</sub> is the maximum iteration number*
- *W<sub>max</sub> is the maximum weight (0.9)*
- *W<sub>min</sub> is the minimum weight (0.4)*

Reducing the weight can give better performance [98]. According to [99], [100] and [101], faster convergence is achieved if the value of the weight is between 0.9 to 0.4 [102]. So, this range of value is used in the research of this thesis.

The second parameter that has a significant impact on speed of convergence are the acceleration coefficients ( $C_1$  and  $C_2$ ). These values have an effect on the step size of a particle in a single iteration. The values of  $C_1$  and  $C_2$  regulate the maximum step size of a particle in the direction of pbest and gbest [102] respectively as shown in (2-2). As mentioned in [100], a time varying acceleration coefficients automation strategy for both  $C_1$  and  $C_2$  linearly decreased time during the course of a run. Simulation results show that fixed acceleration coefficients of 2.0 generated better solutions.

To avoid the particle velocity from escaping the search space, the equation of  $V_{max}$  (2-6) is used. The search space is defined by the bounds  $[X_{min}, X_{max}]$ . The value of  $X_{min}$  and  $X_{max}$  is the range of number of substations on a network. For example, if the total number of substations in a network is equal to 10,  $X_{min} = 1$  and  $X_{max} = 10$ . The value of  $V_{max}$  is typically set to:

$$V_{max} = k \times (X_{max} - X_{min}) \quad (2-6)$$

where;

$$0.1 \leq k \leq 1.0$$

The PSO is usually performed several times with different values of key parameters of  $k$  to achieve satisfactory results. The value of  $k$  may be valued from 0.1 until 1.0. A suitable  $k$  value is evaluated from 0.1 to 1.0 (increased by 0.1 for each step) and suitable  $k$  is selected when the simulation produces faster results with a correct answer.

In [103], a modification was made to the updating of the position of the particle by changing the direction for reaching the search space boundary to improve the speed of convergence. The direction of the particle modified to keeps the particle inside its range when the velocity takes the particle out of its boundary  $[X_{min}, X_{max}]$ . So the new position of the particle will be updated based on Equation (2-7) instead of Equation (2-4).

$$X_{i(it+1)} = X_{i(it)} - V_{i(it+1)} \quad (2-7)$$

If the optimal solution is close to the boundary, the ' $\alpha$ ' factor helps to reach the solution faster by using Equation (2-8) where  $\alpha$  is an optimally chosen number between 0 and 1. A value of  $\alpha$  chosen for this study was selected after several trials to be matched with different topologies of the network like the way of previous parameter selected ( $k$ ).

$$X_{i(it+1)} = X_{i(it)} - \alpha V_{i(it+1)} \quad (2-8)$$

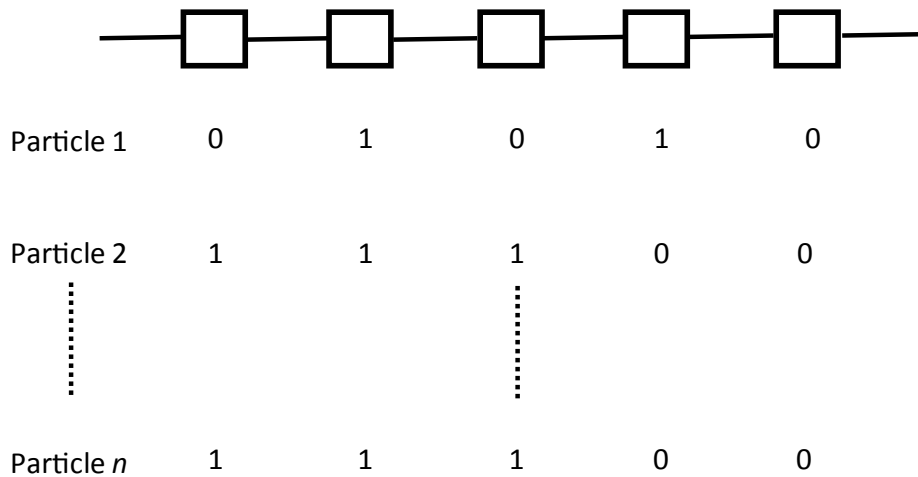
The advantages of using the PSO in handling the distribution system reconfiguration problem is manifold according to [104]. The PSO-based method achieves fast convergence with few required tunes parameters for suitable solutions. This statement is also supported by [105] where both PSO and GA were applied in searching of optimisation in the feeder reconfiguration problem. It was demonstrated that the PSO has faster convergence than the GA, and a better global search ability compared to GA, according to [106].

### ***2.2.7.2 PSO applied to a restoration of supply problem***

Swarm intelligence is a simple concept of the benefits of cooperation where, in a situation, information or knowledge of an environment is unknown, however some information is known. Individuals within a group interact with each other to solve the global objective by locally exchanging available information. At the end of propagating through the entire group, the global objective or problem can be solved more efficiently than can be done by a single individual [107]. The group in this case is defined as a swarm which is a mobile agent that communicates with each other in a local environment and interacts between agents resulting in a distributive collective problem solving strategies. The objective of computational swarm intelligence is to model simple behaviours of individuals and local interactions with the environment and neighbouring individuals to obtain more complex behaviours that can be used to solve complex problems. However, it was later found that PSO performs optimisation [107]. The PSO is a model comprising two simple behaviours in which each individual moves towards its closest best neighbour (best neighbour possible switch pair referring to network example) and moves back to the state that the individual has experienced to be the best location for itself. The particle moves along the path of the feeder at random possible locations. As an outcome, the collective behaviour that emerges from all individuals converges to the best environment or best locations state for them. In the numerical implementation of this simplified social model, each particle has four attributes; 1) the position vector in the search space, 2) the velocity vector, 3) the best position in its track and 4) the best position of the swarm.

### 2.2.8 Discrete Particle Swarm Optimisation (DPSO)

Some problems are not naturally suited to the conventional, continuous form of PSO. For example, it is difficult to frame a PSO algorithm to work with combinational problems, where a solution is defined within a set of discrete combinational options. In these cases, the basic principle of PSO may still be used, but instead of each particle moving in space towards the solution, a particle is instead defined as a set of states at each possible location. For example, in a 5-node feeder, with 5 possible locations for ROS pairs, a particle is defined as a group of ones on zeros which signify the state of each node. In this case, the state determines whether a ROS pair is installed (1 = yes, 0=no). *Figure 2-15* shows a group of  $n$  particles (in arbitrary states) on a 5-node feeder.



*Figure 2-15: Representation of each particle in DPSO*

Like the continuous version of PSO, DPSO works by calculating  $g_{best}$  and  $p_{best}$ , then attempts to pull each particle towards better solutions on each iteration. In the case of the 5-node feeder, the objective function would be run for each particle on each iteration, and  $g_{best}$  and  $p_{best}$  are updated. However, unlike continuous PSO, it is not obvious how each particle can intelligently move towards better solutions. A solution presented in [56] is to define each binary state as a probability,  $V_{j,k}$ . The  $V_{j,k}$  represents the likelihood that bit  $j$  in particle  $k$  are '1'. Instead of updating the particle's

position in space (as the continuous version of PSO does), in DPSO, it is the probability,  $V_{j,k}$ , which is adjusted on each iteration. If  $g_{best}$  represents a particular set of 1's and 0's with the current best global solution, DPSO will increase the probability of the corresponding bits in other particles of matching that set. The updated formula in DPSO, carried out on each iteration, is shown below.

$$V_{i+1} = V_i + C_1 \times rand(0,1) \times \Delta V_{i,1} + C_2 \times rand(0,1) \times \Delta V_{i,2} \quad (2-9)$$

Where  $c_1$  and  $c_2$  are learning factors (similar role to in the continuous PSO),  $V_i$  is probability of the next  $i^{th}$  (iteration) bit is a 1 and  $rand(0,1)$  is a uniformly distributed random number between 0 and 1.  $\Delta V_{i,1}$  and  $\Delta V_{i,2}$  can take only 3 values, -1, 0 or 1, and are used to direct the small changes in probability in the right direction (i.e. if a particle has a bit of 1 at some node location, but the  $g_{best}$  has bit 0,  $\Delta V_{i,2}$  will take on a value of -1 in an attempt to reduce  $V_{i+1}$ , and therefore reduce the probability that the given bit will still be a 1 on the next iteration.

$$\Delta V_{i,1} = p_{best_i} - X_i \quad (2-10)$$

$$\Delta V_{i,2} = g_{best_i} - X_i \quad (2-11)$$

It is clear to see that the two  $\Delta V$  variables depend on the comparison between  $p_{best}/g_{best}$  and  $X$ , where  $X_i$  is the current set of 1's and 0's for a given particle. The 3 outcomes are: 1)  $\Delta V$  is 1, when  $p_{best}/g_{best}$  are 1 and  $X_i$  is a 0 – this will direct the probability of  $X_i$  becoming a 1 on the next iteration, 2)  $\Delta V$  is 0, meaning that no change to the probability of  $X_i = 1$  will occur on the next iteration (it is already sitting on  $g_{best}/p_{best}$ ), 3)  $\Delta V$  is -1, meaning  $p_{best}/g_{best}$  is 0 and  $X_i$  is 1 – this will direct the probability of  $X_i$  becoming 0 on the next iteration. These calculations are how DPSO converges to better solutions.

$$X_i = \begin{cases} 1 & \text{rand}(0.1) < S(V_i) \\ 0 & \text{Otherwise} \end{cases} \quad (2-12)$$

Where:

$$S(V_i) = \frac{1}{1 + \exp(-V_i)} \quad (2-13)$$

Where  $S(V_i)$  is the sigmoid limiting transformation. The role of this is to convert  $V_i$ , which may vary between  $-\infty$  and  $+\infty$ , to a probability between 0 and 1. In [108], it was suggested that  $V_i$  be limited to  $\pm V_{max}$  order to discourage entrenched solutions. Setting  $\pm V_{max}$  to 5 will limit the range of probabilities to 0.9933 and 0.0067.

The reason behind the selection of the DPSO as a medium for searching the optimal locations of the ROS pairs is that the PSO technique is considered to have fewer required parameters than a standard GA and it is highly resistive to be stopped at local optimisation points [56]. Swarm intelligence optimisation methods or meta-heuristic methods have been widely used in the distribution system reconfiguration for reliability enhancement. However, among these methods, the DPSO-based method is recognized as the most viable tool in solving reconfiguration problem of the distribution system for reliability improvement. MATLAB code has been written to implement a binary version of DPSO.

### **2.3 REVIEW OF CURRENT ELECTRICAL NETWORK TECHNOLOGY: STATE OF THE ART AND FUTURE REQUIREMENTS**

Following a recent report [81], there are a number of automated switching schemes associated with securing the 132kV and 33kV networks which have been applied in the East Midlands in the UK. These are a mixture of automatic load transfer (generally break before make), auto close and last resort de-load which involve switching on the 132, 33 and 11kV networks [109]. Auto-reclosers are also applied on

all predominant overhead circuits for the 132 and 33kV networks to restore supplies or maintain the integrity of the network. There are also plans to reduce a number of customers affected by 11kV faults and restore supply quickly together with ongoing initiatives to install more protective zones and remote control on the 11kV network.

### **2.3.1 SCADA Systems**

According to [14], the majority of proposed automation strategies are for centralised Supervisory Control and Data Acquisition (SCADA) systems as they are currently implemented by the majority of DNOs. The basic SCADA architecture begins with programmable logic controller (PLCs) or remote terminal units (RTUs). PLCs and RTUs are microcomputers that communicate with an array of objects, such as factory machines, human machine interface (HMIs), sensors and devices [110]. The information is routed from those objects to computers with SCADA software. The SCADA software process the information, distributes and displays the data, helping operators to analyse the data and make important decisions. The availability of SCADA in the distribution network system will help the application of automation system with extra information provided between plant and control centre. Monitoring processes will become much easier if remotely operable switches are applied.

### **2.3.2 Intelligent Devices**

It has been demonstrated that there is a need to convert or transform power distribution networks to smart grid systems to increased reliability and reduce interruption costs. Instead of operating the system manually during restoration by sending the crew to plant, DNOs are searching for devices with the capability to restore customers from an outage area automatically without requiring the mobilization of a



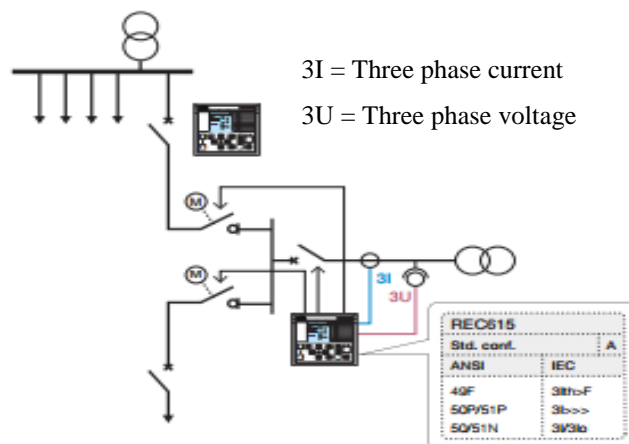
crew to the plant. Therefore, such demand from DNOs has built competition among suppliers to produce devices with automation features and user-friendly interfaces to accomplish the need of automation systems. Such plant are also known as intelligent devices.

To be inline with today's need of improvement of reliability of a network, most electrical equipment companies are working on developing new technology in the form of intelligent switching devices that have capability to monitor, protect and control a network. Companies such as Siemens, ABB and Schneider are all active in producing updated technology for automation systems. Such companies provide intelligent controller systems that helps the network to protect the network and isolate a fault, restore the network and send the data and report to the DMS without operators interface. Such products come with variety of functions and user friendly characteristics [111][112].

In network operations, one of the most promising emerging technologies in recent years is the feeder switching device with Intelligent Electronic Device (IED). The device with IED has automated capabilities such as measuring, monitoring, control and communication functions that enable it to implement automated fault identification, isolation and power restoration [35]. Such devices, although more expensive than conventional switches offer potential overall benefits with customer outage savings. The economic case for investment in such devices will be more compelling if capital investment costs can be minimized by identifying optimal numbers and locations on the network. An important feature of such devices in the context of this research is the ability to determine whether fault current has passed a particular point in the network, which enables the fault location on a feeder to be identified.

### 2.3.2.1 Automatic Switches and Circuit Breakers

One of the most recently developed controllers is known as Siemens Distribution Feeder Automation (SDFA) introduced by Siemens in 2013, with capability to (i) detect a fault location on a line section, (ii) sectionalize the faulted section and (iii) to restore power to unfaulted sections via an alternate power source up to the point of its rated capacity [113]. The controller operates as a self healing medium to operate the recloser and circuit breakers. If there are temporary faults, the SDFA will clear the fault and restore the section back to normal condition but, if there are permanent faults, a message will be sent to the outage management system to dispatch a line crews to solve the problem. The company claims the process of reconfiguration of healthy sections could be completed in less than half a second. The controller is also designed to have the ability to send information to a SCADA system if needed. Details of switch controllers produced by different companies are shown in *Table 2-3*. *Figure 2-16* illustrates the switch controller produces by ABB also designed with protection, automation, measuring and monitoring of the power system. The controller has the ability to do automatic switching for pairs of switches and could send the information, if needed, to DMS.



*Figure 2-16: REC615 switch controller by ABB [114]*

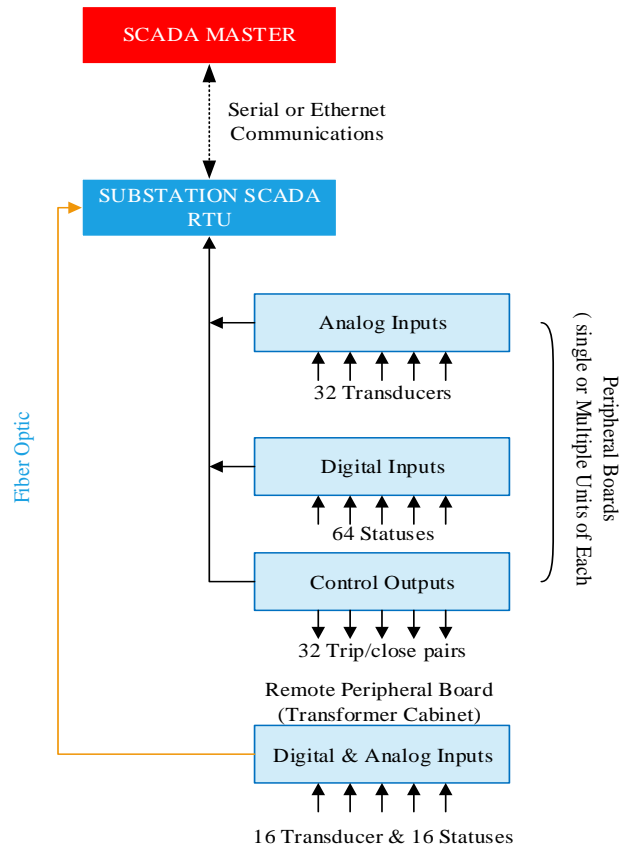
Table 2-3: Currently available intelligent switch controllers

Company		ABB	SIEMENS	SCHNEIDER	
Dedicated Location		Overhead	Underground and overhead line	Underground	Overhead
Product Name		REC615	SIPROTEC 5	Easergy R200 and ATS100 (underground)	Easergy T200 P
Year Produced		2015	2013	2014	2014
Capacity		one breaker and 8 load-break switch via HMI or remote system	NI	NI	Control of 1 or 2 switches, PM6 or other load break switches
Communication Interfaces and Protocol		IEC 60870-5-101/104, DNP3 level 2 and Modbus, simultaneously also supporting IEC 61850 with GOOSE messaging	IEC61850	Modbus/IP, IEC 870-5-101/104, DNP3, DNP3/IP	IEC 870-5-101 and IEC 870-5-104, Serial DNP3 and TCP/IP, Serial Modbus and TCP/IP, Other proprietary protocols
Controller	Rec	Both	Both	Both	Both
	CB	Both	Both	NI	NI
Operation Mode	Manual	Both	Both	Both	Both
	Auto	Both	Both	Both	Both
Main Features		Provides superior fault location, isolation and restoration (FLIR) to lower the frequency and shorten the duration of faults.	Protection, control, monitoring, and measuring. Intelligent network automation functions and communication.	Control and monitoring through embedded devices in MV switchgear. Ensure remote control and automated management.	Switch monitoring and control. Fault passage detection phase-to-phase and phase-to-earth faults. Automation systems: sectionaliser, automatic power source transfer.

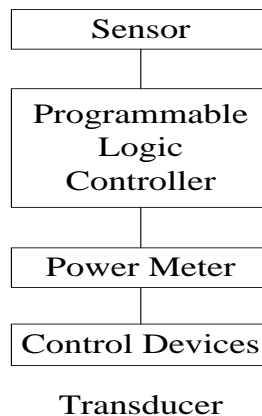
### 2.3.2.2 Transducers

The process of sending data from substations to DMS using conventional methods with SCADA implementation are shown in Figure 2-17. A traditional hardwired SCADA architecture consists of discrete transducers mounted throughout the substation measuring current from currents transformer (CTs), voltages from potential

transformers (PTs) and station batteries, and power (MW and Mvars) from the combination of these transducers [112]. Transducers is sensor used to convert energy from one form to another. Example of typical transducer encountered in a typical SCADA shown in *Figure 2-18*.



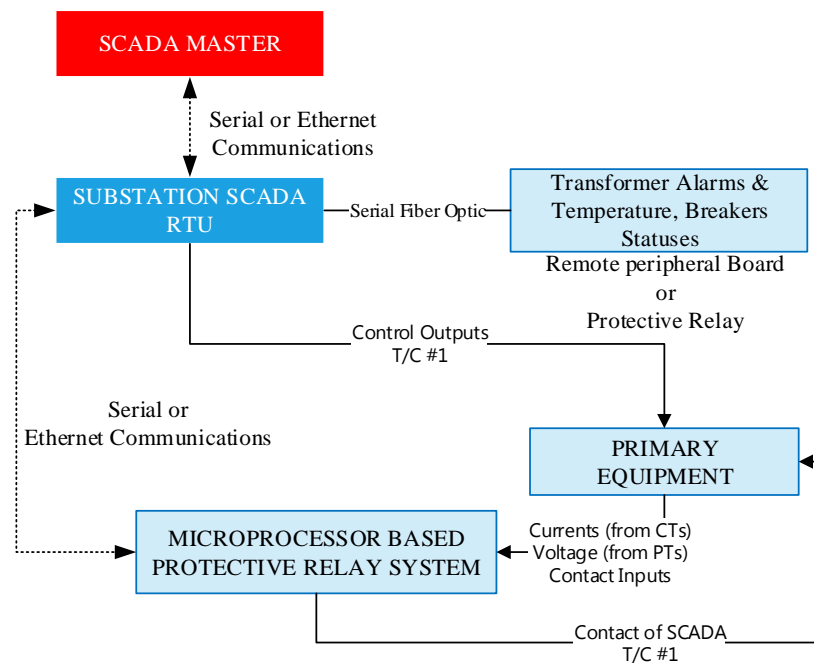
*Figure 2-17: Traditional hardwired SCADA architecture [112]*



*Figure 2-18: Transducer in a typical SCADA*

In newer substations, that fully utilize microprocessor based relays and meters as IEDs, metered data can be used to provide the same capability and communicate it digitally to the RTU. By using a communication protocol such as IEC61850, DNP3 and Modbus RTU, the data can be sent by IEDs with settable scaling factors and also with multiple simultaneous connection to the devices.

Transmitting the analog signals from the substation primary equipment is best accomplished by direct substation SCADA RTU communications to IEDs via serial or Ethernet communications as shown in *Figure 2-19*. This new technology will eliminate the discrete transducer hardware and remove associated installation (less copper wire), operating and maintenance costs, and improve reliability by reducing the hardware to manage [112].



*Figure 2-19: Merger of SCADA and P&C within substation [112]*

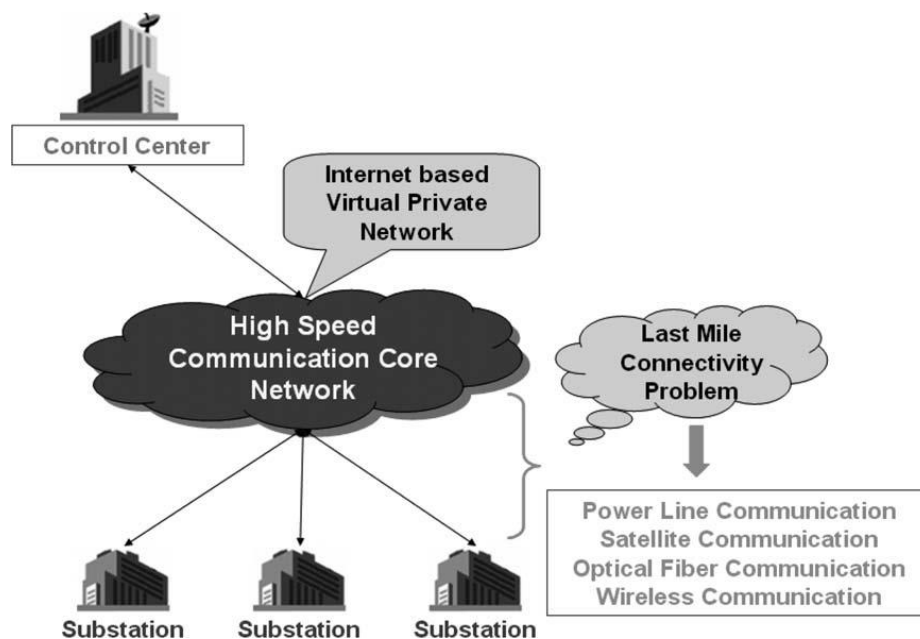
### 2.3.3 Communication Requirements

Recent developments in communication technologies have enabled reliable remote control systems, which have the capability of monitoring the real time operating

conditions and performance of electric systems [115]. Communications technologies are classified into four classes, Power Line Communication, Satellite communication, Wireless communication and Optical Fiber communication. Communication technologies between substations and a remote control center are required to be highly reliable, scalable, secure, robust and cost-effective [116]. Transmitting the information or data via the internet cannot guarantee very strict Quality of Service (QoS) requirements as demanded by automation systems and there is also a cyber security concern. Internet based Virtual Private Network (Internet VPN) technologies are used, which transform the internet into a secure high speed communication network and providing strict QoS guarantees for electric systems automation applications [117]. Internet VPN technologies offer a shared communication network backbone in which the cost of the network is spread over a large number of users while simultaneously providing the benefits of a dedicated private network [115]. Internet VPN technology can be claimed as a high speed communication core network and can be utilised to enable minimum cost and highly reliable information sharing for automation applications. Internet VPN technologies are considered as reliable communication for substations in urban areas but not suitable for rural areas because a high speed communication core network might not be available. For this reason, a hybrid communication network has to be considered in this situation. *Figure 2-20* illustrates a hybrid communication network (Internet VPN and last mile connectivity) for an electrical network with communication medium availability.

‘Last mile’ represents a challenge of connecting substations to the high speed communication core network. The last mile connectivity media can be classified as; i) power line communication ii) satellite communication iii) optical fiber communication and wireless communication [115].

Developments in communication technologies and the international communication standard for electric system automation are tabulated in *Table 2-4*. Most recent communication protocols and standards use TCP-IP, IEC 61850 and XML. However, IEC61850 is the most popular in IED for sending data. Sending data via IEC 61850 communication protocol is one of the well-known communication medium between network and control center. The communication system protocol in IEC 61850 is normally adopted with distributed Network Protocol LAN or wide area network (WAN). To employ this protocol, a gateway is needed to collect and process data from the IEDs via IEC 61850, converting these data to LAN or WAN and sending those to the local HMI and the remote control centre [118].



*Figure 2-20: Overall communication network architecture for electrical system automation [115]*

Most of the devices use the same communication medium. However, there are limitations of IEC 61850 during handling incoming messages and processing cryptographic computation depending on the number of packets [119]. IEC 61850 exchanges messages between substations by using General Object-Oriented Substation (GOOSE) or sample value message. To ensure the security of messages, authentication

and integrity are needed during substation operation. If the messages are false, it may cause a disastrous result in the substation protection operation. The security objectives are to assure only authorized access within the system and prevent spoofing and playback of captured data from non-trusted entities. The disadvantages of the GOOSE and sample value message with limited computing power and memory in that packet loss can happen [119]. Other types of communication media include Modbus and DNP 3.0 Level 2- all using TCP/IP but some of them only communicate with selected protective devices or controllers. However, IEC 61850 communication implementation supports all monitoring and control functions.

*Table 2-4: Summary of communication system development activities for electric utilities [115]*

Phase	Years	System Characteristics	Network Architecture	Communication Media	Communication Protocol and Standard
Local Area Networks (LANs) and Wide Area Networks (WANs)	1995 - 2000	• Introduction of LANs in substations	• peer to peer communication in substation	• Ethernet	• TCP-IP
		• Merging protection and SCADA networks	• joining substations via WAN	• spread spectrum radio	• FTP
				• frame relay	• Telnet
				• megabit data rates	• HTTP
					• DNP3 WAN/LAN
• UCA 2.0					
Integration into Business	2000 to present	• Merging automation and business networks	• linking of utility WAN to corporate network	• digital cellular	• TCP-IP
		• corporate IT departments	• extension of network to customer premises	• IP radios	• IEC 61850
		• Asset management	• use of internet	• wireless ethernet	• XML
				• gigabit backbones	



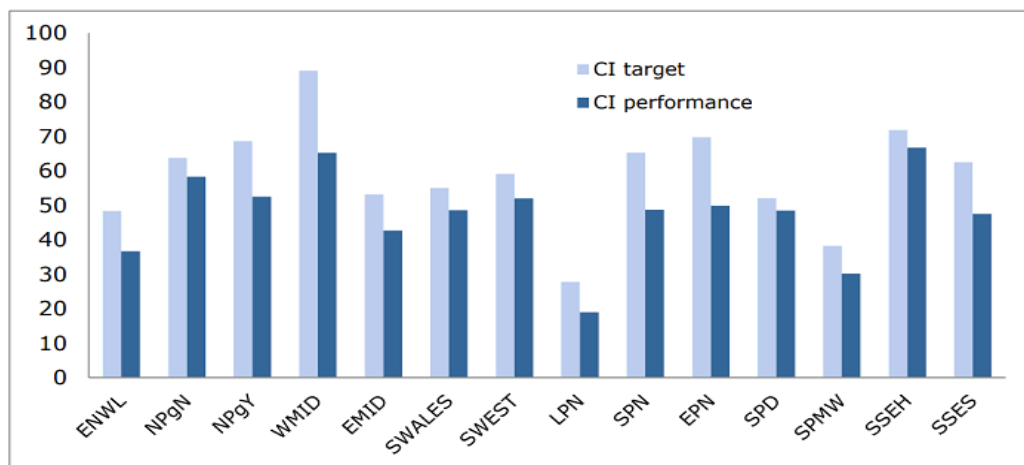
To overcome the problem with packet loss or non-processing, other communication media known as power line communication may be needed. Power line communication provides packets of information between remote nodes in a distribution network to the control center if any event (e.g. a fault) occurs within a timescale and does not exceed the time it takes for protection circuitry to operate [120]. An Overhead Line Monitoring System (OHMS) device (device capable of remotely processing captured data) may be used to communicate in digital form between other devices and the control center. The device would allow the control center to access real time voltage and current information, also implementation of new fault location schemes. The information is sent using a single 256 or 512 subcarrier orthogonal frequency division multiplexing (OFDM) symbol with differential binary phase shift keying (DBPSK) or differential quadrature phase shift keying (DQPSK) which could provide enough capacity to convey the information. Within 300ms, approximately 40 transmitters are able to transmit in 512 subcarrier systems, and around 60 and 80 can transmit in a 256 and 128 subcarrier system respectively. The highly parallel nature of digital electronics allows several processes to be carried out simultaneously at the remote node, increasing the processing power of each device and easing the communication burden. This proposed communication medium is suitable for better decision making and avoids loss of packet data during the application of the automated protection and control plant on the HV network.

Some power utilities [52], have implemented a control system for a decentralised model of operation centre in each region of the state (16 distribution centres). A general Packet Radio Service (GPRS) was installed in each equipment at each distribution operation center for transferring information from the equipment (reclosers, voltage regulators and three pole switches). In the area without GPRS

availability, an alternative communication medium was used, e.g satellite communication or digital radio. A disadvantage of this project is that the human resources needed are larger for a decentralised system compared to a centralised system. Communication systems in the countryside or smaller cities are also often seen as challenges in obtaining a good signal coverage.

## 2.4 COST BENEFITS ANALYSIS

There are 14 DNOs owned by six companies in Great Britain. Each year, all network companies are evaluated by OFGEM in terms of performance. A report from OFGEM has compared the rewards from CI and CML for 2015-2016 earned by each DNO. *Figure 2-21* shows the customer interruptions for DNOs with the CI target by OFGEM and CI real performance. The CML target and performance shows in *Figure 2-22*. *Table 2-5* tabulates the summarise from the Interruption Incentive Scheme (IIS) for the DNOs for year 2015-2016 with total of £160m. IIS is financial reward (or a financial penalty) depending on their performance against a target for both the number and length of their network supply interruptions.



*Figure 2-21: Number of customer interruptions per 100 customers on the network [11]*

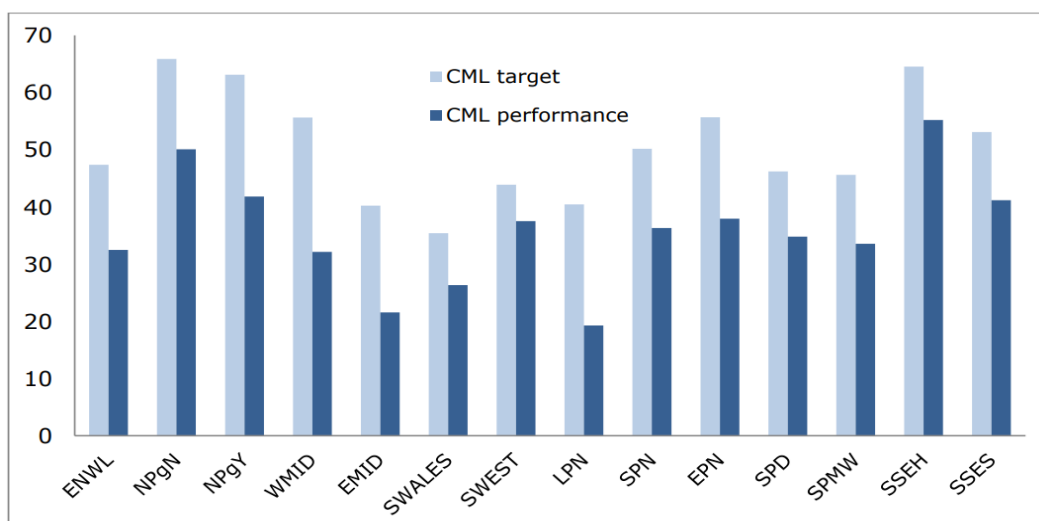


Figure 2-22: Durations of customer interruptions [11]

Customers received more than £1.5m in payments for supply interruptions in 2015-2016. Between the 2014-2015 and 2015-2016 periods, CI and CML decreased by 9% and 12% respectively [11].

Table 2-5: IIS performance [11]

DNO	CI Reward (£m)	CML Reward (£m)	Total Reward	DNO Ranking (Based on CI Performance)	DNO Ranking (Based on CML Performance)
ENWL	3.34	10.2	13.54	3	5
NPgN	0.96	7	7.92	12	13
NPgY	4.16	13.55	13.88	11	12
WMID	8.41	20.28	18.77	13	4
EMID	3.92	17.16	18.13	4	2
SWALES	1.03	3.55	4.58	8	3
SWEST	1.60	3.51	5.11	10	10
LPN	2.19	12.86	13.8	1	1
SPN	4.1	8.32	12.08	9	9
EPN	7.72	16.79	21.32	5	7
SPD	0.79	6.05	6.86	7	8
SPMW	1.32	4.77	6.12	2	6
SSEH	0.47	1.96	2.36	14	14
SSES	4.17	10.84	15.98	6	11
<b>Total</b>	<b>45.18</b>	<b>136.8</b>	<b>160.43</b>		

Therefore, to achieve the target set by OFGEM, each DNO is incentivised to plan to reduce the CI and CML. For an example, WPD is one of the DNOs that has made a move to increase the reliability of their service by increasing the speed of restoration. An initiative of increasing the reliability known as “Target 60”, aims to restore supplies to as many customers as possible within one hour of a fault on the HV network [121]. In 2012 – 2013, 87.1% and 85.7% customers were restored within one hour for WPD West and East Midlands and WPD South Wales and South West respectively. However, the “Target 60” is still considered high, and an improvement by reducing the time from 60 minutes to less than 3 minutes would be highly economically beneficial to DNOs. In addition, customer satisfaction and reliability on the given service by the DNO has a high impact on the customers loyalty to a particular DNO. According to the UK government website, over £16 billion has invested to increase the system reliability since 2002 and reliability has been improved by 30% [122].

Nevertheless, building and operating an electric power system that is 100% reliable is not economical [123]. The financial viability of the proposed improvement on the reliability of the distribution network has been demonstrated to give a diminishing return on the investment of the ROS pairs. In alignment with the main objective of this research, the identification of minimal and optimal placement of ROS to achieve maximum gain is likely to gain most interest from DNOs in the context of the financial regulatory framework.

*Table 2-6* shows the actual fault rate and duration for the three case study networks that are to be used in this thesis between 2012 and 2013. From the first observation, it is clearly seen that the rural network is far more prone to faults than both the urban and semi-urban networks. The main reason for this is the high number and route length of overhead lines present in the rural network. In rural networks, majority

of the network is form from overhead line and, hence, the fault rate is higher in comparison to the urban networks that cover mainly of underground cable sections. Most overhead lines experience transient faults such as trees touching conductors, and lightning strikes which are automatically restored by auto-reclosers that are installed on the network. On the other hand, semi-urban networks have a mixed installation comprising both underground cables and overhead lines.

*Table 2-6: Fault rates including CI and CML values [124]*

Network	Total Number of Incidents	Total Customers Minutes Lost	Total Customers Interrupted	CI Value (£)	CML Value (£)	Total Value (£)
Urban	7	41,740	522	8,007.48	15,608.14	23,075.62
Semi Urban	10	113,334	2,954	45,314.36	40,917.18	86,231.54
Rural	27	193,167	3,876	59,457.84	69,733.29	129,191.13

As expected, the rural network scores a large amount of excess expenditure to customers due to its high frequency of faults occurrence. In this case, the highest total interruption costs are paid to rural and semi-urban customers compared with urban customers. The value of CI and CML calculated by using data from *Table 2-6*;

$$\begin{aligned}
 \text{Value CI} &= \frac{\sum \text{CI Value per year}}{\sum \text{Customers Interrupted}} = \frac{\text{£8,007.48}}{522 \text{ customers}} \\
 &= \text{£15.34 per } \frac{\text{customer}}{\text{year}}
 \end{aligned} \tag{2-14}$$

$$\begin{aligned}
 \text{Value CML} &= \frac{\sum \text{CML value per year}}{\sum \text{Customers Minutes Lost}} = \frac{\text{£15,608.14}}{41,740 \text{ minutes}} \\
 &= \text{£0.36 per customer / minute}
 \end{aligned} \tag{2-15}$$

By adding a protective devices in a network, the payback period for the investment cost versus cost of CI and CML can be calculated by using Equations (2.14) and (2.15) and the cost of each protective device given by [125] is equal to £1450. However [126], assume the cost of switch higher, £17 000 per switch including

installation cost. So, from the [125] and [126] research cost of the switch has a huge different for both analysis.

The outage cost for each customer can be given by:

$$\text{Customer Outage Cost} = CI + (CML \times \text{minutes loss}) \quad (2-16)$$

By using data from *Table 2-6*, the total CML is 41,740 for urban network and the customers outage cost can be calculated as:

$$\text{Customer Outage Cost} = 15.34 + 0.36 \times \frac{41740}{522} = \text{£ } 44 \text{ per customer failures}$$

Benefit of adding a switch on a network can be calculated as:

$$\text{Total cost of switches} = \text{cost of a switch} \times \text{number of switch}$$

$$\text{Total customers outage cost}$$

$$= \text{number of expected customers restored} \times \text{£}44$$

*Net benefits of adding switches*

$$= \sum \text{cost of switches} - \sum \text{customers outage cost} \quad (2-17)$$

Equation (2-13) will be used in this thesis as an objective function to evaluate a beneficial of adding switch on a networks. Negative value cost from Equation (2-13) means beneficial of adding a switch on the network and if the positive cost, the cost of switch much higher than customer safe from outage cost, there are no beneficial for the DNO. Example of calculation can be made by assuming cost a protective device is £1000, outage cost per customers per year is £44 and expected restored 50 customer failures/year one switch install.

$$\text{Net benefits of adding switches} = (1 \times 1000) - (44 \times 50) = -\text{£}200$$

From the calculation, the net benefits of adding the customers is shown negative value. There are beneficial of adding the switch on the feeder.

Specifically, rural 11 kV networks have the highest potential to benefit from the restoration algorithms. If utilised efficiently, it could significantly reduce CML and CI rates. However, there is normally a smaller number of customers on rural networks compared with urban networks. The addition of CML optimisation obtained from the optimisation of the locations of the protective devices would allow the restoration algorithm to prioritise restoring ‘high priority’ loads and the loads with high density of customers.

## **2.5 CONCLUSION**

From the review, it is recognised that a fully-automatic distribution system would involve a very high cost that may make the investment uneconomic. Therefore, optimal selective deployment of automated devices on the system offers a more economic possibility. While many methods have been developed for reliability assessment of complex distribution systems [63], [64], [66], [68], [127] few studies focus explicitly on identifying the optimum locations of pairs or clusters of sectionaliser switches and others are associated with examining single open split points on ring feeders rather than a pair. According to the literature, therefore, previous work has focused on searching for optimal locations of a single switch on a limited possible number of locations in the network.

The review has identified the commercial availability of protective devices and controllers, specifically designed for distribution automation. Such equipment will help the DNOs to improve the reliability of the network and at the same times offer opportunities to save CI and CML. The work of this thesis will extend research in this area to propose a technique that will obtain an optimal solution to the required numbers and locations of automated switch pairs (ROS pairs). Unlike previous work, the aim is

that there will be no restriction on the number of possible location combinations in the network. Furthermore, the technique will be applied to representative examples of real selecting systems (urban, semi-urban and rural) and also an artificial network with very large number of substations (122 substations).



## CHAPTER 3

# OPTIMISATION OF LOCATION AND NUMBER OF PROTECTIVE DEVICES

### 3.1 INTRODUCTION

As described in Chapter 2, a fully automated distribution system allowing complete upstream and downstream restoration from an alternative supply would provide the highest level of security of supply for radial-type distribution networks. However, this level of automation would likely come at a prohibitively high cost. Nevertheless, any degree of automation would provide an improvement in reliability, though this raises two questions: (i) what degree of automation is best, i.e. how many automatically controlled switch pairs should be installed and (ii) of this certain number, where should they be placed to achieve maximum benefit. One can say, therefore, that there is a requirement to optimise the overall number of switches and their placement. With regard to the former, it would be an economic optimisation determined by a cost benefit analysis, while for the latter, the optimisation is determined by the arrangement that delivers the maximum number of restored customers kW. In general, optimisation can be described as a sophisticated analytical technique which aims to find the “best” solution to a particular problem, with due consideration to cost and other constraints. Specifically in this work, five types of optimisation have been investigated: targets (optimum number of restored customers), limits (optimum reliability), choices (optimal locations of the ROSpairs), cost benefits related with switch and customers outage cost; and data (characteristics of the networks).

The main objective function of DPSO and Brute Force is designed to search for optimal locations of ROS pairs with optimum number of customers restored. The DPSO

and Brute Force should be able to search an unlimited number of optimal locations of ROS pairs on different types of network. Different equations are used for different network topologies, with one of the most important characteristics being whether it includes branches. The complexity of the equations to achieve maximum objective function will increase when the number of branches for the feeder increases. The objective function equations used in the DPSO and Brute Force Method are discussed in more detail in the following section.

### 3.2 PROBLEM FORMULATION – OBJECTIVE FUNCTION

Mathematically, the expected number of customers restored upstream and downstream is formulated as an objective function. The objective is to maximise the expected number of customers restored upstream and downstream with the selected optimal location of ROS pairs. Two general expressions may calculate the expected number of customers restored are shown by Equations (3-1) and (3-2). Both equations give the same expected number of customers restored. The difference between the equations is the method to calculate the expected number of customers saved supply. Equation (3-1) calculates the expected number of customers restored upstream and downstream separately and the summation of these two components will produce the total expected number of customers restored.

On the other hand, Equation (3-2) calculates the same in reverse. Here, the total expected number of customers restore is calculated by the total number of customers on a feeder less the total expected customers that lose supply.

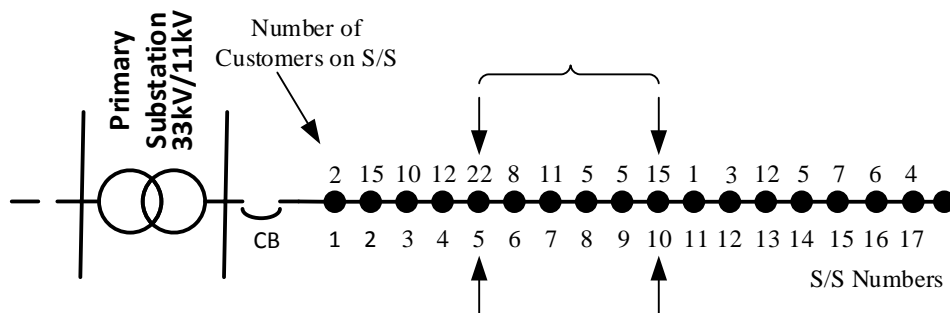
$$N_T = \textit{Upstream Customers Saved Supply} + \textit{Downstream Customers Restored} \quad (3-1)$$

$$N_T = (Total\ customer\ on\ a\ feeder - total\ customer\ loss\ supply) \quad (3-2)$$

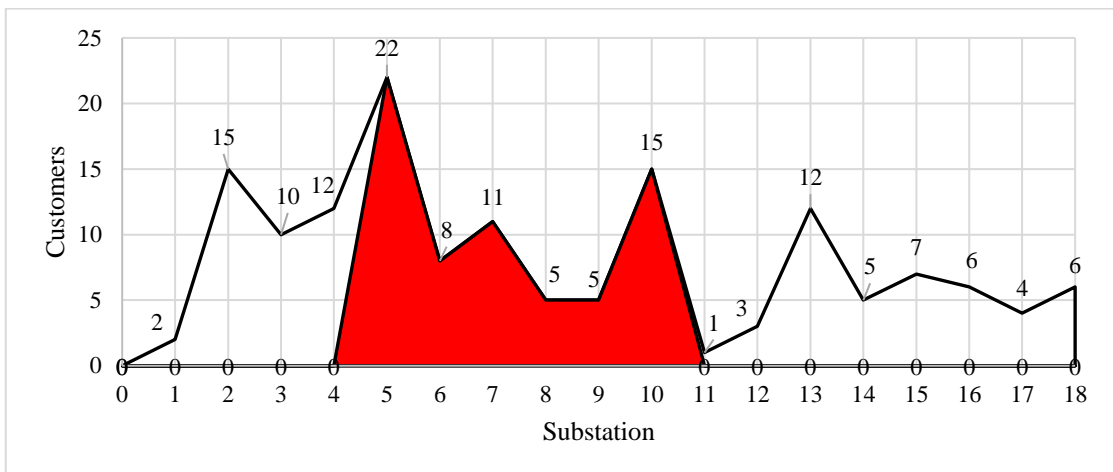
Where;

$N_T = Expected\ Number\ of\ Customers\ Restored\ per\ fault$

The question as to whether Equation (3-1) or Equation (3-2) is used to calculate  $N_T$  is determined by the efficiency of the calculation, i.e to minimise the simulation or calculation time. For example, a network with 18 substations is shown in *Figure 3-1*. Here, the number of customers bounded by two switches (S/S 5 and 10), calculated by a pre-allocation matrix is illustrated in *Figure 3-2*. Details of the pre-allocation matrix written are given in Section 3.2.6. It can be seen that the number of customers bounded by two switches = 22 + 8 + 11 + 5 + 5 + 15 = 66 customers.



*Figure 3-1: Single feeder network with 18 substations*



*Figure 3-2: Customers bounded by two switches*

The mathematical expression for the Equation (3-1) and (3-2) are given by Equation (3-3) and (3-4).

$$\max(N_{TROSji}) = \sum_{i=1}^N N_{Ti} = \sum_{i=1}^N (N_{ULRj} + N_{DLRj})i \quad \text{for all possible } N_{fs} \quad (3-3)$$

$$\max(N_{TROSji}) = \sum_{i=1}^N N_{Ti} = \sum_{i=1}^N (N_s - N_{LS})i \quad \text{for all possible } N_{fs} \quad (3-4)$$

Where:

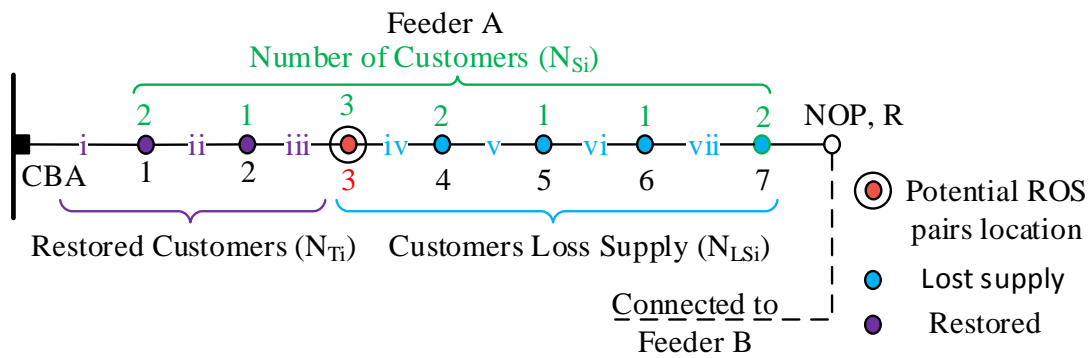
- $N_{TROSji}$  is the total number of expected customers restored downstream and upstream for all possible fault (from 1 to N) for any number of ROS pairs
- $N_{fs}$  is the number of the faulted section
- $N_{ULR}$  is the total number of expected customers restored upstream / per fault
- $N_{DLR}$  is the total number of expected customers restored downstream / per fault
- $N_T$  is the total of expected customers restored downstream and upstream /per fault
- $N$  is the total number of S/S on a feeder
- $j$  is the number of the ROS pairs
- $i$  is the possible location of fault
- $N_s$  is the number of customer on a substation
- $N_{LS}$  is the expected number of customers that lose supply after restoration

Equation (3-4) has been chosen and applied in this research because the simulation time is much less compared to first method. Instead of searching the number of upstream and downstream customers separately and adding up the total number of customers restored, Equation (3-4) searches the total number of expected customers restored by using Equation (3-14). The equations required to determine the expected number of customers loss supply depend on the topology of the network. Therefore, a challenge in this work is to develop and implement an algorithm which is “generic” in

the sense that it can evaluate the objective function for an arbitrary network and with minimal user intervention. More details regarding the calculation of numbers of restored customers are provided in Sections 3.2.1, 3.2.2 and 3.2.3.

### 3.2.1 Customers Restored Assessment For A Single ROS Pair

The method to calculate the number of customers restored for a feeder without branches is shown in *Figure 3-3*. The ROS pair, which in the figure is placed at an arbitrarily selected position, is to be placed somewhere along Feeder A and the task is to determine its optimal position, defined as the position which maximises the expected number of customers restored.



*Figure 3-3: One-line diagram of Feeder A and B of network reconfiguration if single ROS pairs placed at S/S 3*

To calculate the number of customers restored for a feeder without any branches and with one ROS pair requires two sub-calculations. Consider the example where substation No.3 is chosen as a possible locations for an ROS.

**Sub-calculation (i):** Outage occurring in section (i), (ii) or (iii)

The subsequent calculations now calculate the number of customers losing supply should a fault occur at any other position on the network. Consider first, a fault occurring on Section (i) on the feeder. All customers connected to the feeder will lose supply initially as a result of the tripping of the circuit breaker due to overcurrent

protection operation. Prior to any restoration, the upstream switch of the ROS pair at A3 must be opened in order to isolate the fault. Customers at A3, and those downstream on the feeder can have their supply restored from DLR by closing the switch at the normally-open split point R to allow back-feed from Feeder B. The same number of restored DLR customers will be produced if an outage occurs at any section between (ii) and (iii). The number of restored customers in this condition may be calculated using Equation (3-5). The customers who are served by substations A1-A2 will not be restorable because the fault has occurred in Section (i) (see Figure 3-4).

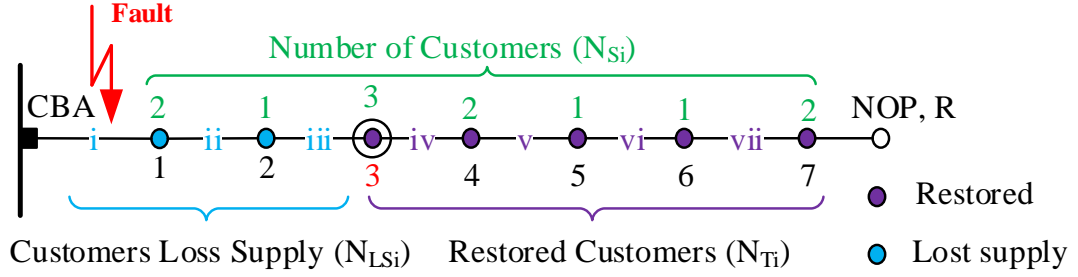


Figure 3-4: Number of expected customers restored if an outage occurs at Section (i) or (ii) or (iii)

$$N_{Ti} = \left( \sum_{i=1}^N N_{Si} - \sum_{i=1}^{N_{ROS1}-1} N_{LSi} \right) \times \sum_{i=1}^{i=N_{ROS1}} P_{fi} \quad \text{for } N_{fs} \leq N_{ROS1} \quad (3-5)$$

Where

- $ROS_1$  is the first ROS pair
- $N_{ROS1}$  is the number of the substation at which the ROS pair is installed
- $P_{fi}$  is probability of failure for each section (fault rate/ annum)

Equation (3-5) is applied numerically by summing all the customers on the feeder (12 customers) and deducting the number of expected customers loss supply (2+1 = 3 customers). The result (9) is then multiplied by the sum of probability of fault occurrence on the respective sections (i, ii and iii).

$$N_{Ti} = \left( \sum_{i=1}^7 N_{Si} - \sum_{i=1}^{3-1} N_{LSi} \right) \times \sum_{i=1}^3 P_{fi} \quad \text{for } N_{fs} \leq 3$$

$$N_{T(1-3)} = ((2 + 1 + 3 + 2 + 1 + 1 + 2) - (2 + 1)) \times \sum_{i=1}^3 P_{fi}$$

$$N_{T(1-3)} = (12 - 3) \times \sum_{i=1}^3 P_{fi} = 9 \times \sum_{i=1}^3 P_{fi} \quad (3-6)$$

**Sub-calculation (ii):** If an outage occurs at Section (iv) or (v) or (vi) or (vii) with the ROS still at S/S No. 3, customers connected to substations A1-A3 would benefit from restoration if an outage occurs at Section (iv) or beyond, and the same set of customers will be restored during ULR if a fault occurs at any section between (v) to (vii), as shown in Figure 3-5. The expected total number of restored customers in this condition is calculated using Equation (3-7). Figure 3-5 illustrates such conditions.

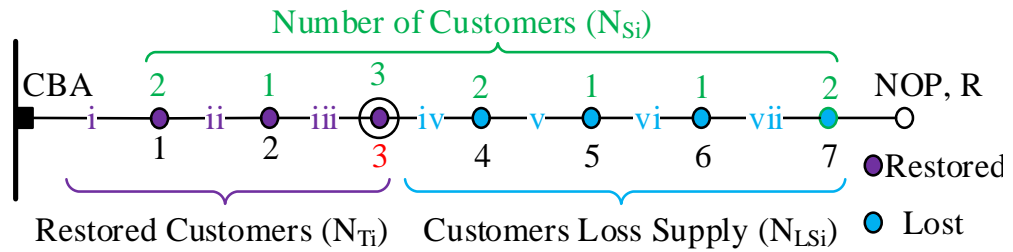


Figure 3-5: Calculate number of expected customers restore if an outage at section (iv) or (v) or (vi) or (vii)

$$N_{Ti} = \left( \sum_{i=1}^N N_{Si} - \sum_{i=N_{ROS1}+1}^N N_{LSi} \right) \times \sum_{i=N_{ROS1}+1}^N P_{fi} \text{ for } N_{fs} > N_{ROS1} \quad (3-7)$$

Applying Equation (3-7) gives:

$$N_{Ti} = \left( \sum_{i=1}^7 N_{Si} - \sum_{i=3+1}^7 N_{LSi} \right) \times \sum_{i=3+1}^7 P_{fi} \text{ for } N_{fs} > 3$$

$$N_{T(4-7)} = ((2 + 1 + 3 + 2 + 1 + 1 + 2) - (2 + 1 + 1 + 2)) \times \sum_{i=3+1}^7 P_{fi}$$

$$N_{T(4-7)} = (12 - 6) \times \sum_{i=4}^7 P_{fi} = 6 \times \sum_{i=4}^7 P_{fi} \quad (3-8)$$

Equations (3-5) and (3-7) provide the total number of expected restored customers if an outage occurs at any section of the feeder. Therefore, there are two equations needed to search for one optimal location of ROS pairs on the feeder without branches.

Table 3-1 describes available load restorations for the full range of possible fault locations of the example network. The process of searching for the optimal location of ROS pairs will continue until the DPSO or Brute Force manages to find the optimum number of restored customers with selected optimal locations.

Table 3-1: Summary of load restoration of each section on Feeder A applying ULR and DLR

ROS Pair Location	Fault Section	ULR	DLR
A3	i/ii/iii	-	A3 - A7
	iv/v/vi/vii	A1 - 3	-

### 3.2.2 Failure Rate ( $P_{fi}$ )

The failure rate, i.e. the chance that a section will fail in a given time period, will vary depending on the length (longer lines will have a greater chance of failure than shorter lines) and type of line (OHL have a greater failure rate than UG cables). To incorporate this into the calculations, it is assumed that the failure rate is proportionate to the length of the section.

During simulation, the value of  $P_{fi}$  has been calculated and given in Equation (3-9). The failure rate values used for OH and UG cables are taken from [128], and given as:

Failure rate OH line 0.0750 fault/km/year

Failure rate UG cable 0.0275 fault/km/year

$$P_{fi} = L_{fi} \times \lambda_{fi} \quad (3-9)$$

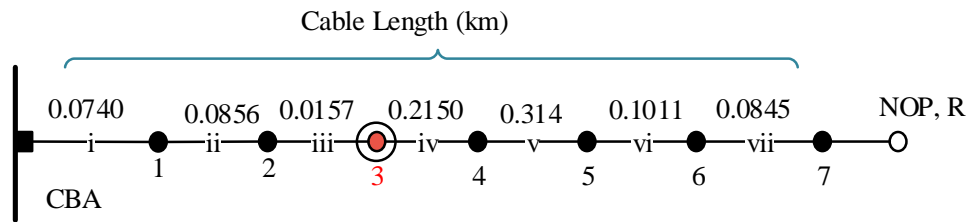
- $L_{fi}$  is the length of cable section
- $\lambda_{fi}$  is the fault rate for OH or UG cable



With reference to *Figure 3-6*, the cable sections are labelled with roman numerals. The feeder has seven cable sections (i – vii). The length of each cable section is given in (km). The probability of fault for each cable section calculated by using Equations (3-9) and (3-10). However, respective to failure rate, if there are no ROS pair on the feeder, the expected total number of customers outage for the feeder calculated by;

$$\text{Expected customers outage, } E = L_{ft} \times N_{si} \times \lambda_{fi} \quad (3-10)$$

- $L_{ft}$  is the total length of cable section



*Figure 3-6: Feeder with cable section length*

Using the previous example in Section 3.2.1 and assuming that all the feeder sections are cables, the expected customer outage if there are no ROS pair located on the network can be calculated by using Equation (3-10) and the value of probability of failure for each section by using Equation (3-9) is given by:

$$E = 0.8899 \times 12 \times 0.0275 = 0.2937 \text{ customer failures/year}$$

$$P_{f1} = 0.074 \times 0.0275 = 2.035 \times 10^{-3} \text{ failure/year}$$

$$P_{f2} = 0.0856 \times 0.0275 = 2.354 \times 10^{-3} \text{ failure/year}$$

$$P_{f3} = 4.3175 \times 10^{-4} \text{ failure/year}$$

$$P_{f4} = 5.9125 \times 10^{-3} \text{ failure/year}$$

$$P_{f5} = 8.635 \times 10^{-3} \text{ failure/year}$$

$$P_{f6} = 2.7802 \times 10^{-3} \text{ failure/year}$$

$$P_{f7} = 2.3237 \times 10^{-3} \text{ failure/year}$$

Table 3-2: Probability of failure rate per year for example feeder

Cable Section	i	ii	iii	iv	v	vi	vii
$P_{fi} \times 10^{-3}$	2.035	2.354	0.43175	5.9125	8.635	2.7802	2.3237

Therefore, the number of customers restored if the ROS pair is located at S/S3 is given by two Equations (3-6) and (3-8):

$$N_{T(1-3)} = 9 \times \sum_{i=1}^3 P_{fi} = 9 \times (2.035 \times 10^{-3} + 2.354 \times 10^{-3} + 4.3175 \times 10^{-4})$$

$$N_{T(1-3)} = 0.0433 \text{ customer failures/year}$$

$$N_{T(4-7)} = 6 \times \sum_{i=4}^7 P_{fi} = 6 \times (5.9125 + 8.635 + 2.7802 + 2.3237) \times 10^{-3}$$

$$N_{T(4-7)} = 6 \times 0.803 = 0.1179 \text{ customer failures/year}$$

From both equations, the total number of expected customers restored with one ROS pair on S/S3 is found by testing all possible sections which a fault might occur and by including the probability of failure for each section, given by:

$$N_{T(1-7)} = N_{T(1-3)} + N_{T(4-7)} = 0.1612 \text{ customer failures/year}$$

This method of calculation is applied to all types of case study networks in this thesis searching for the benefit of adding a ROS pair on the network.

### 3.2.3 Restoration Assessment For Two ROS Pairs

With two possible locations of ROS pairs, the number of equations to determine the total expected customers restored is increased. In the previous case of only one ROS pair location, the total expected customers restored required two equations according to whether the fault is upstream or downstream of the ROS pair location. In this case, three equation combinations of ULR and DLR are required depending on whether the fault occurs:

- (i) upstream from the first ROS pair (e.g S/S A3),
- (ii) in between the first and second ROS pair substations and,
- (iii) downstream from the second ROS pair (e.g S/S A5)

Consider an example, where the ROS pair locations are chosen as positions A3 and A5; if a fault occurs on Section iv, all customers connected to Substations A1-A7 lose supply initially due to the operation of the main substation circuit breaker. However, the normally-closed switches at ROS1 and ROS2 (A3 and A5) may open to isolate the faulted section (iv).

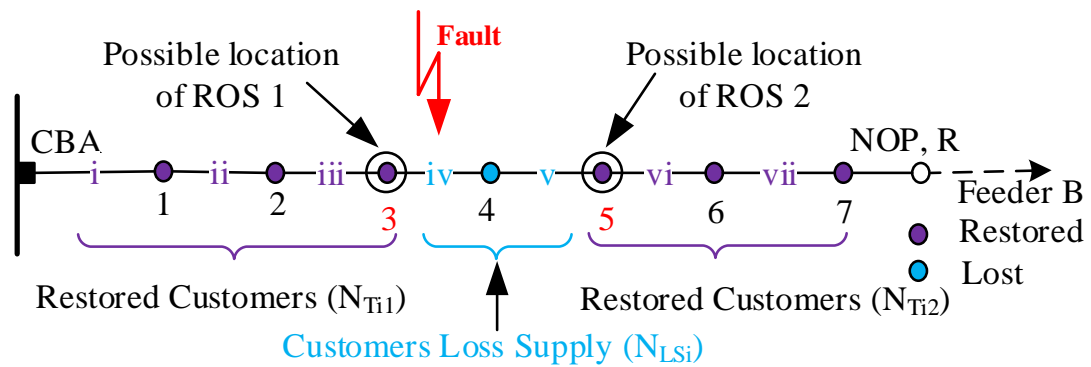


Figure 3-7: One-line diagram of a feeder of a network reconfiguration during ULR and DLR with an optimal location of two pairs of ROS pairs

The isolation of the fault within a section of the feeder now allows a degree of both ULR and DLR; customers connected to substations 1-3 benefit from ULR with reclosure of the main circuit breaker while the customers at Substations 5-7 receive DLR by closing the normally open point split point switch R and feeding supply from neighbouring feeder. Substation 4 remains disconnected. The objective function for the restored customers is based on the summation of *ULR* and *DLR*, and is calculated by Equation (3-11) to Equation (3-13). The sub-calculations are dependent on where the fault occurs at:

### Sub-calculation (a) – fault occurs in Section i or ii or iii

The total number of expected restored customers are from S/S3-7 if an outage occurs at section (i) and there would be the same number if an outage occurs on Section (ii) or (iii) and given by Equation (3-11).

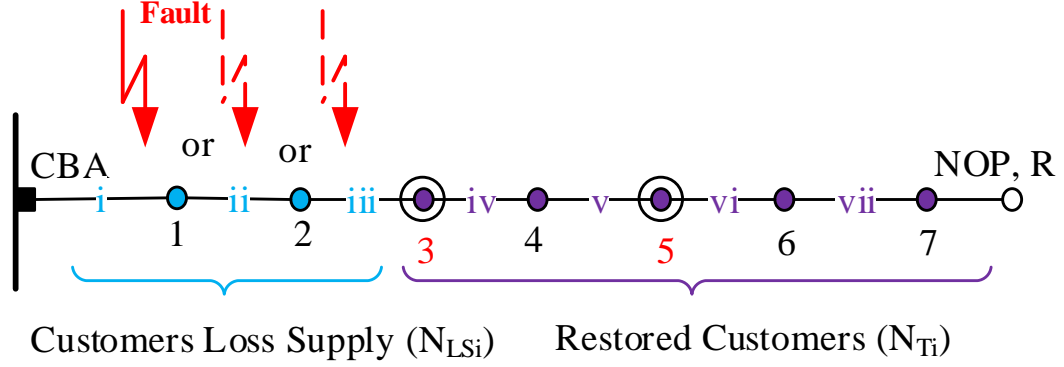


Figure 3-8: Single line diagram for a feeder with an outage at Section i or ii or iii

$$N_{Ti} = \left( \sum_{i=1}^N N_{Si} - \sum_{i=1}^{N_{ROS1}-1} N_{LSi} \right) \times \sum_{i=1}^{i=N_{ROS1}} P_{fi} \text{ for } N_{fs} \leq N_{ROS1} \quad (3-11)$$

The expected number of customers restored during this condition is:

$$\begin{aligned} N_{T(1-3)} &= 9 \times \sum_{i=1}^3 P_{fi} = 9 \times (4.82075 \times 10^{-3}) \\ &= 0.0434 \text{ customer failures/year} \end{aligned}$$

### Sub-calculation (b) – fault occurs in Section iv or v

Figure 3-9 shows the condition if an outage occur at Sections iv or v, where the number of expected customers restored would be the same. Equation (3-12) is used to calculate the number of expected customers restored for the given sections.

$$\begin{aligned} N_{Ti(1+2)} &= \left( \sum_{i=1}^N N_{Si} - \sum_{i=N_{ROS1}+1}^{N_{ROS2}} N_{LSi} \right) \times \sum_{i=N_{ROS1}+1}^{N_{ROS2}} P_{fi} \text{ for } N_{ROS1} < N_{fs} \\ &\leq N_{ROS2} \end{aligned} \quad (3-12)$$

$$N_{Ti} = (12 - 2) \times \sum_{i=4}^5 P_{fi} = 10 \times 0.01455 = 0.1455 \text{ customer failures/year}$$

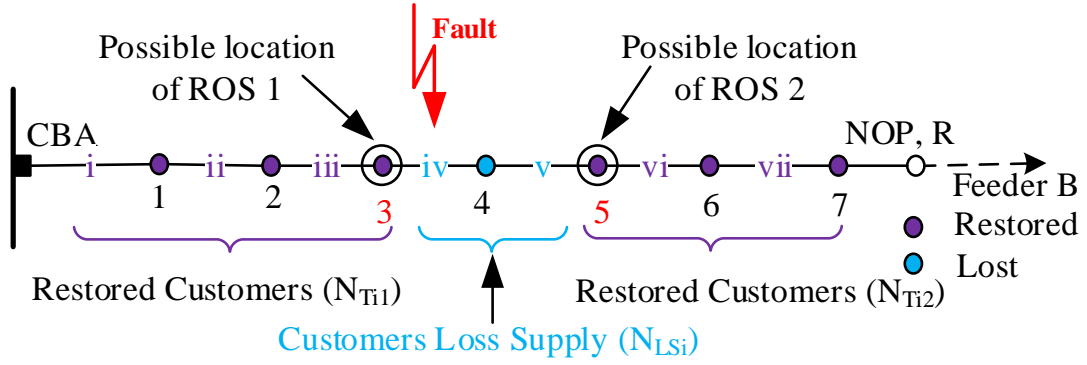


Figure 3-9: Single line diagram for a feeder with an outage at Section iv or v

### Sub-calculation (c) – if fault occurs in Section vi or vii

An outage at Section vi or vii will cause loss of supply on S/S6-7 as shown in

Figure 3-10. However, customers from S/S1-5 will be restored with ULR.

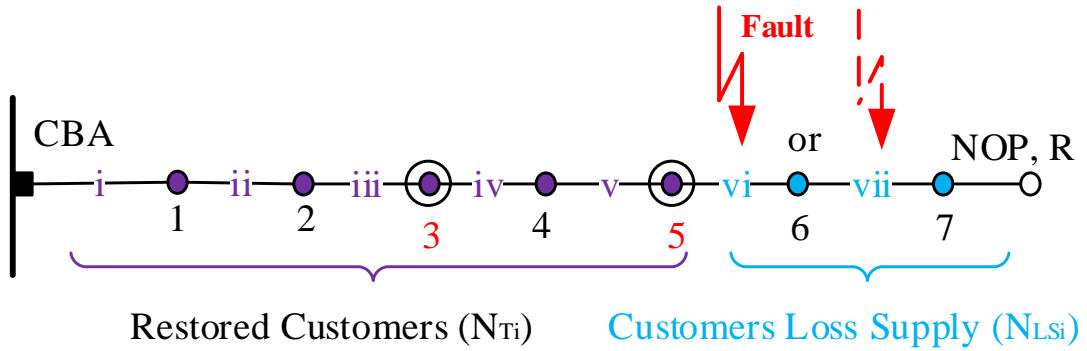


Figure 3-10: Single line diagram for a feeder with an outage at Section vi or vii

$$N_{Ti} = \left( \sum_{i=1}^N N_{Si} - \sum_{i=N_{ROS2}+1}^N N_{LSi} \right) \times \sum_{i=N_{ROS2}+1}^N P_{fi}, \text{ for } N_{fs} > N_{ROS2} \quad (3-13)$$

- $N_{ROS2}$  is the number of the substation at which the second ROS pair is installed  
 $ROS_2$  is the second of the ROS pairs

Where the number of customers saved during this condition is given by:

$$\begin{aligned} N_{T(6-7)} &= (12 - 3) \times \sum_{i=6}^7 P_{fi} = 9 \times 5.1039 \times 10^{-3} \\ &= 0.04594 \text{ customer failures/year} \end{aligned}$$

From this condition with two ROS pairs at S/S3 and S/S5, the number of expected customers that would be restored by testing all the possible locations where a

fault that might occur and including the failure rate probability of each cable section is summarised as below:

$$N_{Ti} = 0.0434 + 0.1455 + 0.04594 = 0.2348 \text{ customer failures/year}$$

Table 3-3 summarises the achievable restoration for all possible faults at the section in the network. For comparison, with the condition of only one available ROS pair, it can be seen that significantly more customers can be restored.

Table 3-3: Summary of restoration of each section F7 applying ULR and DLR

Remotely Operable NC Split Point	Fault Section	S/S Restored ULR	S/S Restored DLR
A3 and A5	i/ii/iii	-	A3-7
	iv/v	A1-3	A5-7
	vi/vii	A1-5	-

### 3.2.4 Unlimited Optimal Locations

Increasing the number of ROS pairs beyond two increases greatly the complexity of the problem. For the case of unlimited ROS pairs, each location is selected and identified by a number starting from the closest ROS pair to the main substation. This process is completed until the total of customers restored is calculated. The selected objective function depends on the topology of the network, most notably the number of branches. The following section describes the construction of the objective function for networks with different numbers of branches. The objective function for a feeder with no branches has the simplest set of equations for unlimited ROS pairs. Equations (3-14), (3-15) and Equation (3-16) are used to calculate the number of upstream and downstream restored customers, respectively, if the ROS pair is selected at any possible location on the feeder via the DPSO algorithm and Brute Force method. The user may select the number of ROS pairs, as required, or the program could perform the simulation for increasing numbers of ROS pairs until it reaches a

fully automated condition (available in Brute Force method). The probability of fault occurrence at the feeder section is calculated using Equation (3-9). Equation (3-14) shows the method used to calculate the ULR for final location of ROS pairs. For the other possible locations of ROS pairs, Equation (3-15) is used to determined the number of customers restored. Equation (3-16) calculates the number of restored customers due to the first pair ROS (nearest ROS to the main supply).

- i) For the condition of final  $ROS_j$  (e.q: if the total number of ROS pairs needed is 5 in a feeder, this is the way  $N_{Tji}$  is calculated with the ROS at the 5<sup>th</sup> S/S.

$$N_{Tji} = N_{T(ji-1)} + \left( \sum_{i=1}^N N_{Si} - \sum_{i=ROS_j+1}^N N_{LSi} \right) \times \sum_{i=ROS_j+1}^N P_{fi} \text{ for } N_{fs} > N_{ROS_j} \quad (3-14)$$

- ii) For others than final  $ROS_j$ , the number of customers restored by using Equation (3-15)

$$N_{Tji} = N_{T(ji-1)} + \left( \sum_{i=1}^N N_{Si} - \sum_{i=ROS_j+1}^{ROS_{(j+1)}-1} N_{LSi} \right) \times \sum_{i=ROS_j+1}^{ROS_{(j+1)}-1} P_{fi} \text{ for } N_{ROS_j} < N_{fs} \\ \leq N_{ROS_{(j+1)}} \quad (3-15)$$

- iii) For the first  $ROS_l$ , the number of customers restored is calculated by using Equation (3-16)

$$N_{Tji} = N_{Tji-1} + \left( \sum_{i=1}^N N_{Si} - \sum_{i=1}^{ROS_j-1} N_{LSi} \right) \times \sum_{i=1}^{ROS_j-1} P_{fi} \text{ for } N_{fs} \leq N_{ROS_j} \quad (3-16)$$

where:

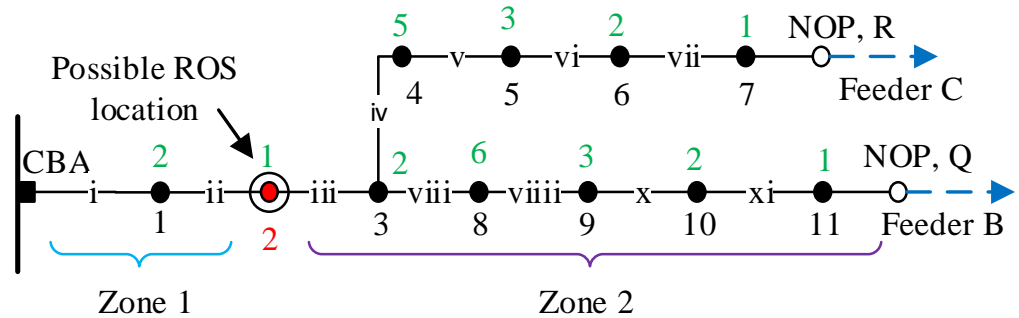
- $ROS_j$  is the number of  $j$ th ROS pairs (from 1 to  $N-1$ )
- $N_{Tji-1}$  is the previous customers restored respective to the previous locations of  $ROS_i$

### 3.2.5 One Branch Objective Function

As already mentioned, the number of possible options increases when the feeder has branches. An example of a feeder with one branch is shown in *Figure 3-11*.

#### 3.2.5.1 Customers restored assessment for a single ROS pair

An example of a network with a feeder with one branch is shown in *Figure 3-11*. As shown, a possible location of one ROS pair is S/S2. It is assumed that all sections are UG cable (0.0275 failure/km/year). Detail of cable length (km) and failure for each section given in *Table 3-4* and *Table 3-5* respectively.



*Figure 3-11: Single line feeder with one branch and a ROS pair located at S/S2*

*Table 3-4: Cable length for each section*

Cable Section	i	ii	iii	iv	v	vi	vii
Length (km)	0.199	0.0762	0.5122	0.223	0.601	0.089	0.236
	viii	ix	x	xi			
	0.269	0.038	0.1173	0.4121			

*Table 3-5: Failure rate per year for each cable section*

Cable Section	i	ii	iii	iv	v	vi	vii
Pfi $\times 10^{-3}$	5.5	2.1	14.1	6.1	16.5	2.4	6.5
	viii	ix	x	xi			
	7.4	1.0	3.2	11.3			



There are two equations needed for this type of network to calculate the number of expected customers restored if an outage occurs at:

(a) Zone 1 – fault at Sections i or ii

$$N_{Ti} = \left( \sum_{i=1}^N N_{Si} - \sum_{i=1}^{N_{ROS1}-1} N_{LSi} \right) \times \sum_{i=1}^{N_{ROS1}} P_{fi} \text{ for } N_{fs} \leq N_{ROS1} \quad (3-17)$$

The number of customers restored from S/S2 until S/S11 using Equation (3-17) is given by:

$$\begin{aligned} N_{T(1 \rightarrow 2)} &= \left( \sum_{i=1}^{11} N_{Si} - \sum_{i=1}^1 N_{LSi} \right) \times \sum_{i=1}^2 P_{fi} = (28 - 1) \times \sum_{i=1}^2 P_{fi} = 27 \times 0.0076 \\ &= 0.2052 \text{ customer failures/year} \end{aligned}$$

(b) Zone 2 – Fault at Sections iii or iv or v or vi or vii or viii or ix or x or xi

$$N_{Ti} = \left( \sum_{i=1}^N N_{Si} - \sum_{i=N_{ROS1}+1}^N N_{LSi} \right) \times \sum_{i=N_{ROS1}+1}^N P_{fi} \text{ for } N_{fs} > N_{ROS1} \quad (3-18)$$

Number of customers restored from S/S1 until S/S2 using Equation (3-18) is given by:

$$\begin{aligned} N_{T(3 \rightarrow 11)} &= \left( \sum_{i=1}^{11} N_{Si} - \sum_{i=2+1}^{11} N_{LSi} \right) \times \sum_{i=2+1}^{11} P_{fi} = (28 - 25) \times \sum_{i=3}^{11} P_{fi} = 3 \times 0.0687 \\ &= 0.2061 \text{ customer failures/year} \end{aligned}$$

The failure rate calculated using Equation (3-9) and the total number of expected customers to be restored:

$$N_{T(1 \rightarrow 2)} + N_{T(3 \rightarrow 11)} = 0.2052 + 0.2061 = 0.4113 \text{ customer failures/year}$$

### 3.2.5.2 Customers restored assessment for two ROS pairs

Figure 3-12 shows the same figure as Figure 3-11 but now there are two ROS pairs located at for example S/S2 and S/S5. Three zones are identified and involved in searching the number of expected customers restored if an outage tested on each cable section on the network, depending on where the fault occurs:

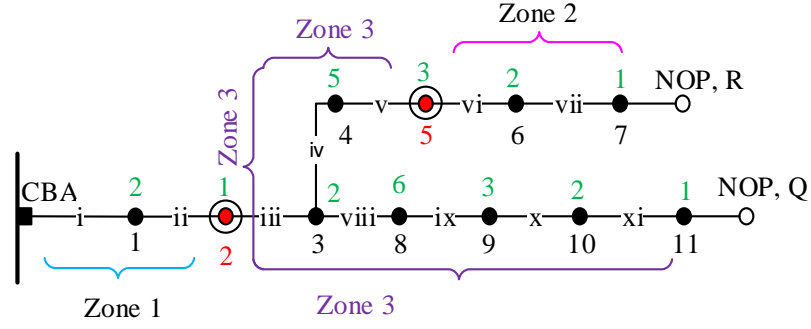


Figure 3-12: Single line diagram for network with feeder plus one branch with two ROS pairs

**(a) Zone 1 – Fault at Sections i or ii**

$$N_{Ti} = \left( \sum_{i=1}^N N_{Si} - \sum_{i=1}^{N_{ROS1}-1} N_{LSi} \right) \times \sum_{i=1}^{N_{ROS1}} P_{fi} \text{ for } N_{fs} \leq N_{ROS1} \quad (3-19)$$

The number of customers restored from S/S2 until S/S11 using Equation (3-19) is given by:

$$N_{T(1 \rightarrow 2)} = \left( 28 - \sum_{i=1}^1 N_{LSi} \right) \times \sum_{i=1}^2 P_{fi} = (28 - 1) \times \sum_{i=1}^2 P_{fi} = 27 \times 0.0076$$

$$N_{T(1 \rightarrow 2)} = 0.2052 \text{ customer failures/year}$$

**(b) Zone 2 – Fault at Section vi or vii**

$$N_{Ti} = \left( \sum_{i=1}^N N_{Si} - \sum_{i=N_{ROS2}+1}^{NOP,R} N_{LSi} \right) \times \sum_{i=N_{ROS2}+1}^{NOP,R} P_{fi} \text{ for } N_{ROS2} < N_{fs} \leq N_{NOPR} \quad (3-20)$$

The number of customers restored from S/S1 until S/S5 and S/S8 until S/S11 using Equation (3-20) is given by:

$$N_{T(6 \rightarrow 7)} = \left( 28 - \sum_{i=6}^7 N_{LSi} \right) \times \sum_{i=6}^7 P_{fi} = (28 - 3) \times \sum_{i=6}^7 P_{fi} = 25 \times 0.0089$$

$$N_{T(6 \rightarrow 7)} = 0.2225 \text{ customer failures/year}$$

(c) **Zone 3 – Fault at Sections iii or iv or v or viii or ix or x or xi**

$$N_{Ti} = \left( \sum_{i=1}^N N_{Si} - \left( \sum_{i=N_{ROS1}+1}^{N_{ROS2}-1} N_{LSi} + \sum_{i=NOP,R+1}^N N_{LSi} \right) \right) \times \left( \sum_{i=N_{ROS1}+1}^{N_{ROS2}} P_{fi} + \sum_{i=NOP,R+1}^N P_{fi} \right) \text{ for } N_{ROS1} < N_{fs} \leq N_{ROS2} \& N_{fs} > NOP, R + 1 \quad (3-21)$$

- NOP,R is the normally open point R

The (R+1) is the number of substation with the next substation after NOP R. for this example (R+1) is S/S8. The number of customers restored from S/S1 until S/S2 and S/S5 until S/S7 using Equation (3-21) is given by:

$$\begin{aligned} N_{T(3 \rightarrow 5)} + N_{T(8 \rightarrow 11)} &= \left( 28 - \left( \sum_{i=2+1}^{5-1} N_{LSi} + \sum_{i=7+1}^{11} N_{LSi} \right) \right) \times \left( \sum_{i=2+1}^5 P_{fni} + \sum_{i=5+1}^{11} P_{fni} \right) \\ N_{Ti(3 \rightarrow 5)} + N_{Ti(8 \rightarrow 11)} &= (28 - (7 + 12)) \times \left( \sum_{i=2+1}^5 P_{fni} + \sum_{i=5+1}^{11} P_{fni} \right) \\ &= 9 \times (0.0367 + 0.0319) = 0.6174 \text{ customer failures/year} \end{aligned}$$

The value of failure rate can be calculated using Equation (3-9). So, the total number of expected customers saved supply if the location S/S 3 and 5 selected to locate the ROS pairs is:

$$\begin{aligned} N_{Ti} &= N_{T(1 \rightarrow 2)} + N_{T(1 \rightarrow 5)} + N_{T(8 \rightarrow 11)} + N_{T(1 \rightarrow 2)} + N_{T(5 \rightarrow 7)} \\ &= 0.2052 + 0.2225 + 0.6174 = 1.0451 \text{ customer failures/year} \end{aligned}$$

### 3.2.5.3 Unlimited ROS pair with a one branch network

For this particular network example, eight equations are required to calculate the DPSO and Brute Force objective function by considering all possible location options of ROS pairs. *Figure 3-13* (a) shows a network consisting of the feeder that has one branch. The feeder consists of two normally open split points to two adjacent

feeders that allow the potential for DLR on each branch. The substation at which the one branch splits off from the main trunk of feeder is denoted Node P. The feeder is divided into 3 sub-sections. With reference to *Figure 3-13*, the feeder has a total of 12 secondary substations with 2 substations on sub-section 1, 4 substations on sub-section 2 and 5 substations on sub-section 3. The possible locations of ROS pairs referring to *Figure 3-13 (a – l)* are:

- a) A feeder with one branches divided with sub-section and junction node label as P - Figure 3-13 (a)
- b) if all of the ROS pairs are located at any S/S on Branch 1 - Figure 3-13 (b)
- c) if all ROS pairs are located on Sub-section 2 - Figure 3-13 (c)
- d) if all ROS pairs are located on Sub-section 3 - Figure 3-13 (d)
- e) if ROS pairs are located on Sub-sections 1 and 2 - Figure 3-13 (e)
- f) if ROS pairs are located on Sub-sections 1 and 3 except node P- Figure 3-13 (f)
- g) if ROS pairs are located on Sub-sections 2 and 3 - Figure 3-13 (g)
- h) if ROS pairs are located on node P and Sub-section 1 (Red circle) Figure 3-13 (h)
- i) if ROS pairs are located on node P and on Sub-section 2 - Figure 3-13 (i)
- j) if ROS pairs are located on node P and on Sub-section 3 - Figure 3-13 (j)
- k) if ROS pairs are located on node P, Sub-sections 1, 2 and 3 - Figure 3-13 (k)
- l) if ROS pairs are located at all Sub-section except node P – Figure 3-13 (l)

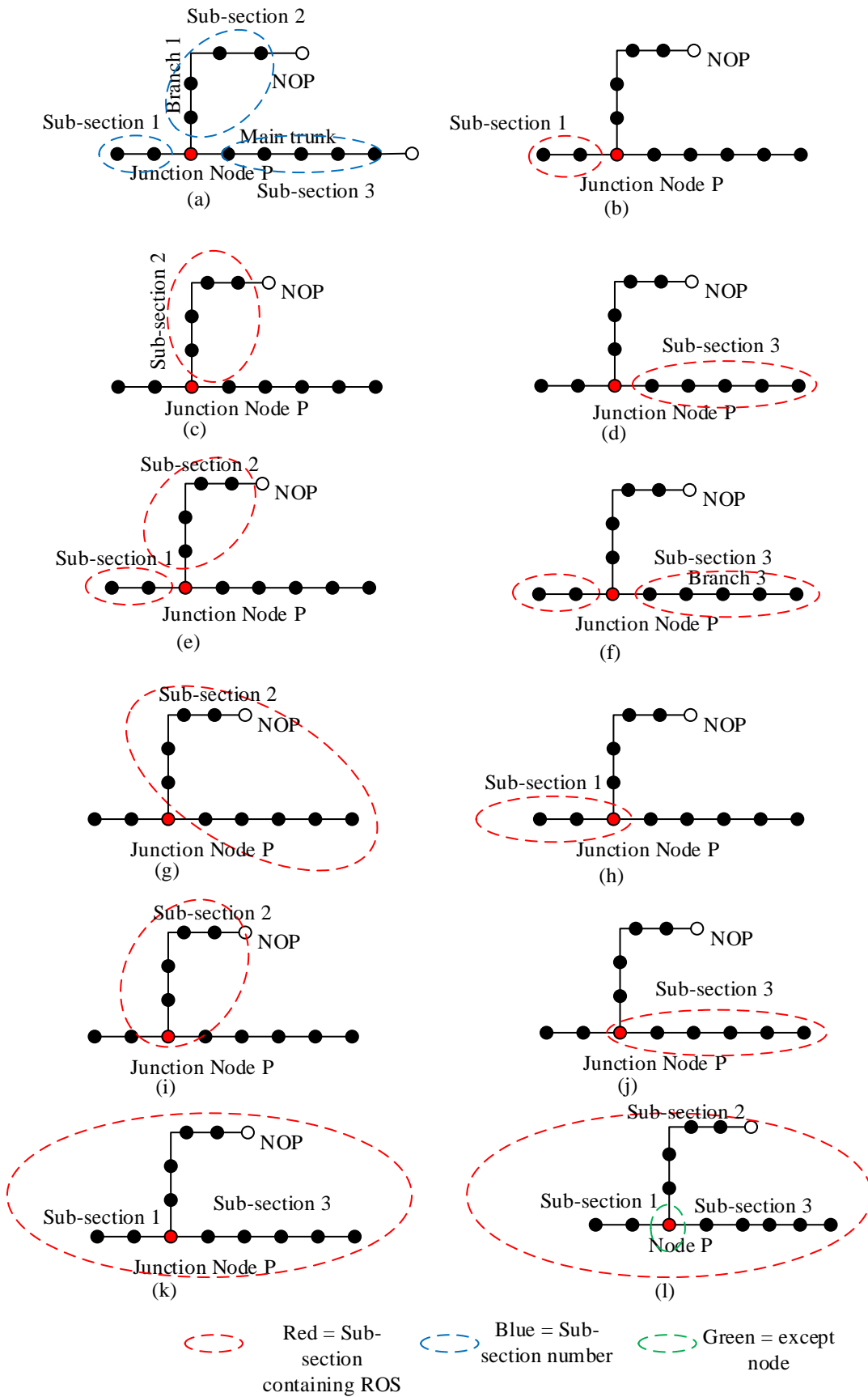


Figure 3-13: Possible combinatorial distributions of ROS pairs on a feeder

Therefore, there are eleven possible combinations of ROS pairs on the feeder requiring eight sets of equations for this particular network. The number of equations will keep increasing as the number of branches increases because the number of possible combinations of ROS pairs are also increased. Moreover, not only are there more equations employed to calculate the number of possible locations of the ROS pairs, but also the complexity of each equation increases as the number of substations increases.

#### 3.2.5.4 Two Branch Objective Function

Figure 3-14 shows a feeder with two branches. Associated with these two branches are junction nodes which connect them to the main feeder. Five sub-sections are available for feeders with two branches. The full set of equations to construct the objective function for this type of network is shown in Appendix 3.

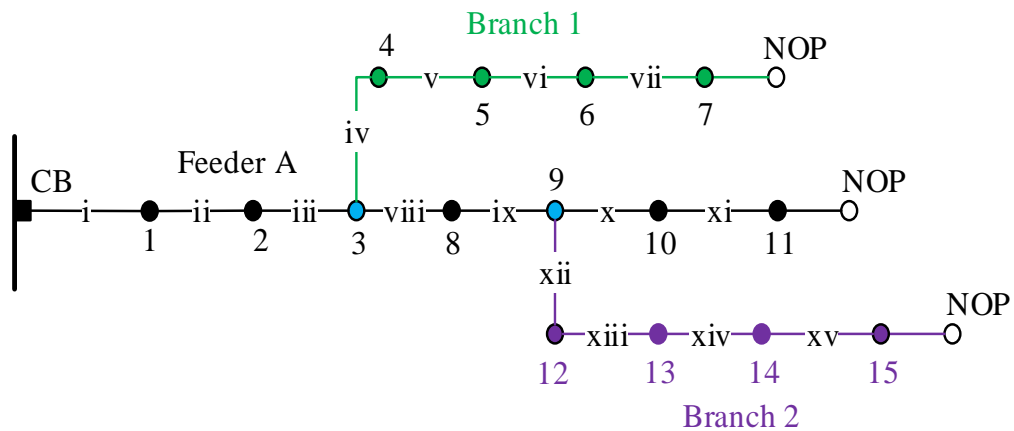


Figure 3-14: Example of a feeder with two branches

#### 3.2.5.5 Three Branch Objective Function

An example of a feeder with three branches is shown in Figure 3-15. The feeder consists of three junction nodes (S/S3, 9, 16) and three branches connected to the main feeder. Four NOPs are available at the end of each branch and at the main feeder that

connects to adjacent feeders with DLR options. Seven sub-sections are available for this type of feeder.

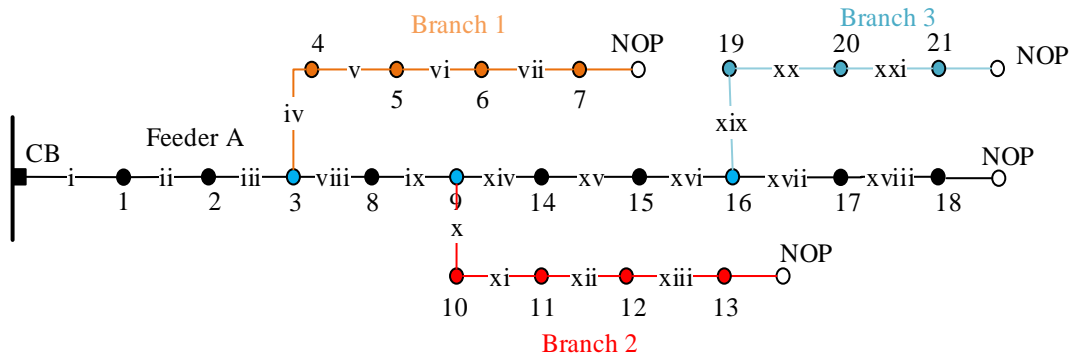


Figure 3-15: Example of a feeder with three branches

### 3.2.6 Pre-allocation Matrix

Calculation of the number of customers restored is achieved with a matrix calculation method by considering to the number of customers connected from one S/S to another S/S. The reason for this calculation is to reduce the simulation time for feeder objective function calculation. The pre-allocation matrix is calculated using Equation (3-22).

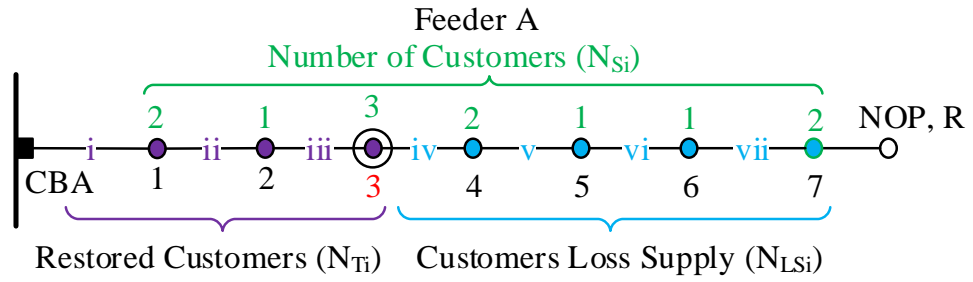
$$pre\ allocation\ customers = \begin{pmatrix} N_{11} & N_{12} & N_{13} & \dots & \dots & \dots & N_{1j} \\ N_{21} & N_{22} & N_{32} & \dots & \dots & \dots & N_{2j} \\ N_{31} & N_{32} & N_{33} & \dots & \dots & \dots & N_{3j} \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \dots & \dots & \ddots & \vdots \\ N_{i1} & N_{i2} & N_{i3} & \dots & \dots & \dots & N_{ij} \end{pmatrix} \quad (3-22)$$

The value of N in the matrices is calculated as follow:

$$N_{12} = N_{1 \rightarrow 2} = N_1 + N_2$$

- *i* and *j* = number of substation
- *i* → *j* mean adding the number of customers from S/S *i* until *j*

Using the previous model of a feeder, as shown in *Figure 3-16*;



*Figure 3-16: Single line feeder*

The pre-allocation matrix calculated using Equation (3-22) is found:

$$Pre\ allocation\ for\ Feeder\ A = \begin{pmatrix} 2 & 3 & 6 & 8 & 9 & 10 & 12 \\ 3 & 1 & 4 & 6 & 7 & 8 & 10 \\ 6 & 4 & 3 & 5 & 6 & 7 & 9 \\ 8 & 6 & 5 & 2 & 3 & 4 & 6 \\ 9 & 7 & 6 & 3 & 1 & 2 & 4 \\ 10 & 8 & 7 & 4 & 2 & 1 & 3 \\ 12 & 10 & 9 & 6 & 4 & 3 & 2 \end{pmatrix}$$

For example, referring to Equation (3-5) with only one ROS pair at S/S3, the number of customers restored is calculated as:

$$N_{Ti} = \left( \sum_{i=1}^7 N_{Si} - \sum_{i=1}^{N_3-1} N_{LSi} \right) \times \sum_{i=1}^3 P_{fi} \quad for\ N_{fs} \leq 3$$

The zone that includes the pre-allocation value is the number of customers that lose supply. The value of  $N_{12}$  read from the matrix pre-allocation is equal to 3. The number of customers for the respective feeder can be read directly from the matrix rather than to repeat the same calculation if searching for a number of customers between two substations:

$$N_{Ti} = \left( \sum_{i=1}^7 N_{Si} - \sum_{i=1}^2 N_{LSi} \right) \times \sum_{i=1}^3 P_{fni} = (12 - N_{12}) \times \sum_{i=1}^3 P_{fi}$$

The same method of matrix pre-calculation also applied on the calculation of the probability of fault on each section of the network to reduce the simulations time. By using the same network as an example, and referring to *Table 3-2*. The difference is instead adding number of customers from S/S i to j, the pre-allocation matrix for failure



rate will add failure rate from S/S i to j and from the same method of matrix calculation, the failure rate will be calculated as:

$$P_{f12} = P_{f(1 \rightarrow 2)} = P_{f1} + P_{f2}$$

So, the pre-allocation matrix for failure rate for the example feeder with 7 substations as discussed in Section 3.2.1 can be written as:

$$Pre P_{fij} = \begin{pmatrix} 0.0002 & 0.0044 & 0.0048 & 0.0107 & 0.0194 & 0.0221 & 0.0245 \\ 0.0044 & 0.0024 & 0.0028 & 0.0087 & 0.0173 & 0.0201 & 0.0224 \\ 0.0048 & 0.0028 & 0.0004 & 0.0063 & 0.0150 & 0.0178 & 0.0201 \\ 0.0107 & 0.0087 & 0.0063 & 0.0059 & 0.0145 & 0.0173 & 0.0197 \\ 0.0194 & 0.0173 & 0.0150 & 0.0145 & 0.0086 & 0.0114 & 0.0137 \\ 0.0221 & 0.0201 & 0.0178 & 0.0173 & 0.0114 & 0.0028 & 0.0051 \\ 0.0245 & 0.0245 & 0.0201 & 0.0197 & 0.0137 & 0.0051 & 0.0023 \end{pmatrix}$$

So, the failure rate of the network section can be read directly from the matrix form:

$$N_{Ti} = \left( \sum_{i=1}^7 N_{Si} - \sum_{i=1}^2 N_{LSi} \right) \times \sum_{i=1}^3 P_{fi} = (12 - 3) \times \sum_{i=1}^3 P_{fi}$$

$$\begin{aligned} N_{Ti} &= \left( \sum_{i=1}^7 N_{Si} - \sum_{i=1}^2 N_{LSi} \right) \times \sum_{i=1}^3 P_{fi} = (12 - 3) \times 0.0048 \\ &= 0.0432 \text{ customer failure/year} \end{aligned}$$

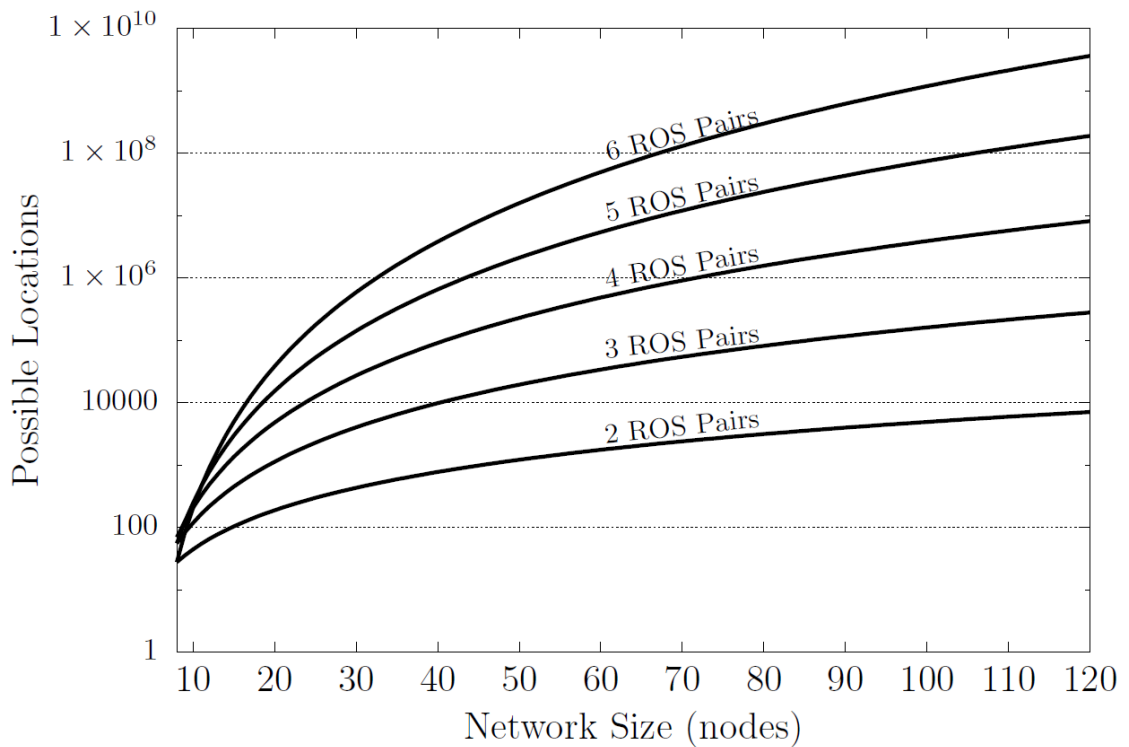
The value of customer calculated by using pre-allocation matrix same as value customer calculated in Section 3.2.2.

### 3.2.7 Comparison of Feeder Possible Location Options or ROS Pairs

The optimum locations of numbers of ROS pairs are found via the DPSO and Brute Force technique based on the methodology described in Sections 3.1 to 3.6. The objective function of the DPSO and Brute Force is calculated using the equations for the upstream and downstream restored customers to search the optimal locations and number of ROS pairs that could gain a benefits.

The number of possible location options depends on the number of total substations and ROS pairs, as shown in Figure 3-17. The number of possible locations options available is calculated using Equation (2-1). A greater number of nodes

(substations) yields a greater number of possible switch pair location options. A network was tested by increasing the number of substations to 122 and with six ROS pairs. The possible number of locations for two ROS pairs on such a network with 122 S/S is 7,140. Moreover, if the number of substations remains the same (122 S/S) but the number of ROS pairs is increased to 6, the possible number of location options available on the network will be equal to 3,652,745,640.



*Figure 3-17: The number of possible locations for ROS pairs increases exponentially with the number of ROS pairs and feeder length (total number of substations in a feeder)*

A clear ‘zoom in’ of *Figure 3-17* is shown in *Figure 3-18* to illustrate the trends of the possible locations of the network with feeders having less than 16 substations. The lines for different numbers of ROS pairs because, as the number of ROS pairs becomes large for small networks, the number of combinations reduce.

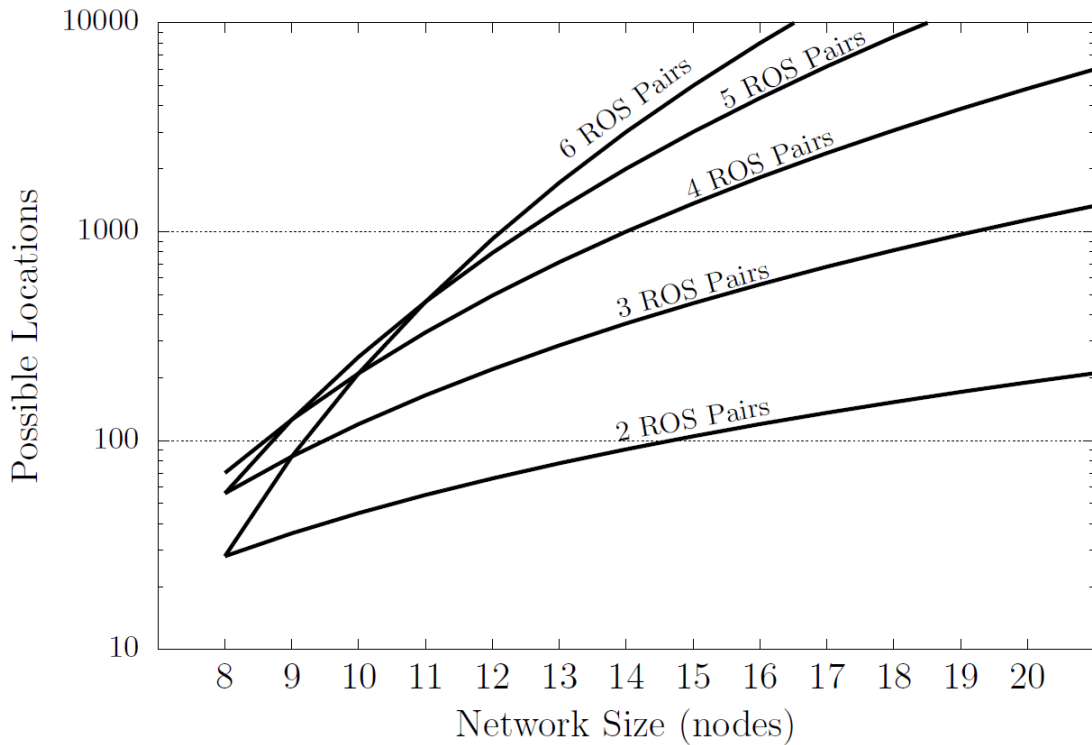


Figure 3-18: Zoom in from Figure 3-17 for possible location with network size 20 and below

To solve the problem and rather than searching until the fully automated condition is reached, a limitation has been setup during simulations. If the number of customers restored reaches 98% of the total number of customers in the process of increasing the number of ROS pairs, the simulation will be stopped. Further, this condition is only applied on feeders with a total of more than 20 substations and associated branches. With these conditions applied, the simulation run-times are found to be manageable. For feeders with less than 20 substations, the ROS pairs search may be continued until the fully automated solution is reached. Only 10 feeders from the semi-urban and rural networks were affected by this limitation in the case studies. Three of these 10, and the seven other feeders are from the semi-urban and rural networks respectively.

### 3.2.8 Computational Time

Real feeders have diverse topologies. One of the main variables which affect the formulation of the objective function is the number of branches. A combination of three equations is used to calculate ULR and DLR for feeders without branches with unlimited ROS pairs. Eight equations are needed to calculate the number of customers to evaluate restoration for feeders with one branch. Feeders with increasing number of branches will increase the possible location option of ROS pairs and also the number of equations. The details of the options available for increasing the number of ROS pairs and feeders with branches has been described in detail in Sections 3.2.5. As discussed in Section 3.2.7, the possible options of locations are high if the number of total substations is high. Moreover, excessive simulation time is a significant problem that needs to be addressed if the total number of substations is more than approximately 40 in a feeder with branches and with more than six ROS pairs. This problem was encountered in the case study network of the rural area because of the large number of substations. For comparison purposes, two tests using the Brute Force method have been performed on several feeders without branches with different numbers of substations. The first test considers the objective function to calculate the number of customers and failure without using pre-allocation matrix and the second test done by considering the pre-allocation matrix in the objective function. To avoid biasing the result, all the feeders were setup with the same number of customers at each substation and also having the same length between sections of the substations. *Figure 3-19* shows the results obtained with 122 feeders ranging from two to 122 and without branches. The simulation time for each ROS pairs for the feeder was recorded to evaluate the effect of possible options available with the simulation time. With only one ROS pair for each feeder, the simulation time for each feeder increases as the number of total

substations increases. The results show that simulation time is proportional to the total number of substations. However, it is also seen that the simulation time increases considerably as the number of network size increases. The simulation time is considered fast if feeder has less than 20 S/S with simulation times less than 5 s searching up to 7 ROS pairs.

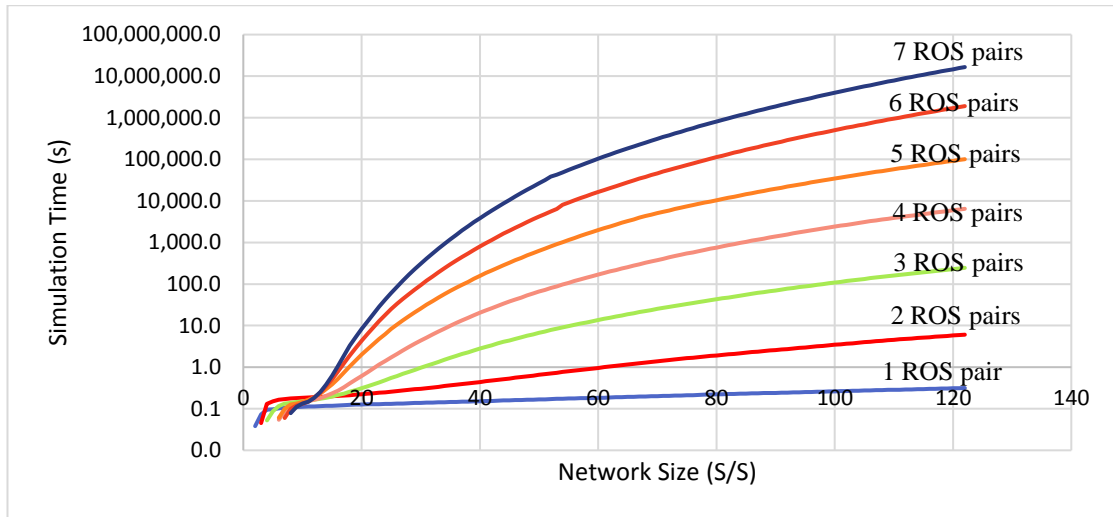


Figure 3-19: Simulation time increased with increasing the number of ROS pairs and number of substations

From the simulations, in order to search for up to seven optimal locations of ROS pairs, it was found that there are three parameters that have a significant effect on the simulation time: (i) the number of ROS pairs, (ii) the number of branches on a feeder and (iii) the network size.

However, barriers that may adversely affect the simulation times may be overcome by using suitable DPSO parameters as will be discussed in Section 3.3.1 and pre-allocation matrix for Brute Force method. For a network with fewer numbers of combinations, the Brute Force method will be used as a medium to search the optimal locations and number of customers restored because shorter feeder has less simulation time.

Figure 3-20 show the simulation times using the Brute Force method searching from 1 to 7 ROS pairs. Comparison for each number of ROS pair for the method using pre-allocation and without pre-allocation matrix is shown in Figure 3-21. Significant time reduction is achieved using the pre-allocation matrix in the Brute Force method searching for optimal location of ROS pairs. Moreover, the proposed equations have the ability to search for optimal numbers and locations of the ROS pairs for a feeder without branch, a feeder with one branch, two branches and three branches.

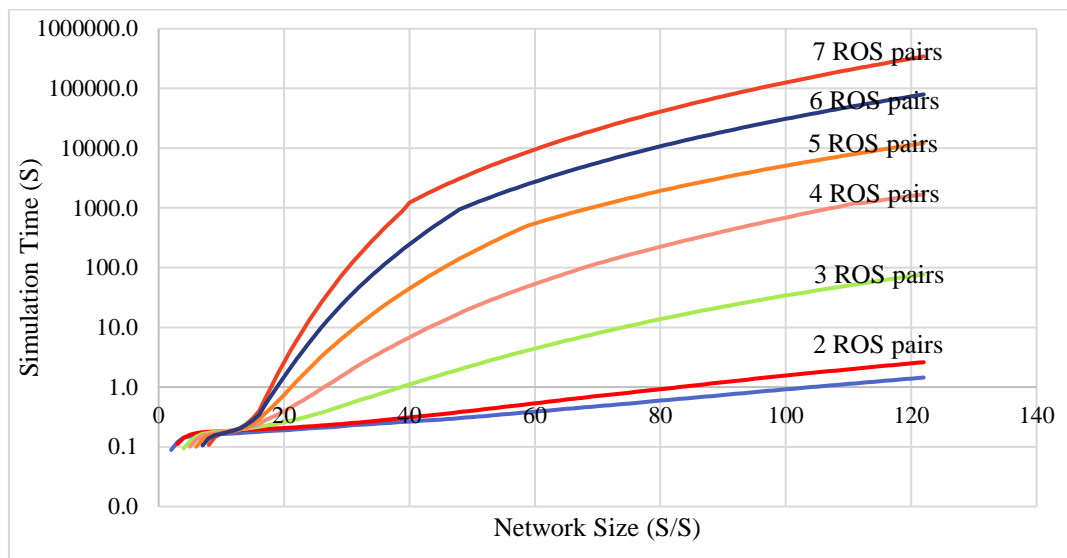
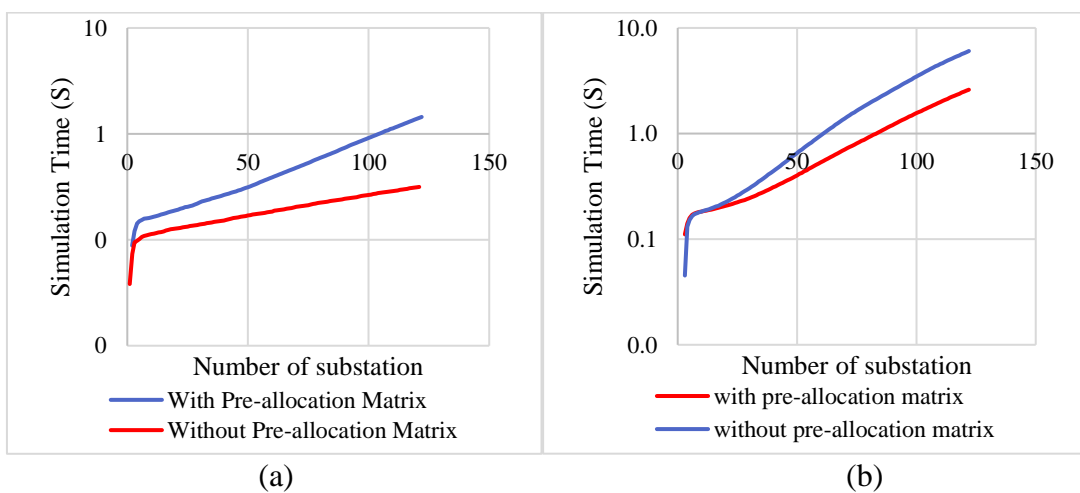


Figure 3-20: Simulation time increased with increasing the number of ROS pairs and feeder length (with pre-allocation matrix included)



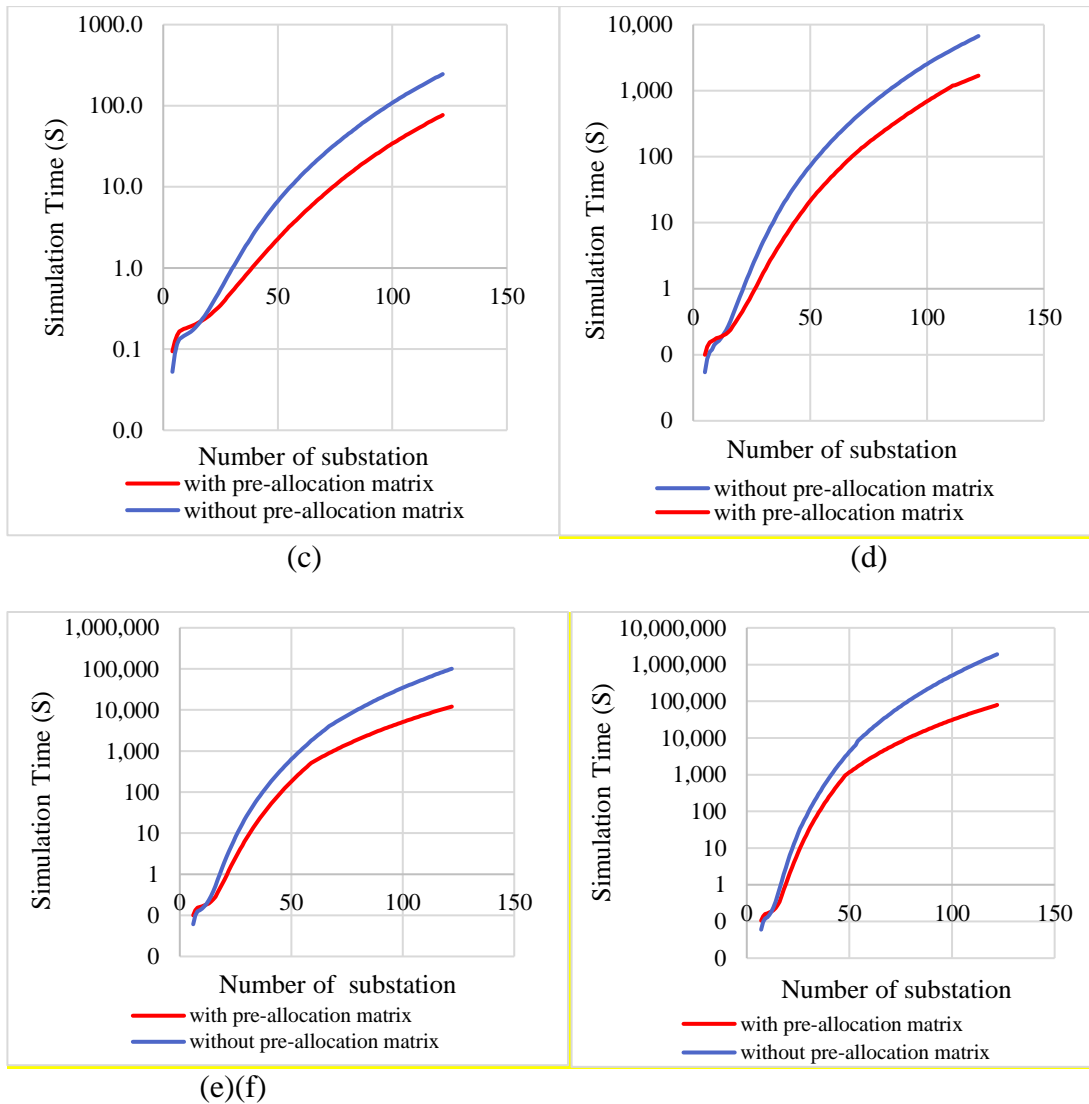


Figure 3-21: Simulation time compared between Brute Force method with and without pre-allocation matrix (a) 1 ROS pair (b) 2 ROS pairs (c) 3 ROS pairs (d) 4 ROS pair (e) 5 ROS pairs (f) 6 ROS pairs

### 3.2.9 Discrete Particle Swarm Optimisation and Brute Force Method Selection

Selection of a suitable algorithm to achieve the objective function is one of the most crucial parts of this research. Based on the detailed literature review and examining the requirements of the study, DPSO was chosen as the suitable medium to search for optimal locations and number of the ROS pairs in searching the most beneficial cost of ROS pairs and customer outage cost and Brute Force method used for a feeder with less number of substations.

The Brute Force method is also chosen to validate the equations employed to calculate the objective function in the DPSO.

Comprehensive testing has been done on a feeder with different numbers of substations ranging from 2 to 122 for both methods and will be discussed in Section 5.3.

### **3.3 THE PROPOSED ALGORITHM TO DETERMINE OPTIMAL LOCATIONS AND NUMBERS OF THE ROS PAIRS**

In Section 3.2, the proposed procedure for determining the optimal ULR and DLR for a given system was described. However, this procedure starts from an assumed set number and location of ROS pairs. As mentioned in introduction Section 3.1, the challenge is to develop an algorithm that is able to calculate the optimal locations and number of ROS pairs. As described in detail in Chapter 2, and comparing with other artificial intelligence techniques, the DPSO technique has been selected as the most suitable to develop an algorithm to determine these optimal quantities.

The details of the generic code for the DPSO including the objective function are shown in the flow chart of *Figure 3-22*. With reference to *Figure 3-22*, the steps are as follows:

**Step 1:** For each particle ( $X_i$ ), the parameters (the locations of the switches and the number of customers at each substation) are set up. Initially, randomly selected velocities (2-2) in the search space (network) are chosen for each particle, and best-known positions (pBest) (2-3) of each particle are defined. The possible number of customers restored on visited candidate locations by particles and calculated using a given objective function is discussed in detail in Section 3.2. The best locations that produce the highest number of customers restored are selected as optimal locations.



Boundaries for each network are different and depend on the total number of substations on the network. The DPSO will recognise the topology of the network by considering the number of substations, section length between substation, junction nodes, interconnection between substation and number of branches. The number of particles for this problem is dependent on the size of network.

**Step 2:** The fitness function ( $F(X_i)$ ) is calculated and, if the current value is better than the previous best fit value ( $pBest$ ), then the current value is updated or else the previous  $pBest$  is kept. Fitness values represent the number of customers restored with ULR and DLR for the respective location.

**Step 3:** Choose the particle with the best fitness value ( $F(X_i)$ ) of all the particles as  $gBest$ . Calculate the particle velocity according to (1) and update the particle position according to (2).

**Step 4:** Repeat Step 2 until the system converges or when the particles find the best optimal locations of remotely operable switch pairs.

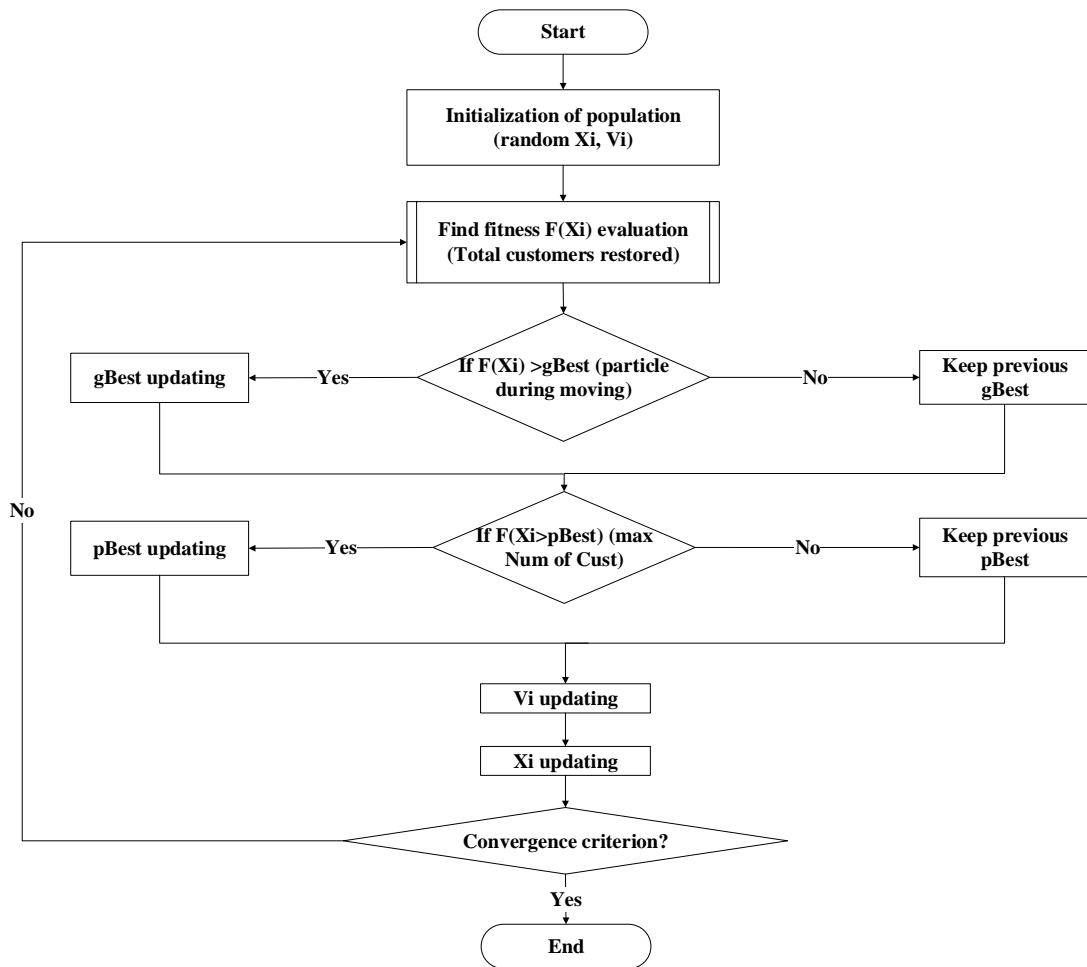


Figure 3-22: DPSO searching the optimal locations of a pair of ROS pairs

### 3.3.1 DPSO Parameter Setting

The DPSO algorithm is initialised using a population of random candidate solutions. The random candidate solutions are particles used to search for optimal locations of switch pairs. They can be conceptualised as positions of particles ( $X_i$ ) or possible locations of switch pairs and assigned with a randomised velocity of particles ( $V_i$ ). Consequently, particles may have large position updates, which result in particles leaving the boundaries of the search space (particle divergence). The particles are moved iteratively through the problem space, in this case, the network. To control the global exploration of particles, velocities are clamped to stay within a boundary. If the

particle velocity exceeds a specified maximum velocity, it is constrained to the maximum velocity [96]. The particles are attracted towards the location of the best fitness,  $F(X_i)$ , in this case, representing the maximum potential number of restored customers and are defined as the best-fit locations achieved across the full population. Also the number and locations of switch selected by the DPSO should gain benefit to the DNO. The developed DPSO with a specific objective function (optimal location of switch pairs) records the best location and maximum number of restored customers. Each location of a remotely-operated point represents a switch pair of switches at a single substation.

The selection of key parameters to setup the DPSO such as  $C_1$ ,  $C_2$  and  $V_{\max}$  is an important task as they govern the convergence rate as discussed in Section 2.2.8. To ensure that the parameters are suitable for any type of network, representative feeders have been selected from different topologies, with variables such as length of feeder (higher, medium and lower number of substations), feeders with branches and without branches and feeders with a different number of customers on each substation.

The networks have a differing number of substations and are connected either as a single line feeder or with branches. The time taken to search is observed to increase when the number of ROS pairs, substations or branches is increased. Increasing the number of branches will increase the number of equations necessary to maximise an objective function (number of customers restored).

In general, the number of required iterations is increased when a feeder has:

- More branches
- More possible locations of ROS pairs

However, the number of required iterations decreases when the total number of switch pairs is greater than half of  $N_T$  ( $N_T$ ; the total number of substations on a feeder).

This is because the total number of unique possible locations for the ROS pairs decreases beyond this point, as discussed in Section 2.2.1.

After several trials with DPSO parameters ( $C_1$ ,  $C_2$  and  $V_{max}$ ), varied from their minimum to maximum values and considering different topologies of network, the parameters finally chosen in this investigation are shown in *Table 3-6*.

*Table 3-6: DPSO Parameters for Different Branches of Feeder*

PSO Parameters	
$C_1$	2
Maximum Iterations	500
$C_2$	2.1
$V_{max}$	$\pm 5$
N (particles)	50 - 70

The complexity of the network will increase the number of iterations. The parameters were tested iteratively to search for a suitable  $C_1$ ,  $C_2$  and iterations for different characteristics of the feeders. In addition, suitable modifications and upgrades were made so that the DPSO algorithm can be matched with different network topologies and differing numbers of ROS pairs. From this finding, different types of network will have slightly different DPSO parameter settings to reduce the convergence time especially the number of iteration and particles.  $N$  is used as the number of particles during simulation of the networks. A higher number of particles influences the simulation time of the DPSO. Therefore, several trials are performed for appropriate parameter value selection for different numbers of substations and increasing number of ROS pairs. Details pseudocode for the DPSO algorithm used in this thesis shown in *Figure 3-23*. The algorithm applied on a single feeder network for unlimited number of ROS pairs.

Total number of node on a feeder is  $j$ , read by the program. By giving the number of particles, random  $X$  generated and  $V$  set to be '0'. Objective function for each  $X$  calculated and pbest for each particle recorded for the first guess including gbest. The

velocity for each particle evaluated. The process of searching the pbest and gbest continue until maximum iteration reach

---

**Algorithm 1** DPSO For a Single Feeder

---

```

1: procedure DISCRETE PARTICLE SWARM OPTIMISATION
2:   j = number of nodes on feeder
3: For i=1 to n: //n particles
4:   Generate Random First Guess  $X_{t,j,1}$ 
5:   Initialise V to zero  $V_{t,j,1} = 0$ 
6: End
7: Evaluate ObjectiveFunction( $X_{t,j,1}$ )
8: For i=1 to n:
9:    $P_{t,1} = X_{t,1}$  //pbest starting value
10: End
11:  $G_1 = best(X_{t,1})$  //gbest of first guess
12: For i=1 to n:
13:    $S_{t,j,1} = \frac{1}{1+\exp(-V_{t,j,1})}$  //sigmoid function
14:   if  $\text{rand}(1,0) < S_{t,j,1} > 0.5$  then  $X_{t,j,2} = 1$ , else  $X_{t,j,2} = 0$ 
15:    $\Delta V_p(i, j, 1) = P_{t,1} - X_{t,j,1}$ ,  $\Delta V_g(i, j, 1) = G_1 - X_{t,j,1}$ 
16:    $V_{t,j,2} = V_{t,j,1} + c1 \cdot \text{rand}(1, 0) \cdot \Delta V_p(i, j, 1) + c2 \cdot \text{rand}(1, 0) \cdot \Delta V_g(i, j, 1)$ 
17: End
18: For it=1 to itmax: //start iterations
19: Evaluate ObjectiveFunction( $X_{t,j,it}$ )
20: For i=1 to n:
21:    $P_{t,it} = best(X_{t,1:it})$ 
22: End
23:  $G_{it} = best(X)$  //gbest
24: For i=1 to n:
25:    $S_{t,j,it} = \frac{1}{1+\exp(-V_{t,j,it})}$  //sigmoid function
26:   if  $\text{rand}(1,0) < S_{t,j,it} > 0.5$  then  $X_{t,j,it+1} = 1$ , else  $X_{t,j,it+1} = 0$ 
27:    $\Delta V_p(i, j, it) = P_{t,it} - X_{t,j,it}$ ,  $\Delta V_g(i, j, it) = G_{it} - X_{t,j,it}$ 
28:    $V_{t,j,it+1} = V_{t,j,it} + c1 \cdot \text{rand}(1, 0) \cdot \Delta V_p(i, j, it) + c2 \cdot \text{rand}(1, 0) \cdot \Delta V_g(i, j, it)$ 
29: End
30: End

```

---

Figure 3-23: DPSO algorithm for single feeder network

### 3.3.2 Network Recognition by DPSO and Brute Force

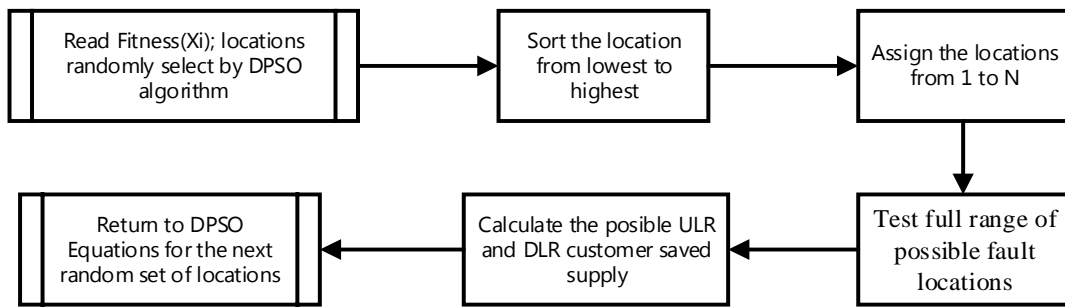
For any given electricity distribution network, there will be a certain number of feeders, each having a different number of branches, branch lengths and numbers of substations. Each substation will have a particular loading condition and number of customers. Feeders, particularly in urban areas, are likely to be interconnected in a ring configuration with an NOP split point defining the end points of the two radial components of that ring. Sometimes, feeders may be interconnected with other feeders

at points along their radial path. In other words, the physical topology and loading of networks may be quite different from one network to another. Therefore, the developed DPSO algorithm and Brute Force must recognise network physical topology by reading the number of branches, locations of NOP, number of customers at each feeder and length of the cable/line section of each feeder. The details of how the developed DPSO and Brute Force obtain such information are discussed in Subsection 4.2.

### **3.3.3 Application of Objective Function in DPSO and Brute Force**

The location of a switch pair is used as the variable to analyse the performance of the network if a fault occurring in any section results in an outage. The location that gives the maximum number of restored customers is selected as the optimum. The NEPLAN/NPL program code will take the position of the selected location into account via the DPSO or Brute Force, ( $X_i$ ) prior to the calculation of the number of restored customers.

The location of the ROS pairs is selected randomly by DPSO until the optimal locations are reach. However, the Brute Force method will search for all combinations of available ROS pairs. If the number of substations is large, the time taken to obtain the optimum location will be longer if the ROS pairs needs to be increased. The locations of the ROS pairs that provide the maximum number of restored customers following ULR and DLR in response to an outage cost and net benefits of installing a ROS pairs, will be selected as the optimum location among others. The process to obtain the optimum location is shown in *Figure 3-24*.



*Figure 3-24: The Flow of the Calculation of the ULR and DLR Customers for One Location*

If the network searches for more than one ROS pairs, (for example to obtain the best locations for two ROS pairs) the situation is more complicated. The DPSO randomly selects two locations of switches which are defined as Location 1 and Location 2. Different positions are required to proceed with both ULR and DLR calculations for each single combination of any two locations. The process returns to the main program so that the DPSO is able to compare the number of restored customers and repeat the process for the next combination of locations until the DPSO finds an optimum position for both locations. When the number of possible locations for the remotely operated switch pairs or clusters increases, the number of permutations increases considerably. The number of permutations according to the total number of possible available switch pair locations and the number under consideration is given by  $Np$  from Equation (2-1).

The program has the capability to increase and search the number of optimal locations of the ROS pairs until it reaches a number representing full automation, i.e. when every switch pair in the network is an ROS pair.

### **3.4 SOFTWARE DEVELOPMENT**

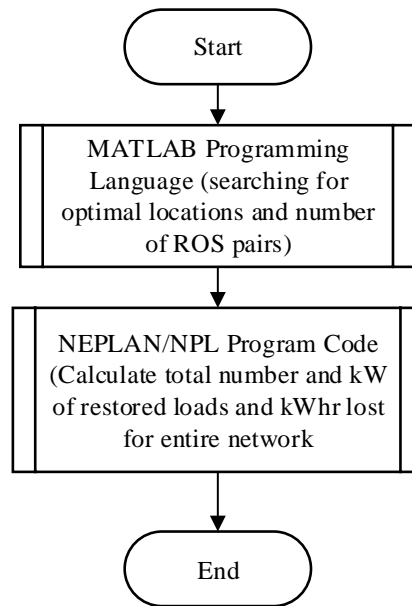
The optimal locations of ROS pairs is decided using an algorithm written in the MATLAB programming language and the total number of kW of restored load, and the

kWhr lost is calculated by using an algorithm written in NEPLAN, using the NPL language. *Figure 3-25* shows a flow chart representing the interaction between MATLAB and NEPLAN. A more detailed flow chart for the algorithm written in the MATLAB programming language was shown in *Figure 3-22* and the algorithm written in NEPLAN/NPL is shown in *Figure 3-27*. The algorithms are written separately and are stand alone. The results from MATLAB are incorporated manually into the NEPLAN/NPL software.

A detailed description is provided of the developed algorithm to determine the maximum extent of upstream and downstream restoration for a generic distribution network with a pre-determined number and location of ROS pairs. A detailed explanation of the objective function of the DPSO and Brute Force method is also provided. The number of customers calculated refers to the number and locations of switches in a network. The investigation is carried out using the MATLAB Programming language.

Details of the DPSO algorithm parameters and possible locations of ROS pairs available in a network are discussed in the Section 3.3.1. The loadflow is performed using the Newton Raphson Method. The code is written using the NPL software, and the developed general algorithm for implementing a fully automated system is also described.





*Figure 3-25: Overall algorithms using MATLAB programming language and NEPLAN/NPL program code*

### **3.5 OPTIMIZATION OF NETWORK ULR AND DLR FOR A GIVEN NUMBER AND LOCATION OF ROS PAIRS USING NEPLAN AND NPL SOFTWARE FOR FULLY AUTOMATED SYSTEM**

NEPLAN comprises an advanced suite of power system analysis tools for electricity systems. Although it is used widely in industry as a standard system analysis tool, it has a particular benefit for research applications in that it incorporates an advanced coding function known as the NEPLAN programming library (NPL) which greatly increases the flexibility and control of power system simulations [124]. NPL is a programming tool based on C++ and provides the means to carry out a very large number of simulations of power networks with proposed restoration algorithms. In this work, the NEPLAN loadflow module is the primary in-built algorithm, and programs are written in NPL to simulate (i) the intact network, (ii) random network outages, (iii) operation of automated devices and (iv) the network conditions post-restoration.

The programming requirements of the NEPLAN software and NPL for the simulation can be described in more detail with reference to a section of a typical urban

distribution supply network shown in *Figure 3-26*. The network in *Figure 3-26* comprises two radial 11kV feeders (Feeder A and Feeder B) supplied respectively from primary substation A and primary substation B. Feeder A has two branches and a total of 12 substations while Feeder B has only 4 substations. The secondary substations along the feeders transform between 11kV and 415V, and each are assumed to have a ring main unit (RMU) comprising two HV switches either side of the transformer tee-off. Traditionally, such switches have been manually operated and the transformer is protected by an HV fuse. In this work, it is assumed that the switches can be made remotely operable during the dead time following fault clearance, either by modification or replacement. The end points of Feeder A and Feeder B are interconnected as is commonly the case in urban distribution networks, and these connection points or 'split points' are typically run in a normally-open condition. In this network, there are three normally open split points: P, Q and R. At each primary substation, a circuit breaker capable of interrupting fault current is located and these devices would operate first in the event of a fault on any section of their respective feeders.

In *Figure 3-26*, all the switches associated with the secondary substations are assumed to be remotely operable; in this state, it can be described as a fully automated network. Since each substation comprises an RMU, the unit of automation is assumed to be a remotely operable switch pair rather than an individual switch. With this complete level of automation, if an outage occurs at any section, there is the opportunity to perform an 'up-stream restoration' (ULR) and also a 'down-stream' restoration (DLR). For example, if a fault occurred on the section of cable between Substations 7 and 8 of Feeder A, the main circuit breaker at substation A would operate on over current protection and supply would be lost to all the secondary substations connected to Feeder A. Feeder B substations would remain unaffected because the feeder is

isolated from the fault already by the split points. If, during the dead-time following the main circuit breaker operation, the downstream switch of Feeder A, Substation 7 and the upstream switch of Feeder A, Substation 8 were to be opened, supply could be restored to Substations 1, 2, 3, 4, 5, 6 and 7 of Feeder A through the reclosure of the main circuit breaker at Substation A. This is referred to and described as ‘upstream load restoration’ ULR.

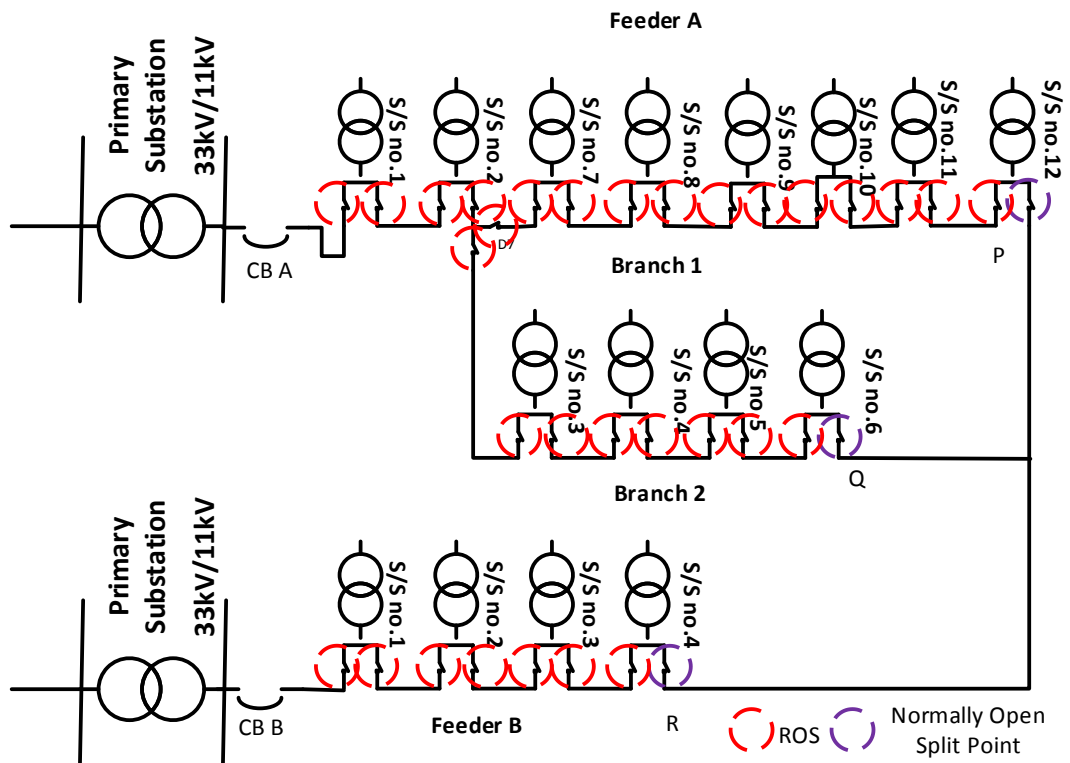


Figure 3-26: Example of fully automated urban network

However, Substations 8 - 12 of Feeder A remain off-supply, and the short-term supply restoration of these substations can only be achieved by the so-called downstream restoration by the operation (closure) of split points. For this simple example network, it can be seen that there are two possibilities: closure of split points P and R, or closure of split points P and Q. The choice between these two options would depend on the merits of the electrical performance of the network following the DLR. It should be noted that DLR will impose an additional load on the ‘donating’ feeder and the thermal capacity and voltage profile would need to be evaluated in each case. In

addition, the reconfiguration of the network would also have an impact on fault current and protection settings. Therefore, it is important that DLR does not introduce any voltage, current or protection performance violations. If such supply restoration were to be performed operationally then on-line system studies may need to be performed prior to DLR operation to avoid violations and to select the best DLR option. ULR would not require any such checks, as the reconfigured feeder would be operating under a lighter load condition. It should also be noted that should such an approach be adopted operationally on networks, in order to carry out pre-restoration DLR switching operation system studies, live loading information (P and Q) may be required from each secondary substation. This implies that there would need to be a communication system in place to gather such data as well as send control signals to the ROS pairs.

The generalisation of this step-by-step process of potential supply restoration in a distribution network is described in the flow chart of shown in *Figure 3-27*. From the figure, it can be seen that a load flow study is carried out for the initial intact system that would contain a certain number of automated devices (ranging from 0 to N switch pairs and M split points, and where N is the total number of secondary substations). A random fault is assumed to occur that causes the operation of the main circuit breaker at the primary supply point. Following identification of the faulty section, the ULR routine systematically checks all upstream nodes from the fault point to the primary substation for automatic switchable devices. There are two possible scenarios for ULR

- i. if there are no ROS pairs, no ULR is possible.
- ii. if one or more ROS pairs are available, the switch nearest to the faulted section is operated, followed by operation of the main primary substation circuit breaker to restore the maximum number of customers.

As could be gleaned from the earlier simple example, downstream restoration is a more complex process that requires an evaluation of possible alternative supply or ‘backfeed’ routes. The type of 11 kV network that is particularly common in urban areas is highly interconnected; although as mentioned earlier, individual feeders are usually radial rather than in a meshed configuration. Therefore, there may be many options available. The generalised process to examine and evaluate DLR, with reference once more to *Figure 3-27* are:

- i. Identification of all possible DLR supply routes including the details of nodes, lines and protective devices and status of switches and circuit breakers
- ii. Performing a study of the load flow with Newton Raphson Method of each DLR supply route for different extents of backfeeding
- iii. Checking to ensure that there is no voltage or current violations along the DLR supply route
- iv. Recording the number of restored customers and kW of restored loads for the best DLR scenario.

The restoration routine currently does not consider protection grading requirements of the reconfigured network, although this important aspect will need to be investigated in future work. It is also assumed that the voltage and current information are available at all points in the network through the deployment of low-cost voltage and current transducers together with necessary communication links to centrally obtain this information and implement the remote operation of switches. The flow chart has been implemented as code in NPL and described in *Figure 3-27*.

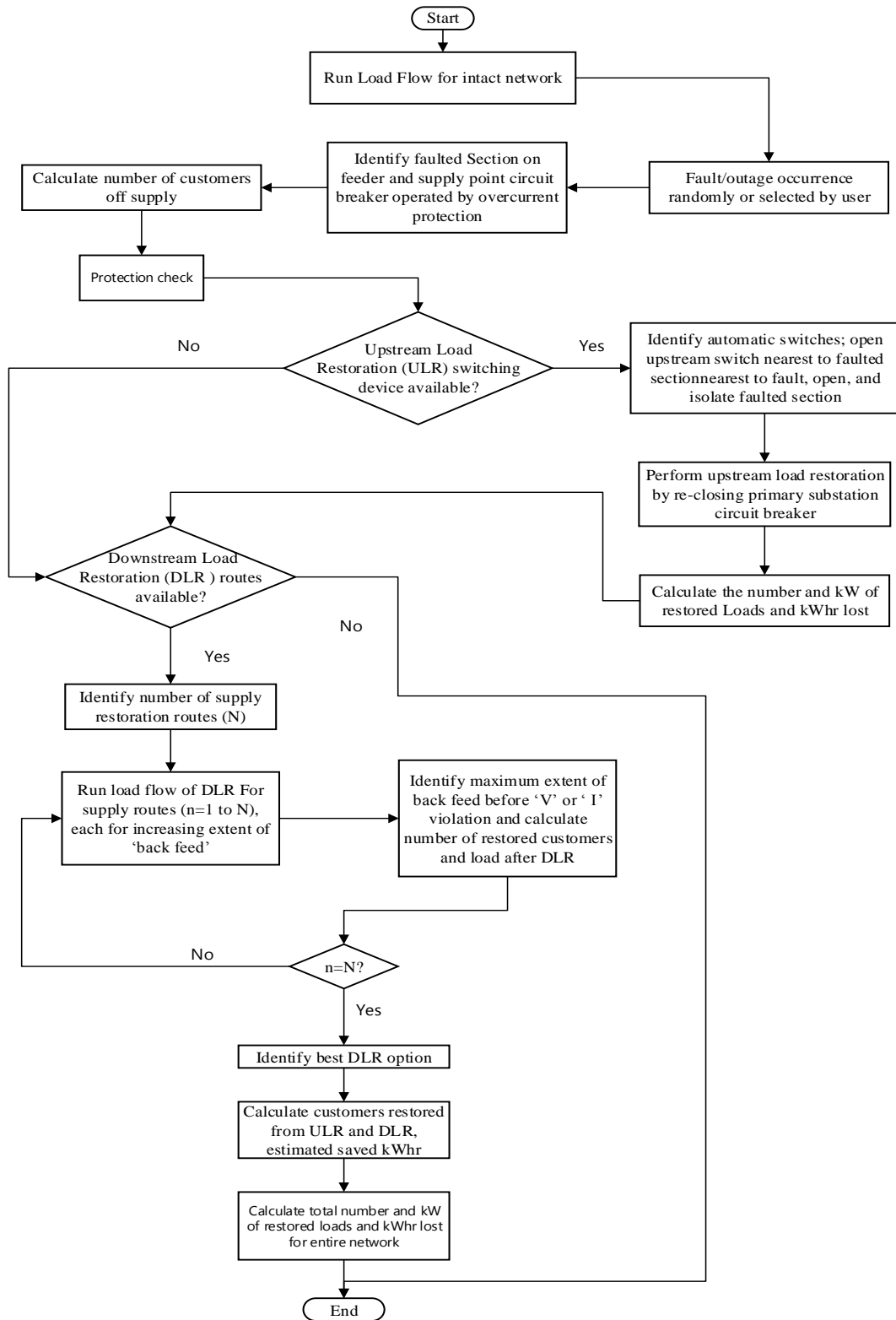


Figure 3-27: Flow chart of the supply algorithm

### **3.6 CONCLUSION**

The problem formulation according to the required objective function has been described and performed using DPSO and Brute Force method. The developed algorithm also includes failure rate associated with the cable and line sections. To reduce the overall simulation time, a pre-allocation matrix was developed and used to calculate the number of customers and failure rates bounded by any two substations.

Details of the selected algorithm (DPSO) have been discussed in this chapter including setting of the parameters of DPSO, adaptation of the algorithm to handle a generic network and implementation of the DPSO and Brute Force on the case study network searching for optimal number and locations of ROS pairs depending on the outage and protective devices cost.

The software packages MATLAB and NEPLAN have been combined to provide a complete restoration search that includes process searching for (i) finding optimal locations of ROS pairs, (ii) determining the best downstream feeder for restoration and (iii) obtaining post-restoration voltage and current profiles to ensure viable restoration.

## CHAPTER 4

# DEVELOPMENT OF CASE STUDY NETWORK MODELS AND IMPLEMENTATION OF PROPOSED ALGORITHM

### 4.1 INTRODUCTION

Three distinct 11kV networks, based on real network data and implemented in NEPLAN, are used as case studies to test and validate the proposed algorithm. The networks possess different characteristics that have to be considered during simulations (e.g. length for each section, number of customers at each substation, number of substations on each feeder, number of branches and location of the NOP). Obtaining these data, then representing it accurately in the simulations, represented a substantial challenge in this research. The one line diagram of the urban, semi-urban and rural networks are shown in *Figure 4-1*, *Figure 4-2*, and *Figure 4-3* respectively. The graphical representation of the networks modelled within the NEPLAN software is shown in Appendix 4. The characteristics of these three networks are summarised in *Table 4-1*. The urban network has the highest number of customers. However, the rural network possesses the largest number of substations, despite having the fewest customers. The rural network also has more complicated connections than the other two networks, and this is generally the case for rural networks. The urban network has 31 feeders, however, only 28 were used for searching the optimal location of ROS pairs because three of the feeders have only one substation. For feeders with fewer numbers of substation, Brute Force method is used to search for optimal locations of ROS pairs because simulation time is not a constraint for such cases.

The result obtained from the optimal location of ROS pairs in a network should produce a negative cost, i.e. the net benefits the costs and the costs of installation of the



switches should be less than ‘outage costs’ of customers saved. A positive cost means that the cost of installation of the ROS pairs is greater than the net benefits and indicates that no switches should be installed.

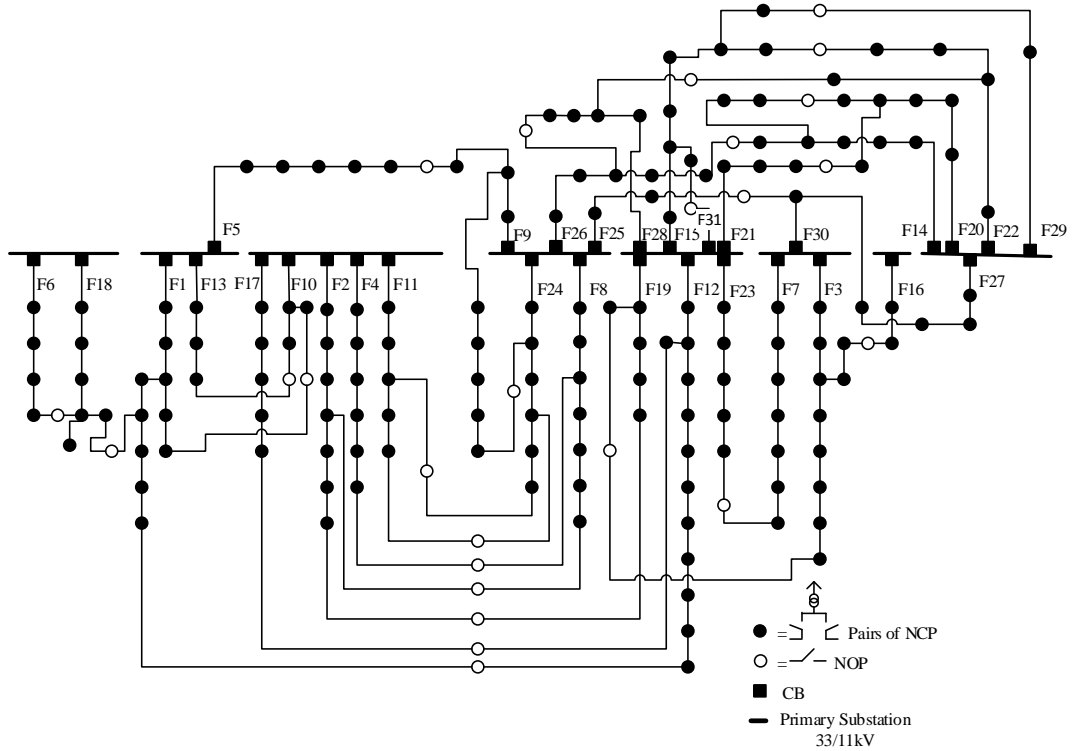


Figure 4-1: Case studies real Urban network

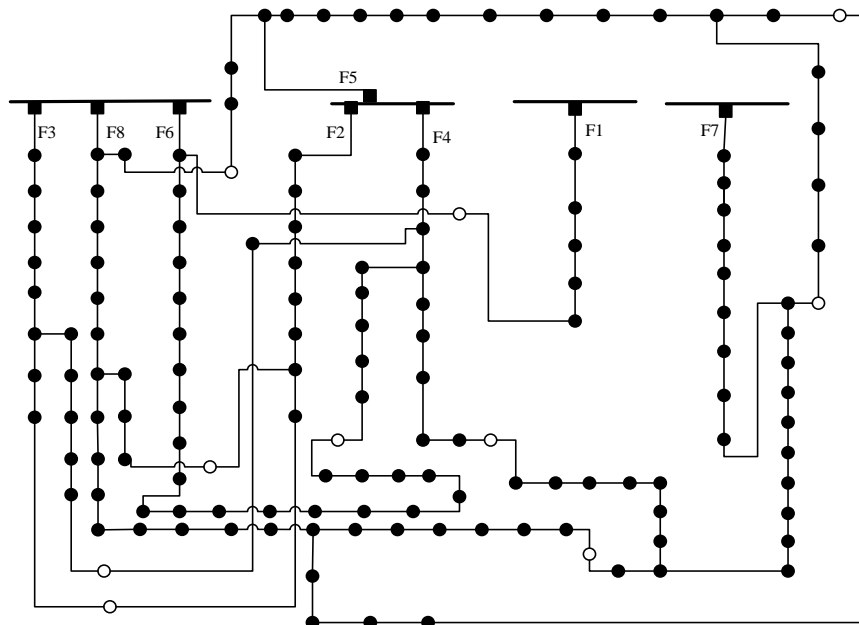


Figure 4-2: Case studies real Semi-urban network

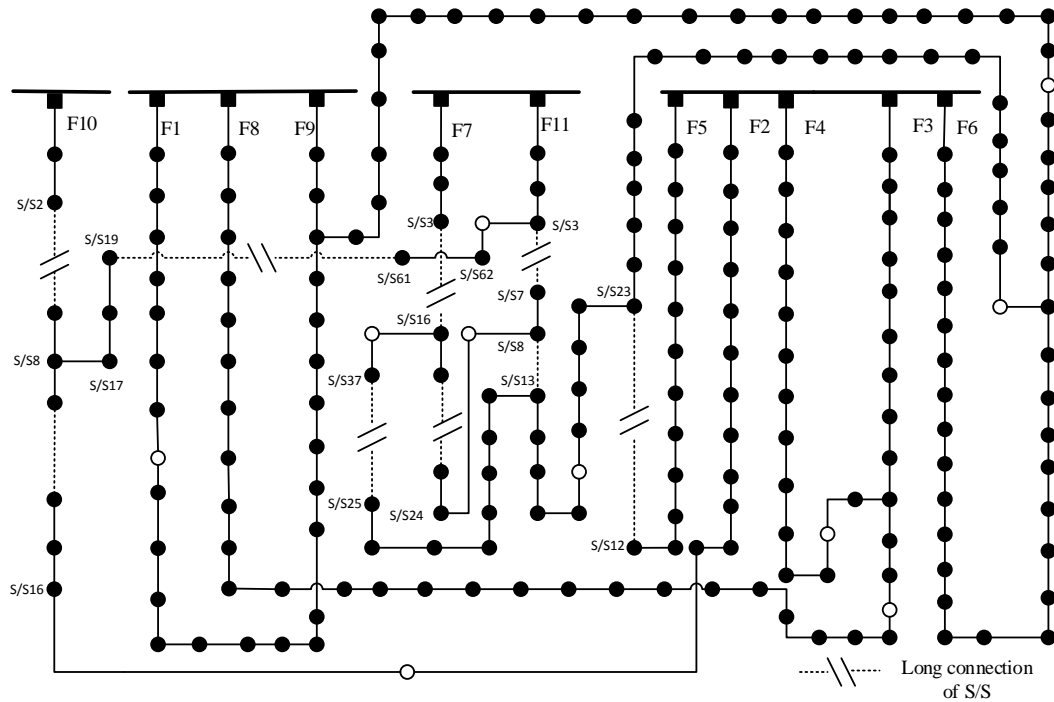


Figure 4-3: Case studies real Rural network

Table 4-1: Characteristic of the three real networks chosen for the case studies

Networks	No. of Substations	No. of Feeders	Feeder Available for Analysis	Total Customers
Urban	162	31	28	10512
Semi Urban	139	8	8	1268
Rural	310	11	11	3680

## 4.2 DPSO AND BRUTE FORCE IMPLEMENTATION FOR OPTIMAL LOCATIONS OF ROS PAIRS– DATA READING

A MATLAB routine was written to prepare the necessary data for the Brute Force method and DPSO (data reading). Three network topologies are defined according to the location of the NOP in the network. Figure 4-4 illustrates the first type of feeder network considered (Type 1). The network consists of a feeder with a NOP at the end of the network, located at substation 8. This is the typical condition of the network connection characteristic and known as a ‘single feeder’ in the network. If the feeder has branches, each of the endings may or may not have a NOP. The NOP termination description for this type is shown in *Table 4-2*. Column 3 of ‘type 1’

indicates if there are NOPs located at any substations other than at substation 8. If, there are no NOP at the other substations, this is denoted by a zero in the column.

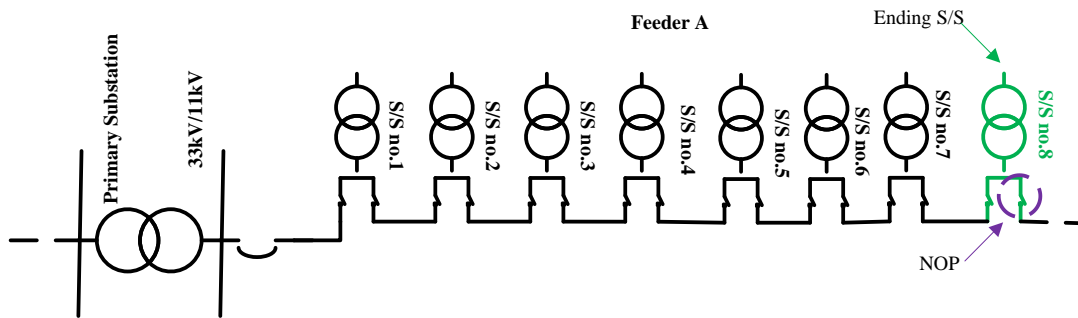


Figure 4-4: Normal condition of feeder with one ending (Type 1)

The ‘type 2’ configuration is shown in Figure 4-5, with two NOPs in the network. The first and second NOP are located at substation 4 and 8 respectively. The uniqueness of this case is that the first NOP located at Substation 4 has no branches coming out from it; i.e it is an interconnection point directly from the main feeder. Therefore, this network also has the possibility of restoration via Substation 4 rather than only from substation 8 as in the ‘type 1’ configuration. In Table 4-2, Column 4, shows all of the feeders are indicated with a “0” except at substation 4 which is denoted “1” indicating that there is an NOP available at the substation.

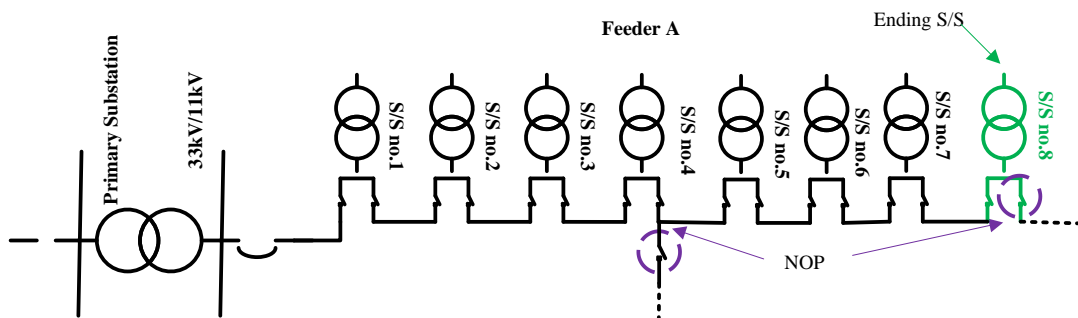


Figure 4-5: Feeder with one ending and NOP connected in the middle of feeder (Type 2)

Table 4-2: NOP termination for Type 1 and 2 feeders

NOP is present other than at the branch ending (Yes = 1, No = 0) or NOP not present at branch ending = 2			
From	To	Type 1	Type 2
1	2	0	0
2	3	0	0
3	4	0	0
4	5	0	1
5	6	0	0
6	7	0	0
7	8	0	0

The third type of network is illustrated in *Figure 4-6*, a network comprising one branch. Typically, such arrangement will have an NOP at both ‘end’ substations (i. e. Substations 6 and 12). However, for this network type, only the end 2 has a NOP while the other is without NOP. To capture this information, the substation without a NOP (ending 1) is denoted with a “2”, as shown in *Table 4-3* Column 3.

If the feeder has branches and NOPs at the end of the branches, this feeder is classified as Type 1 (all are zero).

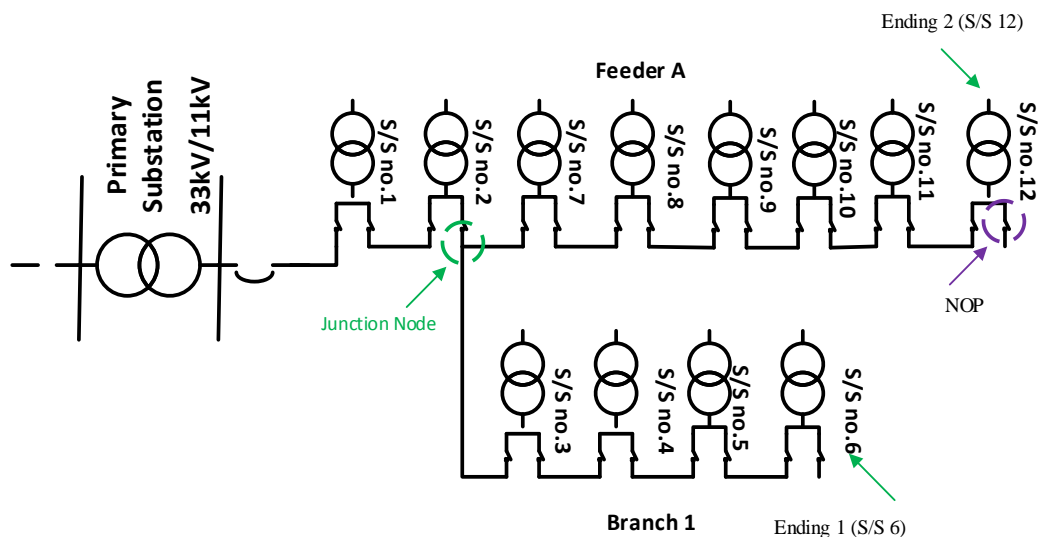


Figure 4-6: Feeder with branches and NOP is not available at one of the branch (type 3)

Table 4-3: NOP termination for 'type 3'

NOP is present at other than ending (Yes = 1, No = 0) or NOP not present at ending = 2		
From	To	Type 3
1	2	0
2	3	0
3	4	0
4	5	0
5	6	2
2	7	0
7	8	0
8	9	0
9	10	0
10	11	0
11	12	0

Table 4-4: Characteristics of Feeder 12 of the urban network (Figure 4-1)

	S/S	Feeder type of (OH =1 or UG = 0)	FeederLength (km)	#Cu
<b>Bus data</b>	A1	0	0.7369	8
	A2	0	0.034	0
	A3	0	0.0799	3
	A4	0	0.3598	1
	A5	0	0.2851	2
	A6	0	0.1907	1
	A7	0	0.1517	1
	A8	0	0.2949	1
	A9	0	0.609	13
	A10	0	0.4607	2
	A11	0	0.216	116
	A12	0	0.321	1

Using Feeder 12 from the urban network as an example, the characteristics of the data are shown in *Table 4-4*. Column 1, "S/S", represents the substation number (used as a label). Column 2 denotes whether the transmission line is an OH or an UG, (OH = 1 or UG = 0). Column 3 gives the length of the linesection in km. The total number of customers on each substation is shown in column 4, "#Cu". The S/S with the

highest numerical value (S/S 12 in this example) indicates the terminating substation on each branch. This would usually coincide with the NOP. Additional information, such as the interconnection between the feeders, is stated in *Table 4-5*. The “From” and “To” columns show the interconnected substations and Column 3 indicates if the feeder is of Type 1, 2 or 3 as mentioned earlier.

*Table 4-5: The line data interconnection of Feeder 12*

Line data	From	To	NOP is present other than at endings (Yes= 1, No =0 ) or NOP not present at endings = 2
	A1	A2	0
	A2	A3	0
	A2	A4	0
	A4	A5	0
	A5	A6	0
	A6	A7	0
	A7	A8	0
	A8	A9	0
	A9	A10	0
	A10	A11	0
	A11	A12	0

The data from both *Table 4-4* and *Table 4-5*; and *Figure 4-7* indicates that Feeder 12 has twelve substations and the labelling of the branches indicates that there is one branch (A2 – A3). The last substation on the shortest branch is denoted Ending 1 and in sequence, by ‘Ending 2’ is denoted as the ending of the main feeder branch. If the feeder has more branches, the labelling process will continue according to the branch length. In this case, Feeder 12 only has one branch.

The last substation at each feeder end represents the ending number, for example, Endings 1 and 2 are located S/Ss A3 and A12 respectively. Each ending has an NOP. Feeder 12 is categorised as Type 1 because the NOPs are available at each

ending substation. The next important characteristic of the feeder to note is the node location or junction in-between branches.

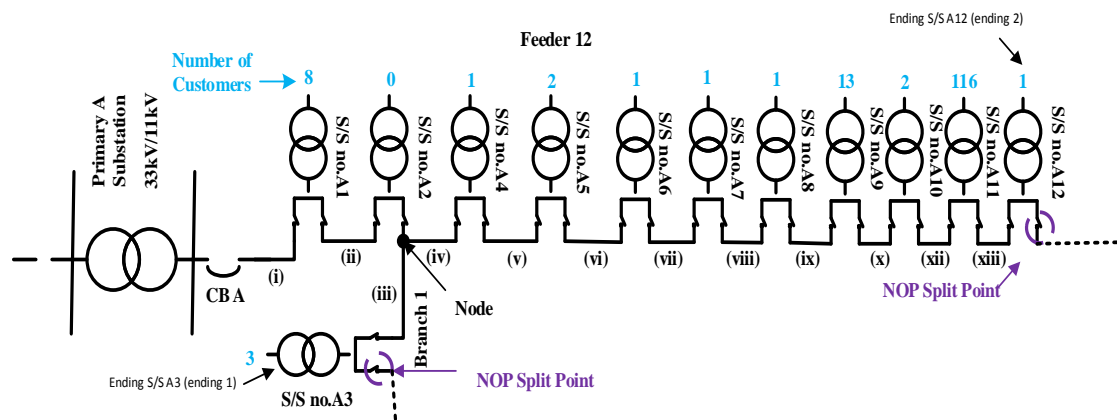


Figure 4-7: Topology of single line Feeder 12 (F12) from the urban network

The junction node for this feeder is located at S/S A2. The code was written to read the characteristics of the feeder such as branches, endings, NOP and junction nodes before the main DPSO simulation is performed. Such information from this data ‘reading’ is used to inform the selection of the optimal locations of the ROS pairs. The main program also gives the user an opportunity to either (i) insert the number of the ROS pairs or (ii) to allow the program to carry out the full range search for the optimal locations starting from 1 ROS pair until it reaches its fully automated state taking into account the previously mentioned computational constraints.

### 4.3 NEPLAN PROGRAM SIMULATIONS TO OBTAIN VOLTAGE AND CURRENT PROFILES

Following the determination of optimal locations of ROS pairs from the Brute Force and DPSO, load flow simulations are required to calculate the voltages and currents at points along the network feeders for each of possible post-restoration conditions. By analysing this loadflow data, suitable solutions of the post-outage

restoration were proposed. Node voltages and branch currents calculations are made for pre-outage and post-outage conditions. The post-outage load flow calculations are described in 4.3.1 and 4.3.2 for a fully automated example and for optimal ROS locations respectively.

### **4.3.1 Fully Automated Case**

All of the networks (urban, semi-urban and rural) are analysed for the fully automated case. However, Feeder 14 as show in *Figure 4-8*, is used as an example to describe the proposed restoration algorithm. This feeder is selected as an example because the feeder consists of one branch and this branch has no NOP. The 11kV feeders are radially operated from their main primary substation. The feeders are interconnected with ‘normally-open’ split points at Q and Z. Feeder 14 has six secondary substations, each supplied by ring main units (RMUs) consisting of two high voltage switches on either side of a tee-off to a HV fuse feeding the transformer.

A load flow computation of the pre-outage network with its assigned loading yields values of voltage and current at each node and line section, which emulates the provision of this data by retrospectively deployed voltage and current transducers throughout the network. Using the pre-outage status and data, and simulating a full range of possible fault positions, systematic system studies are carried out to examine possible options for both ULR and DLR that are present. It is then possible to determine an optimum restoration strategy which allows the maximum number of customer reconnections (from Brute Force method or DPSO) as well as taking into account both thermal and voltage constraints. *Table 4-6* states the number of customers located at each substation on Feeder 14.



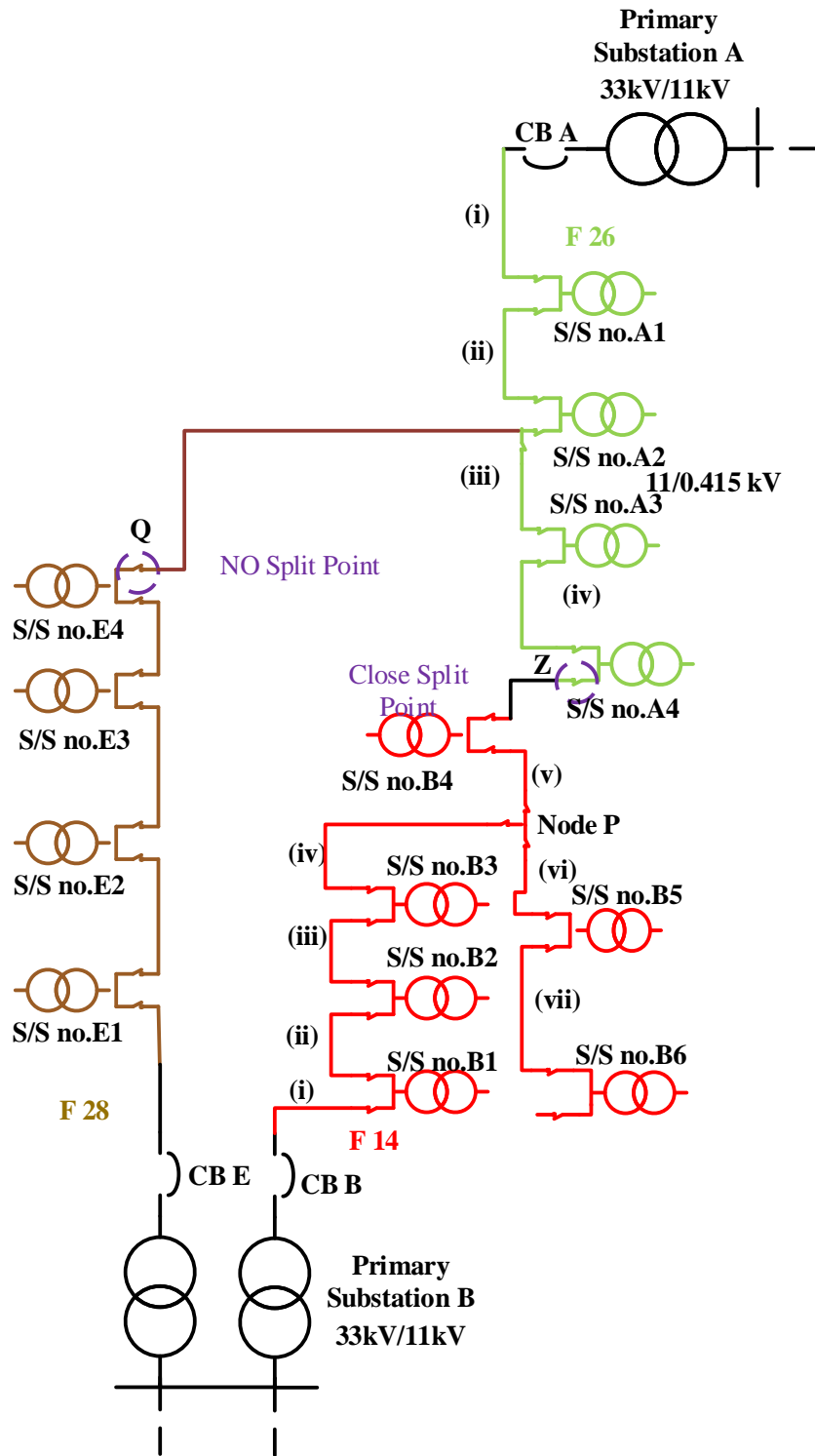


Figure 4-8: One-line diagram of 11 kV Urban network

Table 4-6: Number of customers at each substation on Feeder 14

Substations	Feeder						Total
	B1	B2	B3	B4	B5	B6	
Customers	59	8	79	4	15	5	170

To illustrate the proposed approach for the post-outage condition, a single fault scenario is selected at Feeder 14 in Section (iii) as illustrated in *Figure 4-9*. The detailed flow chart of the restoration algorithm applied in this case study is shown in *Figure 4-10*. When the fault occurs, all customers connected to Feeder 14 up to the normally-open split point at Z (i.e. at S/S B1-6) will lose supply due to tripping of circuit breaker B on an overcurrent protection. Prior to any restoration, the normally closed split points at Y and X must be opened in order to isolate the faulted feeder Section (iii). Customers connected to substations B1 and B2 before the faulted section (iii) may benefit from ULR, while customers at substations B3-B6 can only receive reconnection via DLR. Accordingly, if controllable switches are available at both ends of the faulted Section (iii) i.e. Y and X, they are opened during the dead time and the restoration sequence will start with the reclosure of circuit breaker B to restore all load upstream of the faulted section. Next, the algorithm searches for the optimum downstream restoration option. For this fault scenario, there are two possibilities to consider; firstly, the route via Z to backfeed from Feeder 26 and, secondly, the indirect route from Feeder 28 via a part of Feeder 26. The preliminary observation of these two options reveals that the backfeeding obtained from Feeder 26 (directly) is likely to be better than from feeder 28 because: a) it is more straight forward to implement (fewer switching operations), and b) it transfers power over a shorter distance.

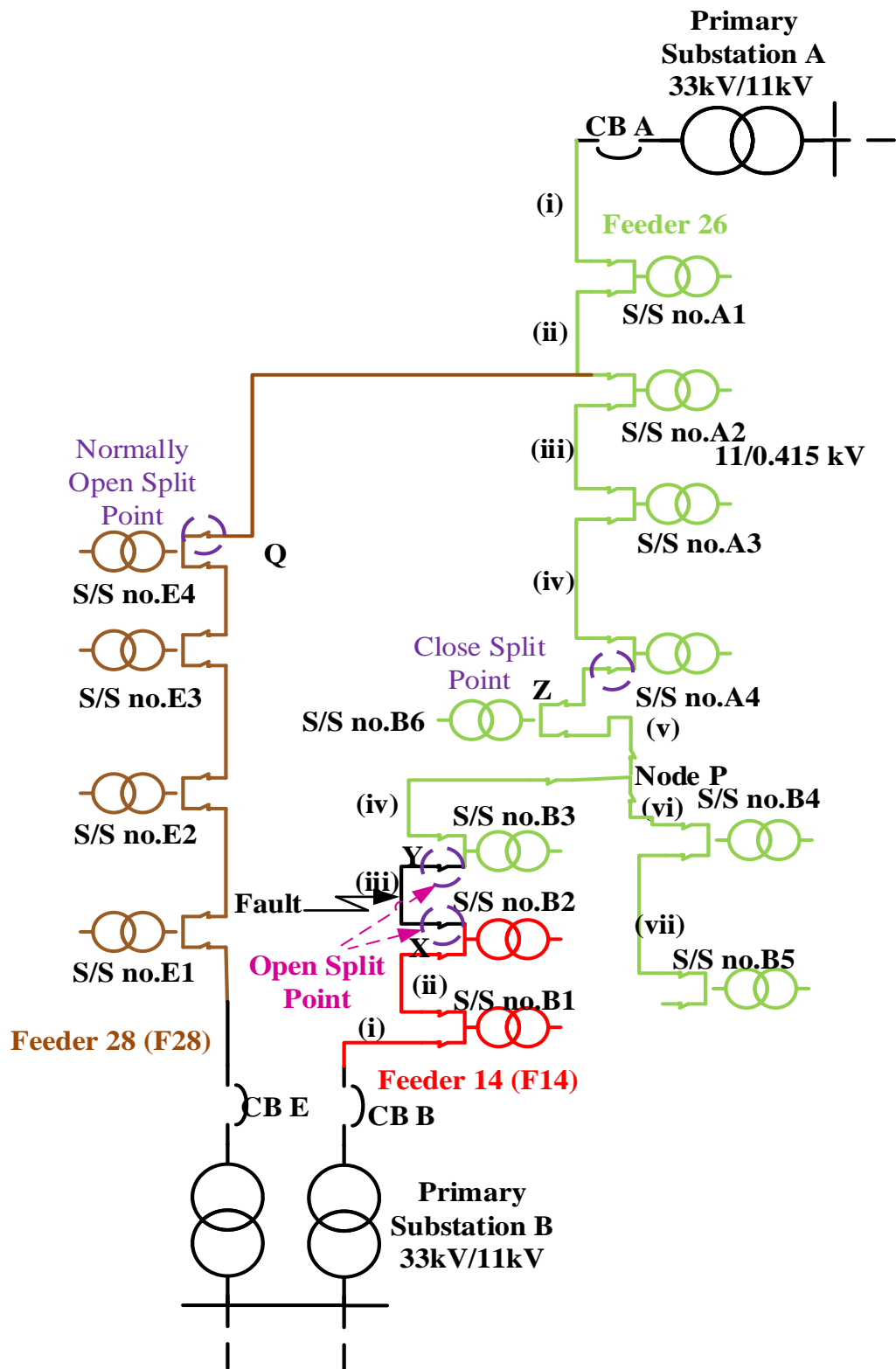


Figure 4-9: Post-outage supply restoration for fault occurring on feeder 14 (F14) in section (iii) with fully automated ROS pairs

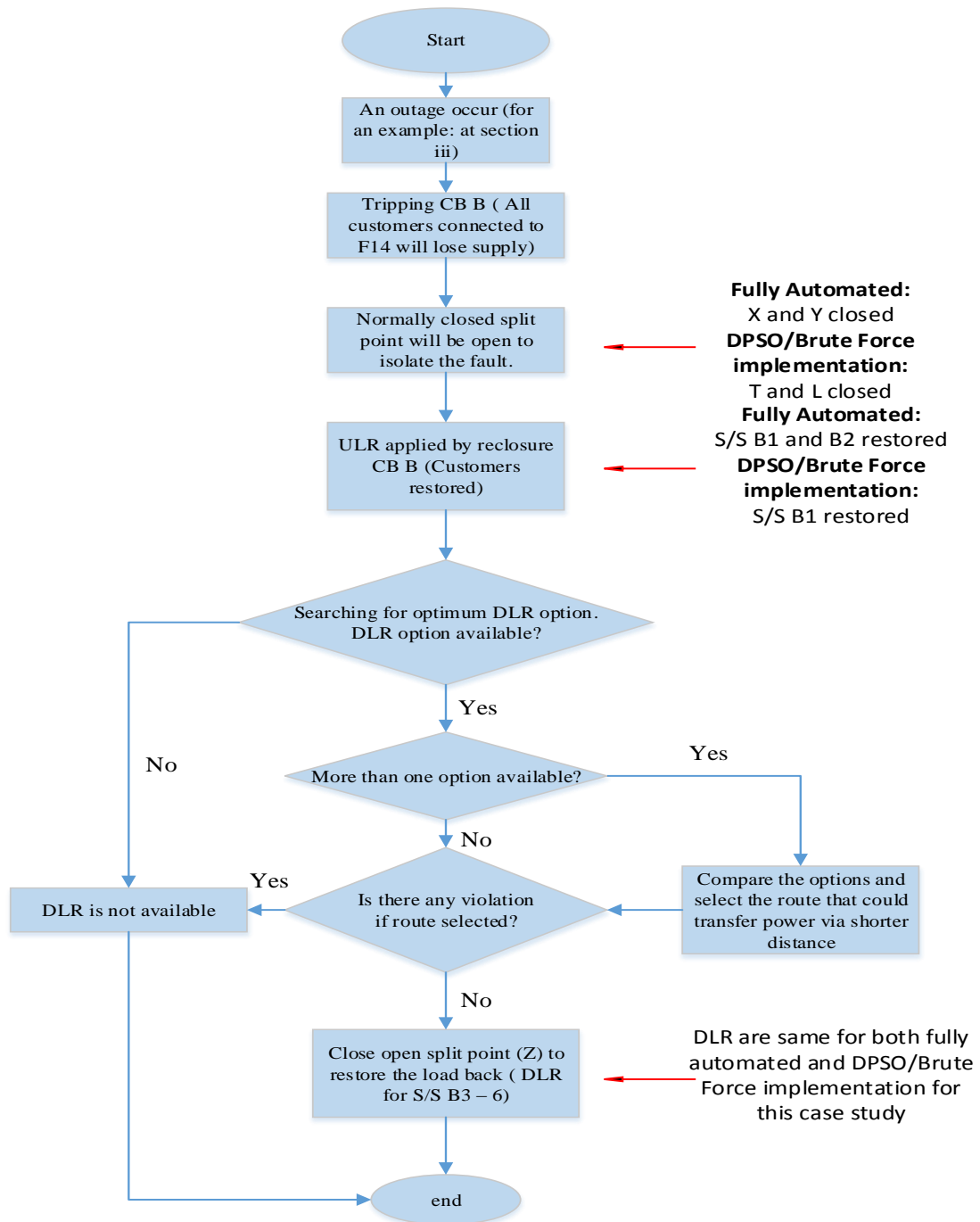


Figure 4-10: Restoration example flow chart

The simulation process proceeds to close the ‘open’ split point at Z to restore the load back to substations B3-6. Post restoration values of voltages and currents are then calculation by NEPLAN. The identification of the alternative supply routes and multiple load flow studies are automatically executed within the NPL. The details of all possible load restorations options for the full range of possible fault locations along

Feeder 14 are tabulated in *Table 4-7*. Customers will only lose supply if an outage occurs at Section vi or vii because, in these cases, there is no backfeeding route or feeder for S/Ss 5 and 6.

*Table 4-7: Summary of the restored customers of the ULR and DLR*

ROS pairs	Fault Section F14	S/S Restored by F14	S/S Restored by F26	Expected customer outage	Expected customer Restored (customer failures/year)
		ULR	DLR	S/S	
Fully Automated System	i	-	B1-B6	-	1.9265
	ii	B1	B2-B6	-	0.1576
	iii	B1-B2	B3-B6	-	0.1393
	iv	B1-B3	B4-B6	-	2.4731
	v	B1-B3, B5-B6	B4	-	0.1355
	vi	B1-B4	-	B5-B6	0.2513
	vii	B1-B5	-	B6	0.0908
	<b>Total of expected customer restored (customer failures/year)</b>				

#### 4.3.2 DPSO or Brute Force Implementation For Limited Optimally Placed ROS Pair

With reference to *Figure 4-8* during the pre-outage, assuming there is a constraint of a maximum of 2 ROS pairs embedded on Feeder 14, they are selected by the Brute Force method as locations B1 and B3. The illustration of the network is as shown in *Figure 4-11* when an outage occurs at Section (iii) of Feeder 14 (i.e. the same position as the previous fully automated example). Before any restoration is applied, the normally closed split points at Y and L must be opened to isolate the faulted feeder section. Customers connected to B1, before the isolated sections, may benefit from ULR. Since the controllable switches are available at S/S B1 and B3, switch Y and switch L will open to isolate the fault at Section (iii) and the restoration sequence will be started by the re-closure of circuit breaker B at Primary B to restore the upstream part of the faulted section. Similar to the fully automated condition, there are two

possibilities for DLR. Substation B2 will lose its supply because of the remotely operated switch located at substation B3. However, substations B3 – B6 will benefit from DLR via Feeder 26. If an outage occurs at any section between Section iv and vii, ULR is only available for B1 – B3, while B4 – B6 will lose supply. A full analysis of all feeder sections is displayed in *Table 4-9*.

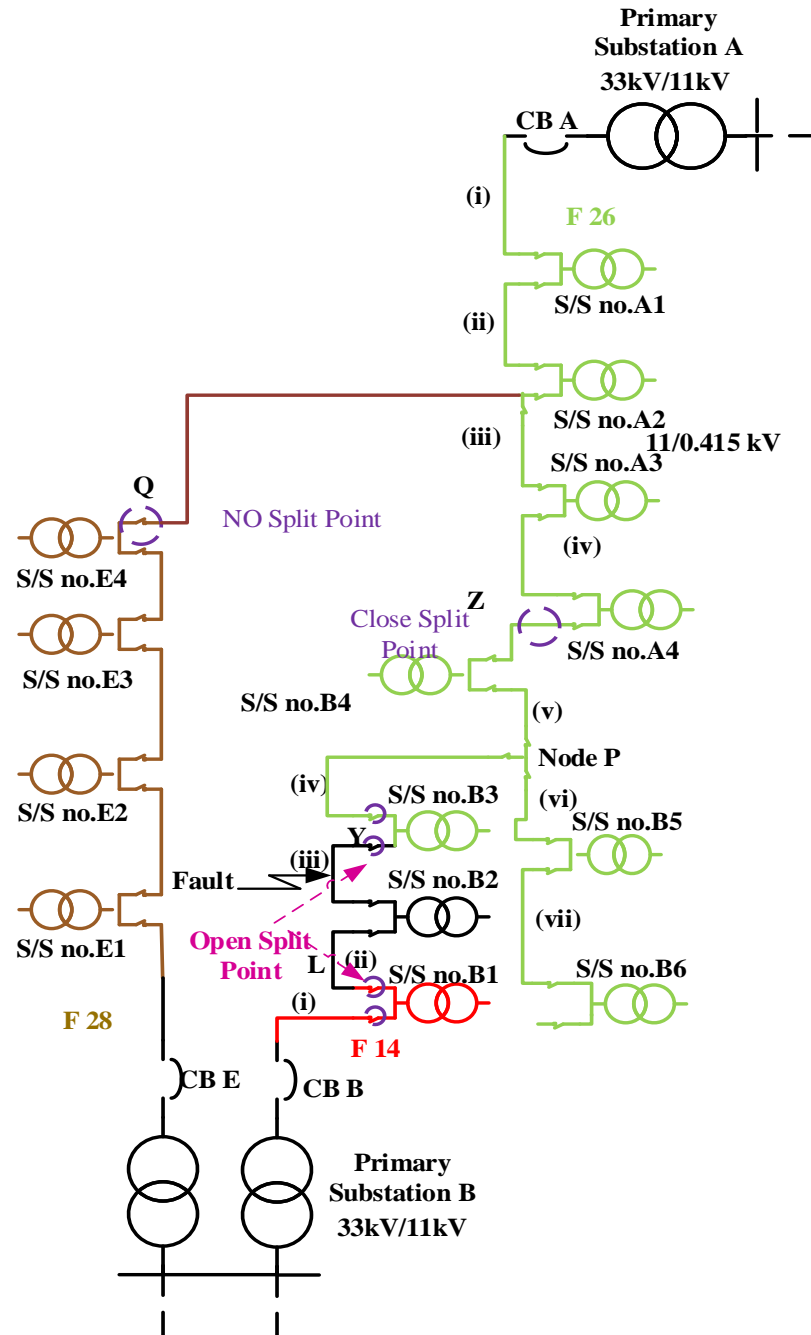


Figure 4-11: Post-outage supply restoration for fault occurring on Feeder 14 (F14), section (iii) with two optimal locations of the ROS pairs

As a comparison, it can clearly be seen from both *Table 4-7* and *Table 4-9* that, the number of restored customers is slightly less with only two optimal locations of the ROS pairs as compared to the fully automated system.

Instead of having 5.2102 customer failures/year restorations with the fully automated case. An actual 1.9266 customer failures/year are prevented with only two ROS pairs if an outage occurs at Section (i). There are 0.2829 expected customer failures per year restored if a fault occurs in a section Section (ii) to (iii). However, 4.7746 customer failures/year are expected to be prevented with two ROS pairs by considering the probability of failure of the cable sections. The number of expected customers restore for Section (i) calculated by using Equation (3.11) and Sections (ii) and (iii) by applying Equation (3.12) and Sections (vi) to (vii) by Equation (3.13). The results for this example indicate that instead of having a fully automated system with seven ROS pairs, which would involve a significant higher investment cost, it is perhaps more economical to only have two ROS pairs. Referring to the failure rate of the cable (assuming all the section is UG cable), if there are no ROS pairs on the feeder, the expected customer outage for the feeder, using Equation (3-10) and referring to *Table 4-8*, is given by;

$$E = 170 \times 1.1145 \times 0.0275 = 5.2102 \text{ customer failures/year}$$

*Table 4-8: Details of feeder length and number of customers on each substation*

# of section	i	ii	iii	iv	v	vi	vii	<b>Total</b>
#Cu	59	8	79	0	4	15	5	<b>170</b>
Section Length (km)	0.4121	0.0337	0.0298	0.529	0.029	0.0609	0.02	<b>1.1145</b>

Table 4-9: Summary of expected customers restored with two optimal locations of the ROS pairs

ROS pairs	Fault Section F14	S/S Restored by F14	S/S Restored by F26	Expected Customer Outage (S/S)	Expected Customer Restored (customer failures/year)
		ULR	DLR		
By Brute Force	i	-	B1-B6	-	1.9266
	ii&iii	B1	B3-B6	B2	0.2829
	iv,v,vi &vii	B1-B3	-	B4-B6	2.5651
<b>Expected customers restored per year</b>					<b>4.7746</b>

#### 4.4 CONCLUSION

This chapter has described the way DPSO and Brute Force ‘reads’ the data for different network topologies. Network feeders are characterised by three different types depending on the feeder branches and NOP locations.

NPL code in NEPLAN was used to carry out load flow analysis and search for suitable back-feed options during restoration for two methods; (i) a fully automated case and (ii) Brute Force determined optimal location of two ROS pairs.

The developed model simulates three types of network feeder configurations: a) Type 1, b) Type 2 and c) Type 3. The NPL controlled NEPLAN studies compute and refine the optimal isolation and restoration choices of the network during ULR and DLR.

In the simple example presented, the results showed that with only two optimal locations of ROS pairs, more than 87% customers (4.7746 customer failures/year) can be restored compared to a fully automated system. The simulation model also allows to account for the failure rate of the cable sections.



## CHAPTER 5

# **DPSO AND BRUTE FORCE APPLICATION ON THREE NETWORKS**

### **5.1 INTRODUCTION**

This chapter presents detailed DPSO, Brute Force and NEPLAN simulations applied to the three case study networks and an analysis of the results for the optimal number and location of ROS pairs, with a baseline comparison to the fully automated system. To verify the effectiveness of the proposed algorithm in solving the optimal locations and number of ROS pairs, a number of restoration scenarios on the three networks were developed for different numbers of customers at each substation with consideration for the fault rate of the feeder sections (affected by the length and type of the feeder section). The benefit of adding the ROS pair in applying the proposed technique was also considered using DPSO and was compared with results with Brute Force method. The customer outage cost (£44 per customer failure) and ROS pair cost considered during the search for the optimal locations by DPSO and the Brute Force method.

### **5.2 EFFECT OF REMOTELY OPERABLE SWITCH INCREASE**

The number of post fault restored customers increases with the number of ROS pairs at optimal locations. Four feeders are chosen from each type of network (urban, semi-urban and rural network) as samples to present. The Brute Force method is used to search for an incremental number of ROS pairs from one until a fully automated state. The net benefits of adding each ROS pair are shown in the Sections 5.2.1 and 5.2.2.

### 5.2.1 Feeder Analysis

**Urban Network:** Information of the feeders used in this analysis given in *Table 5-1.*, the number of customers on each S/S, section length and probability of customer outage per year on the feeder respective to failure of the cable. Results for four of the feeders for the urban network are shown in *Table 5-2* and *Table 5-3*. As can be seen from the tables, by adding only one ROS pair at the optimal location in the feeder, a high number of customers are restored for each feeder (e.g. for Feeder 1, 41,546 customer failures/year are restored from total of 59,341 customer failures/year). The Brute Force searches for additional ROS optimal locations on each feeder until it reaches full automation. The second optimally placed ROS on Feeder 1 will restore an additional 8,571 customer failures/year. Referring to Feeders 1 and 3, where the maximum number of possible ROS pair locations is 10 for each feeder, installing only 6 ROS pairs allows more than 99% of customers to be restored. Feeders 1, 2 and 3 restore 100% of customers even when the number of ROS pairs is less than the fully automated case. However, the benefit of adding ROS pair only giving the negative value if only one ROS pair added on feeders 2 and 3. This results indicates, adding more than one ROS pair on the feeders will not benefit the DNO. For more than one ROS pairs still gain benefits for feeders 1 and 4. So, even the network able to restored almost 100% of customers with less number of ROS pairs, it did not indicated the installation of the ROS pairs would gain benefits to the DNO. The number of customers restored for each additional ROS pair labelled as '#C'.

Table 5-1: Characteristic of feeder 1 until 4 for Urban network

Feeder 1												
# S/S	1	2	3	4	5	6	7	8	9	10	Total	Expected number of customer outages
#C	10	0	0	321	257	1	0	105	1	122	817	59.341
Section Length (km)	0.406	0.267	0.266	0.257	0.881	0.144	0.002	0.1384	0.089	0.191	2.641	
Feeder 2												
# S/S	1	2	3	4	5	6	7	Total	Expected number of customer outages			
Customers	246	445	119	0	142	263	1	1216	37.286			
Section Length (km)	0.336	0.078	0.268	0.246	0.015	0.026	0.146	1.115				
Feeder 3												
# S/S	1	2	3	4	5	6	7	8	9	10	Total	Expected number of customer outages
Customers	1	1	0	316	222	1	5	10	1	10	567	36.809
Section Length (km)	0.199	0.076	0.512	0.223	0.601	0.089	0.236	0.269	0.038	0.1173	2.361	
Feeder 4												
# S/S	1	2	3	4	5	6	Total	Expected number of customer outages				
Customers	406	75	269	265	279	1	1295	77.781				
Section Length (km)	0.561	0.422	0.230	0.344	0.323	0.305	2.184					

Table 5-2: Number of optimal locations of ROS pairs restored customers for Feeders 1 – 4 for Urban network (£1000 switch cost)

Feeder	No. of ROS	Expected Customers Restored (customer failures /year)	Benefits Installing ROS pair (£)	Feeder	No. of ROS	Expected Customers Restored (customer failures /year)	Benefits Installing ROS pair (£)	
1	1	41.546	-828.027	2	1	24.407	-73.923	
	2	50.117	-205.138		2	31.000	636.009	
	3	56.291	523.215		3	33.851	1510.538	
	4	58.034	1446.514		4	36.028	2414.749	
	5	58.905	2408.164		5	37.255	3360.783	
	6	59.196	3395.381		6	37.286	4359.434	
	7	59.196	4395.381		7	37.286	5359.434	
	8	59.269	5392.185					
	9	59.269	6392.185					
	10	59.269	7392.185					

*Table 5-3: Number of optimal locations of ROS pairs restored customers for Feeders 3 – 4 for Urban network (£1000 switch cost)*

Feeder	No. of ROS	Expected Customers Restored (customer failures /year)	Benefit of Installing ROS pair (£)	Feeder	No. of ROS	Expected Customers Restored (customer failures /year)	Benefits Installing ROS pair (£)
3	1	31.681	-393.946	4	1	47.209	-1077.210
	2	35.381	443.236		2	63.546	-796.041
	3	36.160	1408.959		3	71.595	-150.171
	4	36.614	2388.964		4	76.400	638.408
	5	36.679	3386.107		5	77.721	1580.267
	6	36.744	4383.251		6	77.721	2580.267
	7	36.744	5383.251				
	8	36.744	6383.251				
	9	36.744	7383.251				
	10	36.809	8380.395				

**Semi Urban Network:** The details of the results for Feeders 1 – 4 are shown in *Table 5-6* for the semi-urban network. The significance of these results can be observed by looking at Feeder 4. On this feeder, the total number of substations or possible locations of ROS pair is 15. However, the Brute Force code stops searching after six ROS pairs are found. The reason for stopping the simulation prematurely is that it is of negligible value to install another nine ROS pairs in order to save only less than one customer. The percentage of restored customers is calculated to be more than 99 % with only six ROS pairs being installed. *Table 5-6* and *Table 5-7* shows, the increase in the number of customers restored by locating the additional optimally located ROS pairs on the semi-urban network. However, it is shown that all feeder has no benefit of adding a ROS pairs because the cost of customers outages lower than cost of installing a ROS pair. The detail characteristics of the feeder are shown in *Table 5-4* and *Table 5-5*.

Table 5-4: Characteristic of Semi-Urban network for Feeder 1 and 2

Feeder 1										
# S/S	1	2	3	4	5	6	Total	Expected number of customer outages		
Customers	17	19	4	4	3	3	50	8.32		
Section Length (km)	0.21	0.31	0.82	1.26	2.14	1.31	6.05			
Feeder 2										
# S/S	1	2	3	4	5	6	7	8	Total	Expected number of customer outages
Customers	19	17	19	17	17	17	8	9	123	9.57
Section Length (km)	0.5	0.3	0.39	0.3	0.51	0.26	0.07	0.5	2.83	

Table 5-5: Characteristic of Semi-Urban network for Feeder 3 and 4

Feeder 3										
# S/S	1	2	3	4	5	6	7	Expected number of customer outages		
Customers	55	17	19	15	17	0	1	32.18		
Section Length (km)	0.11	0.12	1.3	0.62	0.21	0.64	0.3			
# S/S	8	9	10	11	12	13	Total			
Customers	17	15	17	3	4	15	195			
Section Length (km)	0.3	0.37	0.57	0.44	0.7	0.32	6			
Feeder 4										
# S/S	1	2	3	4	5	6	7	8	Expected number of customer outages	
Customers	4	3	0	9	74	4	4	1	25.05	
Section Length (km)	0.1	0.16	0.72	0.13	1.22	0.5	0.5	0.5		
# S/S	9	10	11	12	13	14	15	Total		
Customers	0	4	5	3	4	9	5	129		
Section Length (km)	0.5	0.5	0.76	0.45	0.45	0.21	0.36	7.06		

Table 5-6: Number of optimal locations of ROS pairs restored customers for Feeders 1 – 2 for Semi-Urban network (£1000 switch cost)

Feeder	ROS	#C	Expected Customers Restored (customer failures /year)	Benefit of Installing the ROS pair	Feeder	ROS	#C	Expected Customers Restored (customer failures /year)	Benefit of Installing the ROS pair
1	1	35	5.82	743.78	2	1	70	5.45	760.30
	2	8	7.15	1685.22		2	23	7.24	1681.54
	3	3	7.65	2663.26		3	12	8.17	2640.45
	4	2	7.99	3648.62		4	6	8.64	3619.90
	5	1	8.15	4641.30		5	4	8.95	4606.21
	6	1	8.32	5633.98		6	5	9.34	5589.08
						7	1	9.42	6585.66
						8	2	9.57	7578.81

Table 5-7: Number of optimal locations of ROS pairs restored customers for Feeders 3 – 4 for Semi-Urban network (£1000 switch cost)

Feeder	ROS	#C	Expected Customers Restored (customer failures /year)	Benefit of Installing the ROS pair	Feeder	ROS	#C	Expected Customers Restored (customer failures /year)	Benefit of Installing the ROS pair
3	1	110	18.15	201.4	4	1	110	21.36	60.31
	2	36	24.09	940.04		2	6	22.52	1009.06
	3	16	26.73	1823.88		3	3	23.1	1983.43
	4	14	29.04	2722.24		4	5	24.07	2940.72
	5	5	29.87	3685.94		5	2	24.46	3923.63
	6	4	30.53	4656.9		6	2	24.85	4906.55
	7	2	30.86	5642.38		15	1	25.05	13898
	8	2	31.19	6627.86					
	9	1	31.35	7620.6					
	10	2	31.68	8606.08					
	11	2	32.01	9591.56					

**Rural Network:** Compared to the urban and semi-urban networks, the rural network has, on average, fewer customers at each substation. Details of the number of customers restored for feeders 1 to 4 for the rural network are shown in *Table 5-11* and *Table 5-12*. All feeders restored 100% of customers before full automation. The effect of adding ROS pairs at optimal locations for the feeders is presented in the same table. However, there are no benefits of adding ROS pair on the networks because the cost of installing ROS pair is much higher than the cost of customer outage (positive value for the benefits of installing ROS pairs). Details characteristic and expected customer failure for each feeder shows in *Table 5-8*, *Table 5-9* and *Table 5-10*.

Table 5-8: Characteristic of Rural network for Feeder 1

Feeder 1									
# S/S	1	2	3	4	5	6	7	Total	Expected number of customer outages
Customers	14	2	1	64	1	4	1	87	7.94
Section Length (km)	0.355	0.785	0.373	0.007	0.587	0.89	0.323	3.32	

Table 5-9: Characteristic of Rural network for Feeder 2

Feeder 2							
# S/S	1	2	3	4	5	6	7
Customers	1	1	34	4	3	0	163
Section Length (km)	0.388	0.081	0.365	0.041	0.076	0.486	0.199
# S/S	8	9	10	11	12	<b>Total</b>	<b>Expected number of customer outages</b>
Customers	2	0	0	3	19	<b>230</b>	<b>21.18</b>
Section Length (km)	0.13	0.277	0.313	0.367	0.625	<b>3.348</b>	

Table 5-10: Characteristic of Rural network for Feeder 3 and 4

Feeder 3								
# S/S	1	2	3	4	5	6	7	8
Customers	2	5	2	1	17	3	0	3
Section Length (km)	0.041	0.267	0.058	0.205	0.466	0.2	0.076	0.105
# S/S	9	10	11	12	13	<b>Total</b>	<b>Expected number of customer outages</b>	
Customers	0	0	0	1	0	<b>34</b>	<b>2.93</b>	
Section Length (km)	0.423	0.386	0.507	0.327	0.076	<b>3.137</b>		
Feeder 4								
# S/S	1	2	3	4	5	6	7	
Customers	19	50	1	2	13	0	0	
Section Length (km)	0.552	0.331	0.65	0.736	0.835	0.366	0.132	
# S/S	8	9	10	11	12	<b>Total</b>	<b>Expected number of customer outages</b>	
Customers	1	3	69	1	0	<b>159</b>	<b>22.02</b>	
Section Length (km)	0.073	0.27	0.188	0.458	0.444	<b>5.035</b>		

Table 5-11: Number of optimal locations of ROS pairs restored customers for Feeders 1 – 2 for Rural network (£1000 switch cost)

Feeder	ROS	Expected Customers Restored (customer failures /year)	Benefit of Installing the ROS pair	Feeder	ROS	Expected Customers Restored (customer failures /year)	Benefit of Installing the ROS pair
1	1	6.94	694.69	2	1	18.14	201.94
	2	7.58	1666.57		2	19.89	1124.97
	3	7.76	2658.54		3	20.72	2088.51
	4	7.85	3654.52		4	20.9	3080.4
	5	7.94	4650.5		5	20.99	4076.35
	6	7.94	5650.5		6	21.08	5072.3
	7	7.94	6650.5		7	21.08	6072.3
			8		21.18	7068.25	
			9		21.18	8068.25	
			10		21.18	9068.25	
			11		21.18	10068.25	
			12		21.18	11068.25	

*Table 5-12: Number of optimal locations of ROS pairs restored customers for Feeders 3 – 4 for Rural network (£1000 switch cost)*

Feeder	ROS	Expected Customers Restore (customer failure /year)	Benefit of Installing the ROS pair	Feeder	ROS	Expected Customers Restore (customer failure /year)	Benefit of Installing the ROS pair
3	1	2.24	901.31	4	1	11.91	475.96
	2	2.5	1889.92		2	19.8	604.58
	3	2.76	2878.54		3	20.21	715.46
	4	2.76	3878.54		4	21.7	760.71
	5	2.85	4874.74		5	21.84	799.58
	6	2.85	5874.74		6	21.9	836.04
	7	2.93	6870.94		7	21.94	870.5
	8	2.93	7870.94		8	21.95	904.83
	9	2.93	8870.94		9	21.95	939.14
	10	2.93	9870.94		10	22.01	970.67
	11	2.93	10870.94		11	22.02	1001.79
	12	2.93	11870.94		12	22.02	1032.91
	13	2.93	12870.94				

### 5.2.2 Overall Feeder Performance

A summary of the overall performance of the urban network by adding the optimal locations of ROS pairs reveal an impressive number of restored customers for a limited number of ROS pairs, as tabulated in *Table 5-13*. The results are sorted according to the highest priority level, i.e., according to the ROS pair placement that saves the most customers. Therefore, based on the results, Feeder 4 is the priority feeder followed by Feeders 1, 6 and so on. As an example, Feeder 4 has the highest number of prevented customers from outages (47.21 customer failures/year) if there is only one ROS pair located at the optimal location. The colours of the tables changed from red to green to indicate the priority level. Such colour coding could help a DNO prioritise automation equipment investment for a particular network.



Table 5-13: Priority feeder for Urban network with increasing number of ROS pairs

Priority Ranking	Total #S/S	Feeder Number	Expected Number of Customer Restored Increased by Adding Optimal Location of ROS Pairs											
			1	2	3	4	5	6	7	8	9	10	11	12
1	6	4	47.21	16.34	8.05	4.81	1.32	0						
2	10	1	41.55	8.57	6.17	1.74	0.87	0.29	0	0.07	0	0		
3	4	6	33.20	6.54	3.99	3.27								
4	10	3	31.68	3.70	0.78	0.45	0.06	0.06	0	0	0	0.06		
5	5	5	29.14	8.64	5.15	2.79	0.04							
6	7	2	24.41	6.59	2.85	2.18	1.23	0.03	0					
7	3	10	22.07	3.02	0.00									
8	12	12	12.34	1.65	0.82	0.31	0.10	0	0	0	0	0	0	0.10
9	5	11	11.97	4.07	0.03	0.03	0							
10	3	13	10.33	3.45	1.48									
11	8	9	8.99	1.18	0.50	0.34	0.11	0.04	0	0.04				
12	2	16	8.57	3.71										
13	5	17	8.11	0.69	0.04	0	0.04							
14	6	18	8.03	2.15	0.75	0.08	0	0.08	0	0				
15	7	7	7.14	1.18	0.28	0.10	0.03	0	0.03					
16	8	8	6.58	0.49	0.07	0.02	0	0	0.02	0				
17	7	14	3.92	0.86	0.37	0.03	0	0	0					
18	5	22	2.61	0.64	0.05	0	0							
19	8	15	2.26	1.01	0.41	0.04	0.02	0	0	0				
20	5	19	2.16	0.09	0	0	0.03	0						
21	6	20	1.56	0.43	0.04	0	0	0.04						
22	3	21	0.65	0.07	0.01									
23	6	24	0.59	0.07	0	0.04	0	0.00						
24	5	23	0.39	0.06	0.02	0.02	0.02							
25	2	25	0.24	0.01										
26	4	27	0.15	0.04	0	0.04								
27	5	26	0.11	0.04	0.01	0.01	0							
28	4	28	0.04	0	0.01	0								

Again, with reference to Table 5-13 adding another switch to Feeder 4 yields an increment of 16.34 customer failures per year prevented from failure. All feeders have been tested until they reach full automation.

Table 5-14 shows the simulation results from the semi-urban network. However, Brute Force code automatically interrupted simulation process before full automation because the number of restored customers has reached more than 95% with

fewer than maximum number of ROS pairs. This constraint is applied to feeders that have 15 or more substations and it is done to limit computational time.

*Table 5-14: Priority feeder for the Semi-Urban network with increasing number of ROS pairs*

Priority	Total # S/S	Feeder ID	Expected Number of Customer Restored Increased by Adding Optimal Location of ROS Pairs																			
			1	2	3	4	5	6	7	8	9	10	11	12	13	15	18	22	27	30		
1	27	7	39.26	13.74	5.24	4.91	2.62	1.96	0.65	0.65									2.29			
5	22	6	32.85	6.64	3.98	2.32	1.99	0.66	1.00	0.33	0.33								1.33			
3	15	4	21.36	1.16	0.58	0.97	0.39	0.39								0.19						
4	30	8	20.51	10.83	7.35															11.61		
2	13	3	18.15	5.94	2.64	2.31	0.83	0.66	0.33	0.33	0.17	0.33	0.33	0.17	0.00							
6	18	5	14.99	7.91	1.67	1.87	0.83	0.42	0.42	0.21	0.42	0.00	0.21	0.21	0.00	0.00	0.21					
7	6	1	5.82	1.33	0.50	0.33	0.17	0.17														
8	8	2	5.45	1.79	0.93	0.47	0.31	0.39	0.08	0.16												

*Table 5-15: Priority feeder for Rural network with increasing number of ROS pairs*

Priority	Total # S/S	Feeder ID	Expected Number of Customer Restored Increased by Adding Optimal Location of ROS Pairs																							
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	16	20	25	30	35	40	45	62		
1	62	10	21.59	17.36	5.79																			7.57		
2	45	5	12.99	54.93	10.05	9.77	6.70																	8.71		
3	30	6	72.89	16.88	5.38	4.40	2.66	2.64	1.47											2.45						
4	12	2	18.14	1.75	0.83	0.18	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09												
5	42	9	62.19	43.18	2.26	3.02	0.00	0.00															7.41			
6	26	8	33.15	9.77	2.09	1.74	0.75	0.02	0.17	0.17	0.17	0.17					0.35									
7	37	11	41.91	29.52	41.91																	6.20				
8	12	4	11.91	7.89	0.42	1.52	0.14	0.00	0.00	0.00	0.00	0.14	0.00	0.00												
9	24	7	19.85	4.52	2.51	0.75	0.05	0.05	0.05	0.05	0.05	0.05					0.50									
10	7	1	6.94	0.64	0.18	0.09	0.09	0.00	0.00																	
11	13	3	2.24	0.26	0.26	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09										

Table 5-15 shows the results for the rural network. As presented in Table 5-15, Feeder 3 has the lowest priority ranking with only 2.24 expected customer failures/year

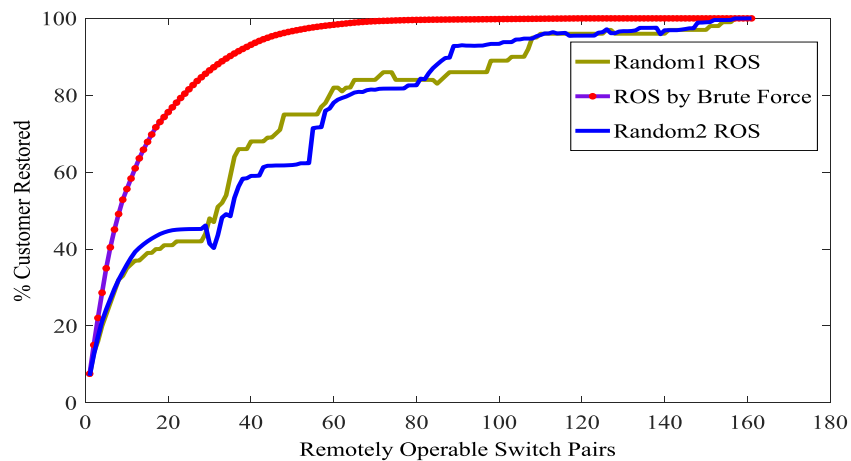
will be prevented from outage if there is only one ROS pair located at the optimal location.

### **5.2.3 Brute Force Performance Analysis**

For all three example networks, the application of the Brute Force algorithm has yielded impressive results in terms of the number of restored customers for an optimal placement of a relatively small number of ROS pairs. It is particularly noticeable that only a small number of ROS pairs are necessary to approach the level of performance seen for the fully automated case. *Figure 5-1* shows the global restoration picture for the urban network, where the number of restored customers as a function of ROS pairs number is expressed as a percentage of the maximum number of restorable customers corresponding to the fully automated system. The total number of possible locations for ROS pairs on the urban network is 161. Therefore, if a full automation is applied to all customers when there is an outage at any section of the network, they will be restored. From the analysis, it shows that the system could restore 99.52% of customers with only the presence of 81 ROS pairs at optimal locations. This compares favourably with the fully automated case, which would require 161 ROS pairs to achieve 100% restoration. Therefore, approximately only half of the ROS pairs are needed to achieve virtually the same level of performance.

To give a benchmark for performance comparison of the Brute Force algorithm, the network was also tested by adding ROS pairs, one by one, at random locations in the networks. The random simulation of the switch is not successive addition of switches, but fully randomised on each iteration. For example, when searching for one optimal location, the next location will not memories for the previous location as optimal location. New set of locations are search randomly for the new set of optimal

locations. Two random simulations were performed: ‘Random 1’ and ‘Random 2’. With reference to *Figure 5-1*, the results show that with the random placement of ROS pairs the number of customers increased as the number of ROS pairs increases, but the restoration curve fluctuates. The slope of the curve for the Brute Force uniformed placement of ROS pairs is much more stable and provides a curve with maximum cost benefit.



*Figure 5-1: Percentage of restored customers by increasing the optimal location of ROS pair using Brute Force and random selection of location on Urban network and compared with the fully automated system*

*Table 5-16* shows the detailed results from the Brute Force applied to the urban network. With full range test on overall urban network, 445 customer failures/year have been prevented if 133 ROS pairs are used in the network at optimal locations selected by Brute Force method, with fewer than 10 customers are still losing supply with the same number of ROS pairs.

The percentage of the restored customers on the urban network increases to more than 60% with only 9 optimally placed ROS pairs in the network, as shown in *Figure 5-2*. Adding ROS pairs at random locations in the network also leads to an increase in customers restored, but the rate of increase is considerably less than the optimised case.

Table 5-16: Details of the performance of the Urban network with the number of restored customers and simulation time for each feeder

Summary of Urban Network					
Feeder	S/S	ROS by Brute Force	Total Expected Customers Restored by Brute Force (customer failures/year)	Total Customers (customer failure/year)	Simulation Time (s)
1	10	9	59.27	59.27	0.097
2	7	6	37.29	37.29	0.094
3	10	9	36.74	36.81	0.097
4	6	5	77.96	77.96	0.093
5	5	4	45.71	45.76	0.092
6	4	3	43.74	47.01	0.091
7	7	6	8.72	8.74	0.094
8	8	7	7.19	7.19	0.095
9	8	7	11.16	11.2	0.095
10	3	2	25.09	25.09	0.090
11	5	4	16.1	16.1	0.092
12	12	11	15.22	15.32	0.099
13	3	2	13.78	15.26	0.090
14	7	6	5.18	5.18	0.094
15	8	7	3.75	3.75	0.095
16	2	1	8.57	12.28	0.089
17	5	4	8.84	8.88	0.092
18	6	5	11.01	11.1	0.093
19	5	4	2.25	2.28	0.092
20	6	5	2.02	2.06	0.093
21	3	2	0.72	0.73	0.090
22	5	4	3.3	3.3	0.092
23	5	4	0.49	0.51	0.092
24	6	5	0.7	0.7	0.093
25	2	1	0.24	0.25	0.089
26	5	4	0.17	0.17	0.092
27	4	3	0.18	0.22	0.091
28	4	3	0.06	0.06	0.091
<b>Total</b>	<b>161</b>	<b>133</b>	<b>445</b>	<b>454.44787</b>	<b>2.597</b>

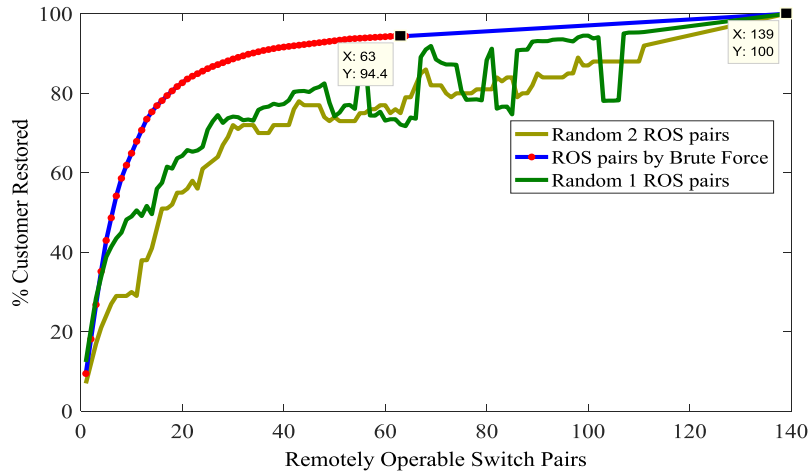
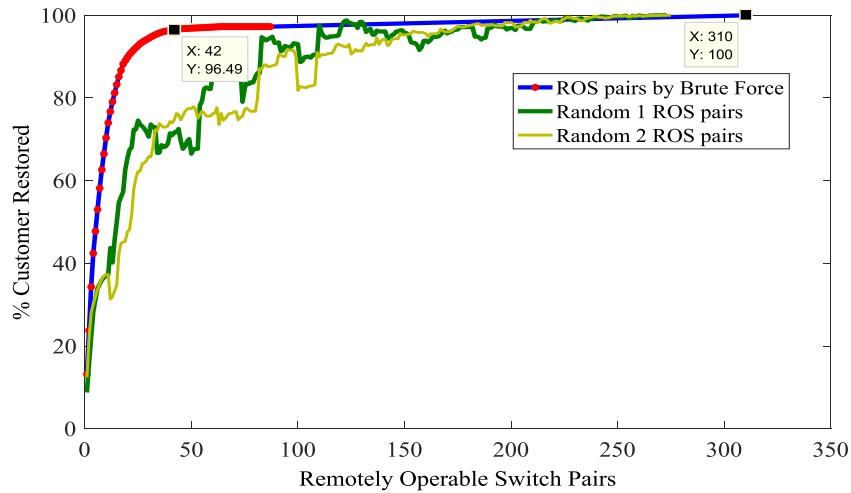


Figure 5-2: Number of restored customer by increasing the number of optimal locations of ROS pairs using Brute Force and random selection of locations, in comparison with the fully automated system on the Semi-Urban network

Table 5-17 shows the results obtained from the Brute Force for all feeders. By having only 62 ROS pairs, 94.4% of customers are restored. In comparison, 139 ROS pairs are required for a fully automated system. This result would be a promising outcome for the DNO since it indicates that significant performance increases can be made with a targeted investment of a limited number of switches.

Table 5-17: The details of the performance of the Semi-Urban network with the number of restored customers and simulation time for each feeder

Feeder	S/S	ROS by Brute Force	Expected Customers By Brute Force (customer failures/year)	Total Expected Customers (customer failures/year)	Simulation Time (s)
1	6	5	8.319	8.319	0.092
2	8	7	9.572	9.572	0.094
3	13	11	51.172	51.436	0.098
4	15	6	24.851	25.045	0.093
5	18	12	29.145	29.353	0.099
6	22	10	31.345	32.175	0.097
7	27	8	69.038	71.329	0.095
8	30	3	38.693	38.693	0.090
<b>Total</b>	<b>139</b>	<b>62</b>	<b>262.134</b>	<b>265.921</b>	<b>0.758</b>



*Figure 5-3: Percentage of the restored customers by increasing the optimal locations of ROS pair using Brute Force and random selection locations of ROS pair and it is compared with the fully automated system in the Rural network*

However, the largest network, the rural network with the highest number of substations, provides remarkable results. With reference to *Figure 5-3* and *Table 5-18* to achieve a customer restoration rate of 96.49%, only 42 ROS pairs are needed instead of the 310 ROS pairs required for a fully automated system.

*Table 5-18: Summary of the total number of restored customers by using the Brute Force for each feeder in the Rural network*

Feeder	S/S	ROS pairs by Brute Force	Expected Customers By Brute Force (customer failures/year)	Total Expected Customers (customer failures/year)	Simulation Time (s)
1	7	6	3.32	3.32	0.093
2	12	11	3.35	3.35	0.098
3	13	12	3.14	3.14	0.099
4	12	11	5.04	5.04	0.098
5	45	5	11.7	12.18	0.092
6	30	7	8.69	8.89	0.094
7	24	9	8.98	9.14	0.096
8	26	10	6.3	6.35	0.097
9	42	6	10.97	11.72	0.093
10	62	3	15.88	16.19	0.090
11	37	3	10.18	10.73	0.090
<b>Total</b>	<b>310</b>	<b>83</b>	<b>87.54</b>	<b>90.03</b>	<b>1.040</b>

Figure 5-4 provides a summary of the performance of the three example networks if the number of optimally placed ROS pairs are increased using the Brute Force algorithm. The urban network has the highest number of total customers, so, as expected, the curve increases at the fastest rate.

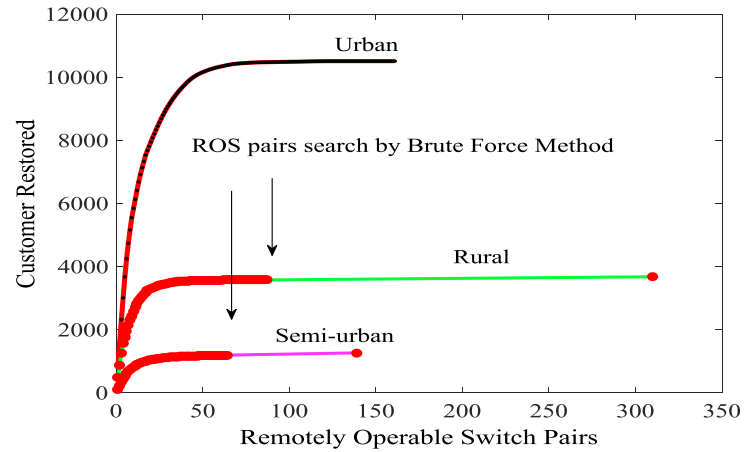


Figure 5-4: Restoration Performance Comparison the three case study networks of the ROS pair

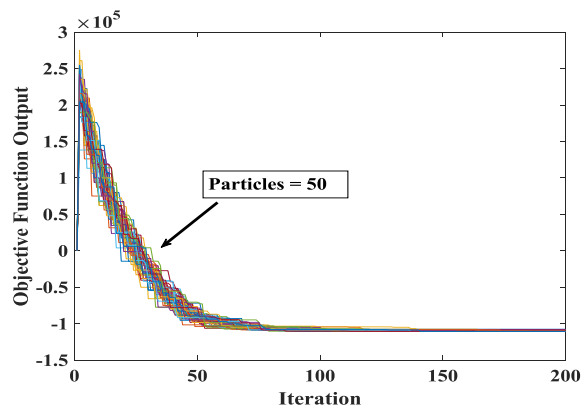
### 5.3 DPSO COMPARED WITH BRUTE FORCE METHOD

The problem formulation is based on a comparison between; 1) the net benefit, in cost terms, deriving from installing a ROS pair, or set of ROS pairs on a given network, and 2) the investment cost associated with installing the ROS pairs. DPSO can be set to minimise the objective function, which in this case calculates the cost of installing a set of switches. A negative cost means the net benefits the costs and therefore, installation of switches is economically justifiable. A positive cost means that the cost is greater than the net benefits and no switches should be installed. A advantages of the developed approach method is that the solution space is, in theory, all combinations of switches. Brute force calculation of the same problem, for large networks, would not be feasible. Three artificial feeders are generated from three types

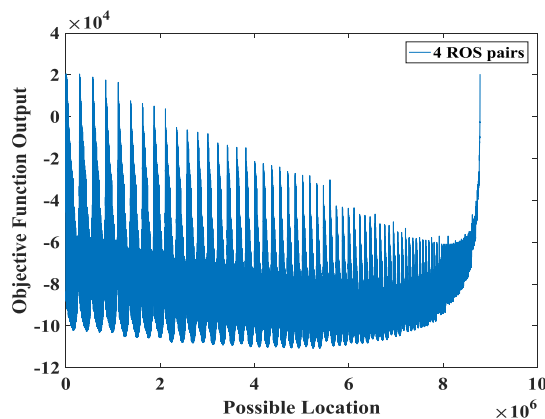


of networks. All feeders generated with 122 substations for a fair comparison. Complete data for the Urban, Semi-urban and Rural network are shown in Appendix 2.

**Urban:** the urban network considered as the highest number of customers on a feeder compare to semi-urban and rural. An estimated of £6550 cost of each ROS pair are assumed during simulation and £44 per customer per failure. With 50 particles and 200 iterations (*Figure 5-5*), Gbest produced an optimum number of ROS pairs at 105 iterations as shown in *Figure 5-7 (b)*. Four ROS pairs are found by DPSO as an optimal number at optimum locations with net benefits to the DNO. Simulations using both algorithms has been done on the feeder. The same minimum value of objective function is achieved by using DPSO and Brute Force method as seen in *Figure 5-7 (a)*.



*Figure 5-5: Pbest for all particles with 122 substations, outage cost = £44 and switch cost estimated with £6550*



*Figure 5-6: Searching optimal location by Brute Force method*

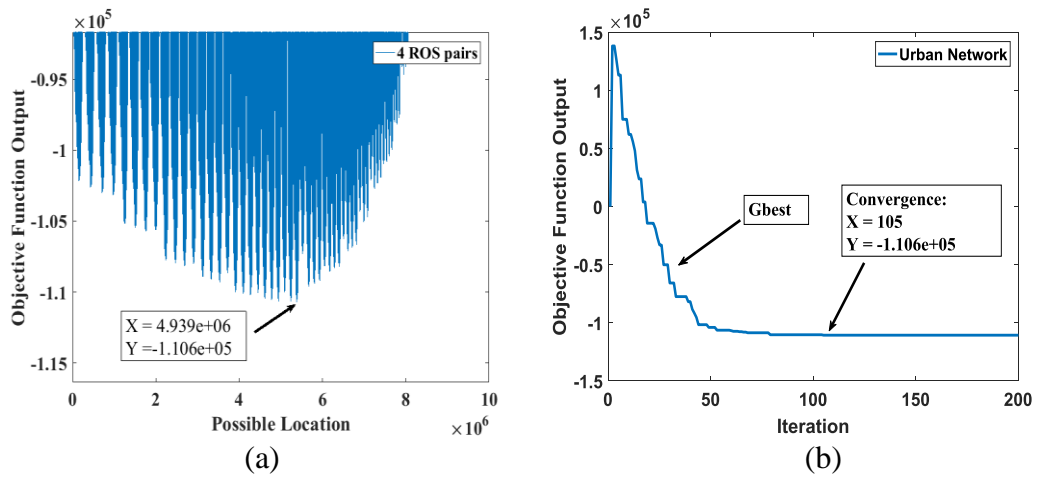


Figure 5-7: Comparison between Brute Force method and DPSO achieving same value of cost net benefits (a) Zoomed in view of the Brute Force output (b) gbest by iteration from the DPSO routine

**Semi-urban:** The network simulated for 500 iterations and 60 particles used to search all combinations of possible locations of ROS pairs and located the best optimum with negative value of cost as illustrated in Figure 5-8. From DPSO, three ROS pairs at optimal locations will return a net benefit with the same cost outage from restoration of customers as Brute Force. The comparison of both results is shown in Figure 5-10.

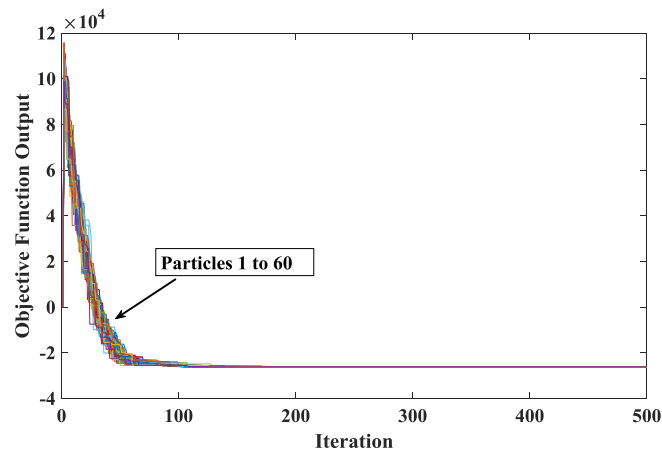


Figure 5-8: Pbest for all particles with 122 substations, outage cost = £44 and switch cost estimated with £2450

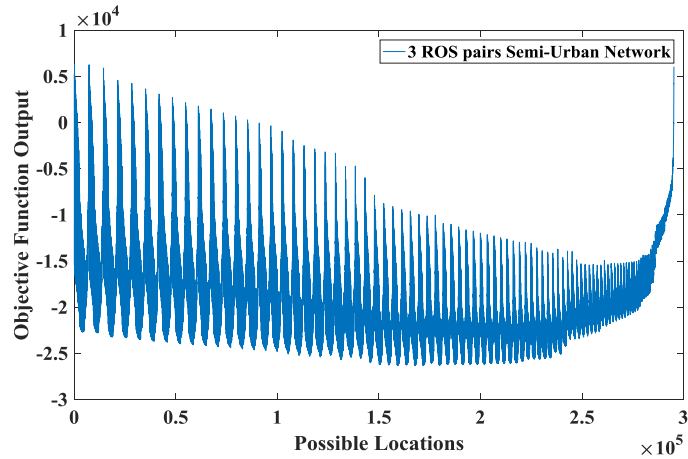


Figure 5-9: Brute Force method searching for 3 ROS pair

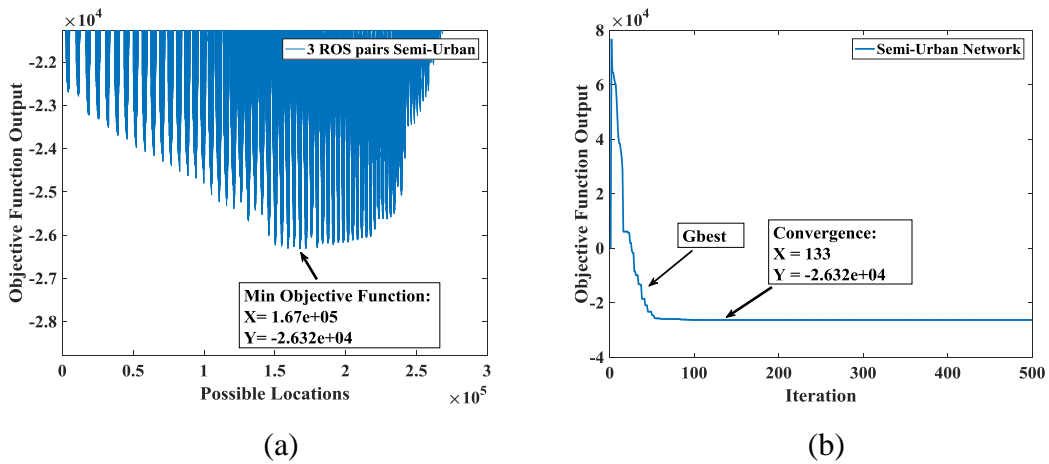


Figure 5-10: Comparison between Brute Force method and DPSO achieving same value of net benefit (a) Zoomed in view of the Brute Force output (b) gbest by iteration from the DPSO routine

**Rural:** The network has been simulated by using 50 particles and 350 iterations as shown in Figure 5-11. All particles reach convergence at 180 iterations as shown in Figure 5-13 (b). With DPSO, the optimal net benefit is achieved with a specific combination of 4 ROS pairs. To validate this result, a simulation has been done using the Brute Force method using same number of ROS pairs. As can be seen in Figure 5-13 (a) (zoom in Figure 5-12) and (b), the optimum combination of switches to achieve maximum economic net benefit is the same, which proves that DPSO has converged to the global optimum.

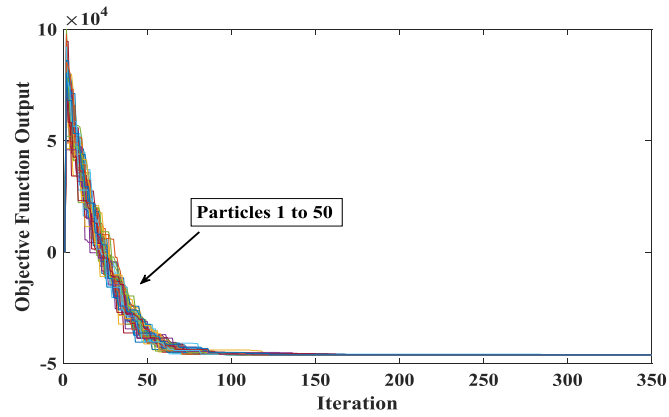


Figure 5-11: Pbest for all particles with 122 substations, outage cost = £44 and switch cost estimated with £2450

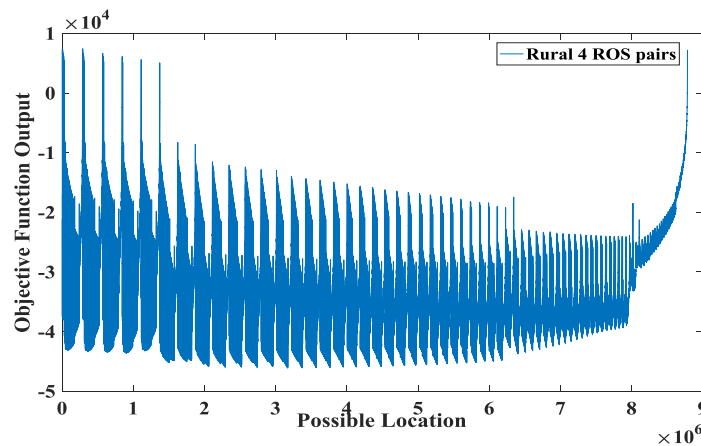


Figure 5-12: Searching all possible combination for 4 ROS pairs using Brute Force method

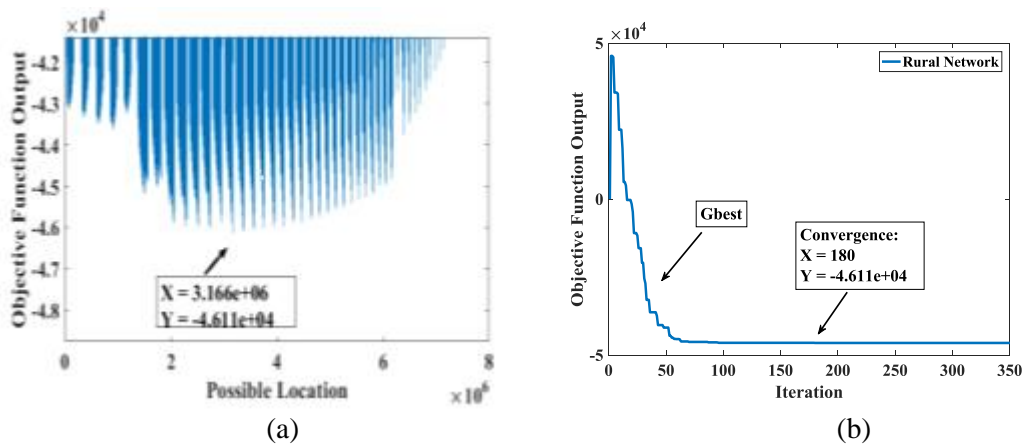


Figure 5-13: Comparison between Brute Force method and DPSO achieving same value of net benefit (a) Zoomed in view of the Brute Force output (b) gbest by iteration from the DPSO routine

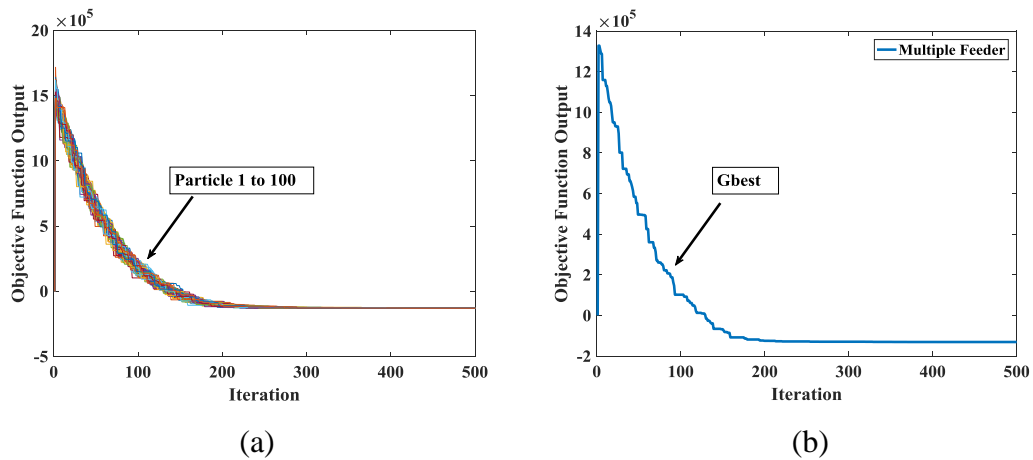
## 5.4 DPSO APPLICATION FOR NETWORK WIDE STUDIES

Rather than searching the number and location of ROS pairs separately for each feeder, the proposed algorithm by using DPSO can also be used to find the optimum number and location of ROS pairs for multiple feeders simultaneously.

**Large number of substation feeders** - ROS pairs across all three feeders with 122 substations each and total of 366 substations shown in *Table 5-19*. The minimum objective function is achieved with optimal number and locations of six ROS pairs.

*Table 5-19: Optimal locations and number by DPSO and net benefits of adding ROS pairs for multiple feeders (3 feeders with huge number of substations)*

<b>Optimal Location of ROS pair</b>	36	60	148	171	202	304
<b>Net Benefits of Adding ROS pairs (£)</b>	-130680.00					



*Figure 5-14: Pbest and Gbest for all particles with 122 substations for each feeder (122 × 3), outage cost = £44 and switch cost estimated with £10000 (a) 100 of particles moving toward optimum location (b) Gbest updated for each iteration*

**Feeders with fewer substations** - A test has also performed on 13 feeders from Urban, Semi-urban and Rural networks, searching ROS pairs across all feeders. Two feeders from semi-urban and rural; and 9 feeders from urban network selected for this analysis. Detailed characteristics of the feeder are included in Appendix 2 and also illustrated in

Figure 5-15. Given the number of customers on each substation, length of section (km) and the number of substation represent in the DPSO simulations.

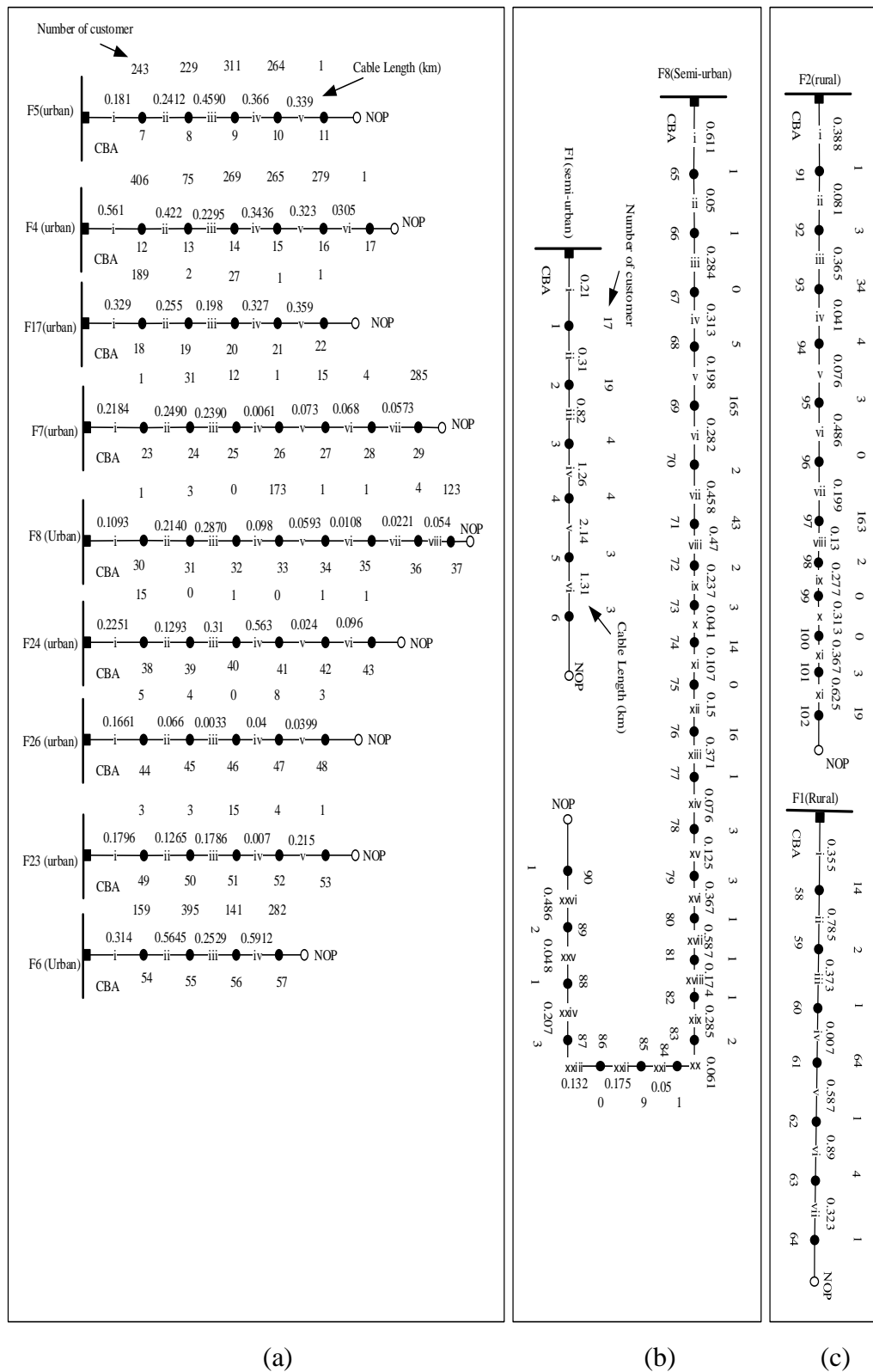


Figure 5-15: Multiple feeders from (a) Urban, (b) Semi-urban and (c) Rural network

Figure 5-16 shows the result for the moving of 100 particles to achieve objective function and Figure 5-17 give the information of ‘Gbest’ reaching the convergence point at 383 iterations. Seven ROS pairs were chosen by the DPSO routine, with net benefits of -£5780 as shown in Table 5-20. The selected locations of the ROS pairs illustrated in Figure 5-18.

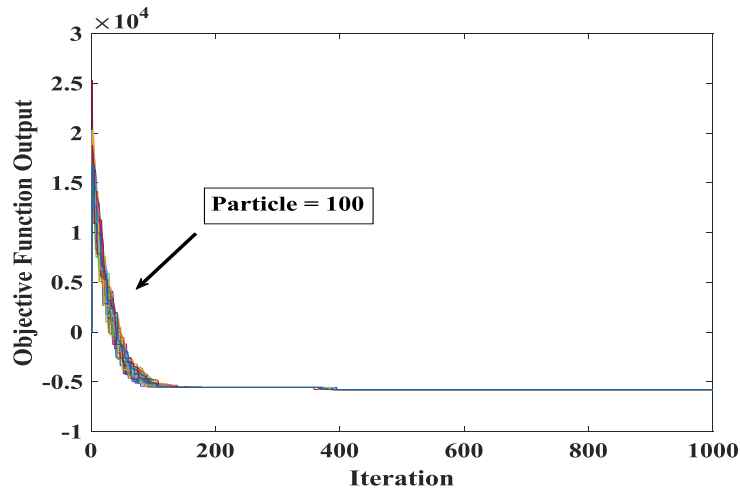


Figure 5-16: Pbest and Gbest for all particles with total of 102 substations and 13 real feeders, outage cost = £44 and switch cost estimated with £10000, 100 of particles moving toward optimum location

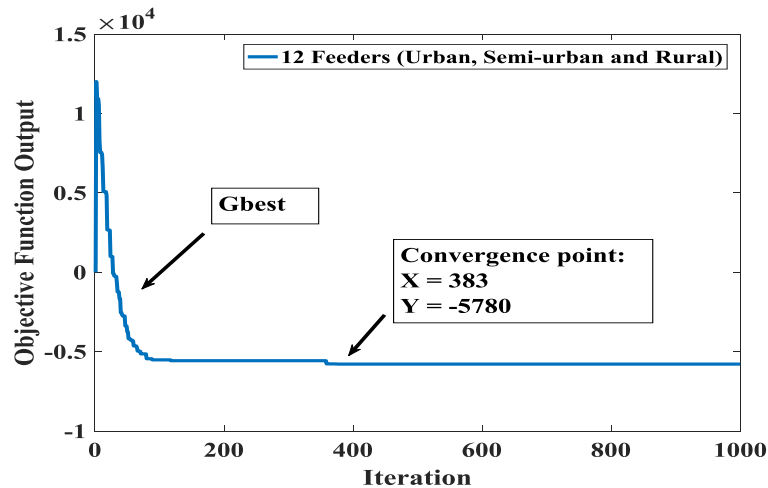


Figure 5-17: Gbest updated for each iteration

Table 5-20: Optimal locations and number by DPSO and net benefits of adding ROS pairs for multiple feeders (13 feeders from different networks)

Optimal Location	8	13	54	67	70	93	95
Net Benefits of Adding ROS pairs (£)	-5780.40						

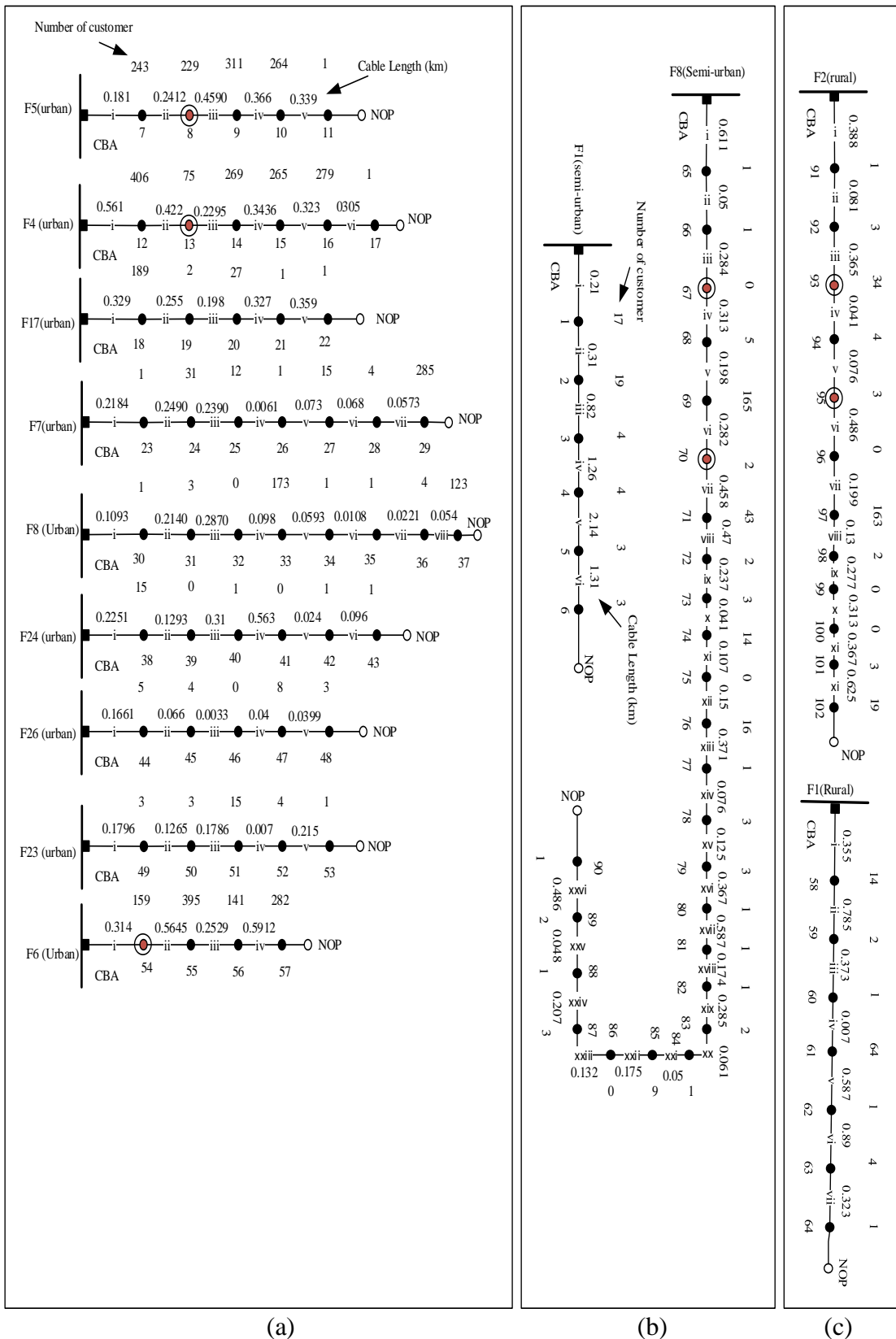


Figure 5-18: Selected optimal locations and net benefits of ROS pairs by DPSO on multiple feeders (a) Urban (b) semi-urban and, (c) rural

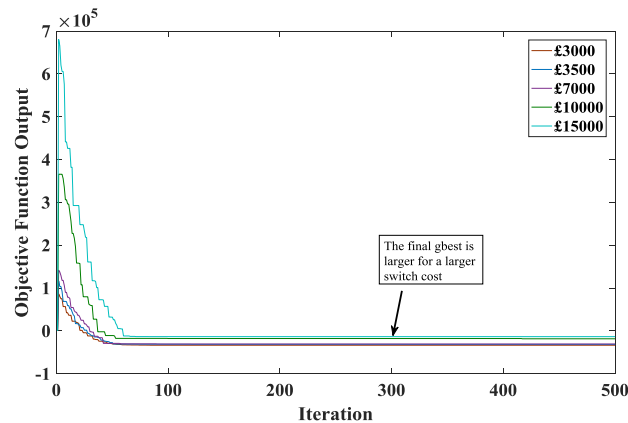


## 5.5 ECONOMIC CONSIDERATION OF DPSO

The increment cost of an ROS pair will influence the net benefits of adding the ROS pairs. Five tests have been done by increasing the investment cost of a ROS pair then comparing with the financial net benefit to the DNO of improving their restoration capability. The semi-urban network with 122 S/S was selected and the cost of a ROS pair increased from £3000 to £15000. The results from the analysis is showed in *Figure 5-10*. It clearly seen that, when the cost of a ROS pair is increased, the overall net benefits of adding the switch is reduced and the optimal number of ROS pairs is also reduced. With a lower cost of a ROS pair, such as £3000, 4 ROS pairs are selected by DPSO and higher net benefits are achieved. The simulation results are shown in *Figure 5-19*.

*Table 5-21: Effect on increment of ROS pair cost on a feeder (sensitivity of analysis)*

Network	Optimum Number of ROS pair	Cost per ROS pair	Net Benefits
Semi-Urban	4	3000	-33257.00
	3	3500	-31991.00
	2	7000	-23771.00
	1	10000	-18321.00
	1	15000	-13321.00



*Figure 5-19: Gbest for different ROS pair costs, with outage cost fixed at £44 per customer per outage*

The net benefits of installing the ROS pair on several feeders on Urban Network has been analysed. Most of the feeders on the urban network have higher number of customers on each substation. The net benefits of adding the ROS pairs on the feeder have been evaluated by DPSO. In *Table 5-22*, eight feeders show different net benefits of adding the number of ROS pair. By assuming the price of the ROS pairs is equal to £700, feeders F5, F4 and F6 has gain a net benefit with one ROS pair added given by DPSO. However, F7 and F8 only will gain net benefits if the ROS pair cost is less as £100. This price of the ROS pairs is impossible. For F24, F23 and F26, even the cost of ROS pair is £100 pound, no net benefit are achieve. From this results, beneficial of adding a ROS pair on a feeder has strong relationship on the total number of customers on the feeder. Feeders with higher number of customers, could achieve reasonable amount of benefits even with only one ROS pair.

*Table 5-22: Net benefits of adding ROS pairs using DPSO on selected feeder (Urban Network)*

Feeder ID Urban Network	Number of ROS pair	NetBenefits(£)	ROS pair Cost (£)	Total customer on the Feeder
F4	1	-1266.60	700	1295
F5	1	-92.9808	700	1048
F6	1	-576.0033	700	977
F7	1	-37.954	100	349
F8	1	-26.4779	100	306
F24	NA		100	18
F23			100	26
F26			100	20

The proposed approach of searching the beneficial adding of ROS pair was also tested on rural networks. Similar results as urban network are also found from the analysis. As expected, feeders with higher number of customers has higher possibility to gain net benefits if ROS pair are added on the network compared to feeder with less number of total customers on the network as seen in *Table 5-23*. Feeder F2 and F8 return

a reasonable beneficial of adding the ROS pair even the cost of the ROS pair is £1000. However, Feeder F1 only returns a benefit on installing the ROS pair if the switch cost is lower than £100.

*Table 5-23: Net benefits of adding ROS pairs using DPSO on selected feeder (Rural Network)*

<b>Feeder ID Urban Network</b>	<b>Number of ROS pair</b>	<b>Net Benefits (£)</b>	<b>ROS pair Cost (£)</b>	<b>Total customer on the Feeder</b>
F1	1	-51.38	100	87
F2	1	-170.52	1000	230
F8	1	-1662.70	1000	281

## 5.6 CONCLUSION

Implementation of the proposed method searching for the optimal locations of ROS pairs has been successfully applied on three case study networks by using Brute Force. All three networks have shown significantly high numbers of customers restored with optimal locations of ROS pairs on a feeder even if only one ROS pair is placed on the network. From the overall performance of the network, the number of customers restored with Brute Force placement of ROS pairs also increases at a much higher rate compared with randomly located ROS pairs. However, the benefits of restored customers is still not guaranteed until the cost of outage and ROS pairs are not counted into analysis. As seen from 4 sample feeders from Urban, Semi-Urban and Rural, only four feeders from the Urban network have a benefit of adding one ROS pair. Others produce positive value of the beneficial calculations. The DSPO method has been applied to several feeders and the results compared with the Brute Force method. It was found that the DSPO algorithm converges successfully to the same global optimum solution found by the Brute Force method. The DSPO algorithm will offer potential advantages in large networks.

## CHAPTER 6

### VOLTAGE AND CURRENT PROFILES AND LIMITS

#### 6.1 INTRODUCTION

The restoration of the network via DLR will only be deemed feasible if there are no violations in the system. This is an important consideration because network reconfiguration using remote switches may lead to voltage or current violations. In the UK, the standard limits for voltages to avoid such violation is ( $106\% \geq V \geq 94\%$ ) and current is ( $I \leq I_{\max}$ ). In the following simulations, the test performed for the overall network has been done by assuming the load at highest demand, as this would represent a worst-case.

The urban network was tested at each stage automation until full automation by using the NEPLAN programming library. The other two networks (semi-urban and rural) were tested to a truncated condition of automation because of the large numbers of substations and for reasons, outlined in Chapter 5. All three networks were analysed by Brute Force or DPSO to search for optimal locations of ROS pairs and now the Brute Force or DPSO is used in conjunction with voltage and current profiling to establish feasible DLR options without voltage or current violations.

#### 6.2 PRE-OUTAGES

By referring to the problem statement in Section 4.3 and *Figure 6-1*, illustrates the pre-outage voltage profiles along Feeder 26 (Green) and Feeder 14 (Red) for substations A1 to A5 and substations B1 to B6 respectively. From *Figure 6-1*, it can be seen that Feeder 14 is considerably longer than Feeder 26, and there is a larger voltage drop. In this study, the voltage drop is small and well within the limits due to the fact

that (i) the feeders comprise high capacity cable with low impedance, and (ii) the assumed base load of the system is low. The first section of the cable length measure from the CB to the first secondary substation. The selected restoration feeder for backfeed should follow the criteria within voltage and current limit. Feeder with lowest voltage drop will be selected as a candidate for the restoration during backfeed process.

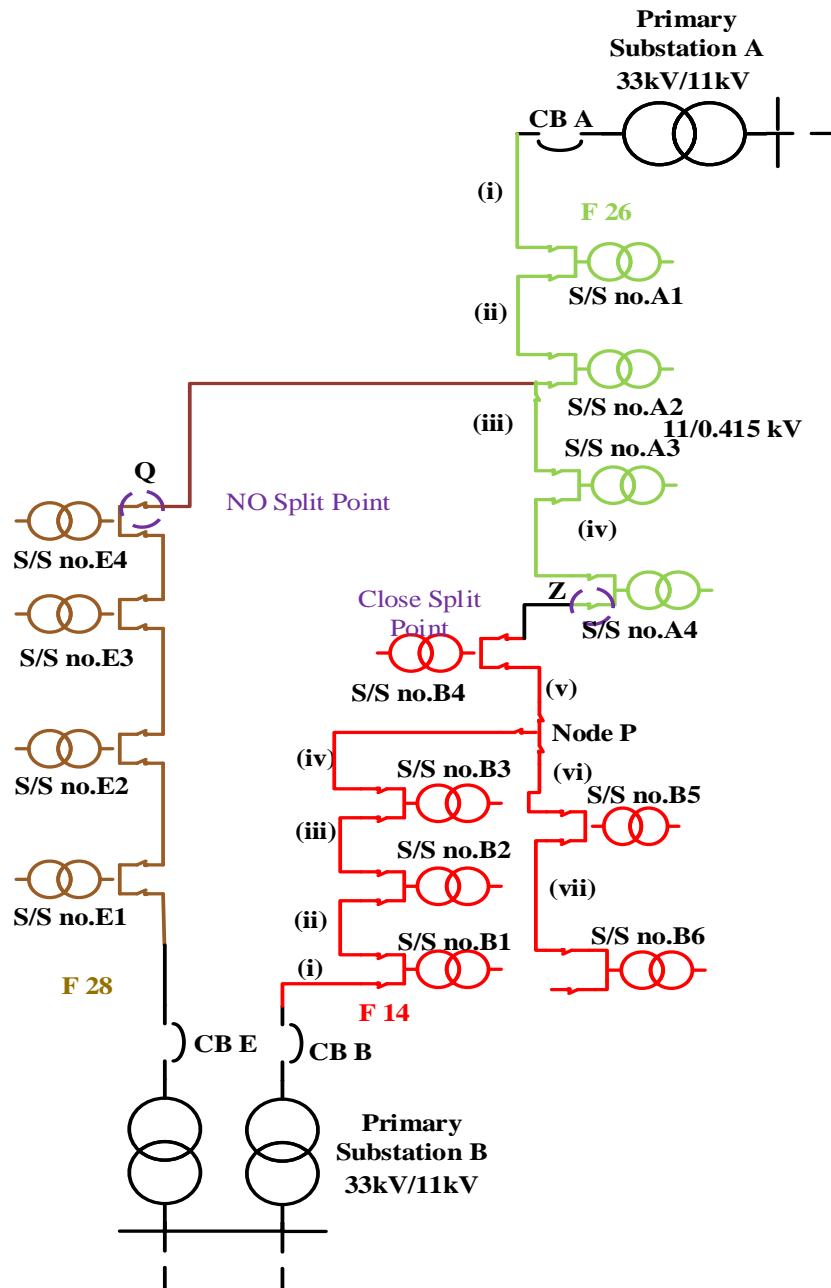


Figure 6-1: One line diagram for Feeder 14 and 26

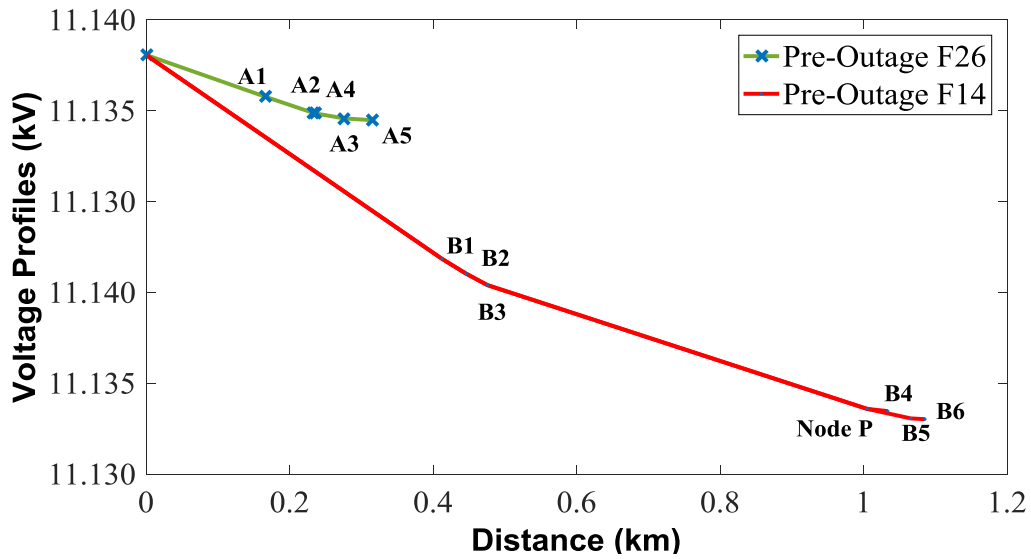


Figure 6-2: Pre-outage voltage profile along Feeder 26 and 14

Figure 6-3 displays the corresponding current profiles of Feeders 26 and 14. The currents of Feeder 26 are lower than those of Feeder 14, and this also contributes to the lower voltage drop along Feeder 26.

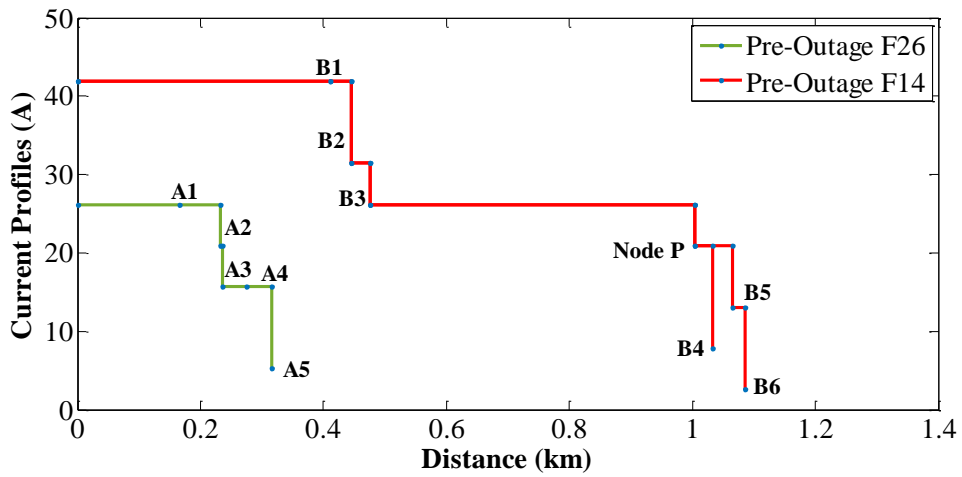


Figure 6-3: Pre-outage current profiles along Feeder 26 and 14

The complete picture of pre-outage voltage and current profiles for the urban network is shown in Figure 6-4- 6.11 for a total of 28 feeders.

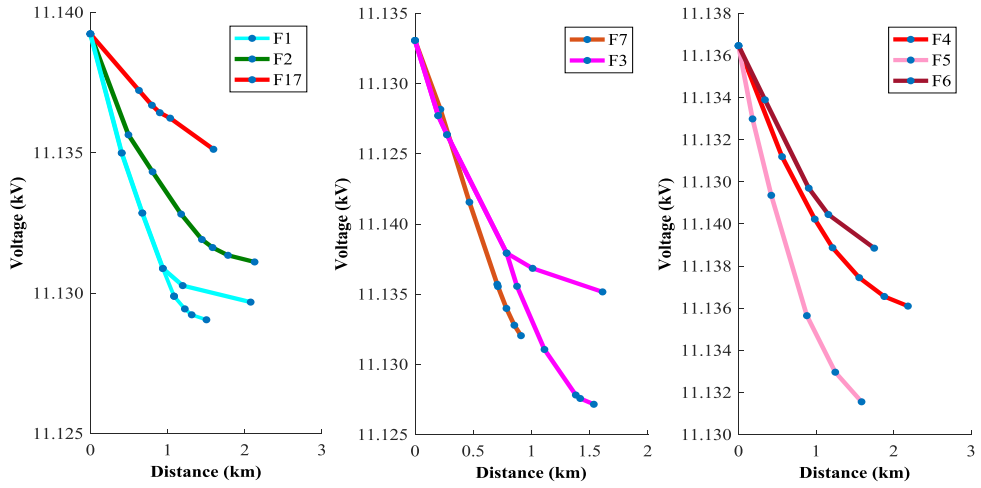


Figure 6-4: Pre-outage voltage profiles for F1-7 and F17

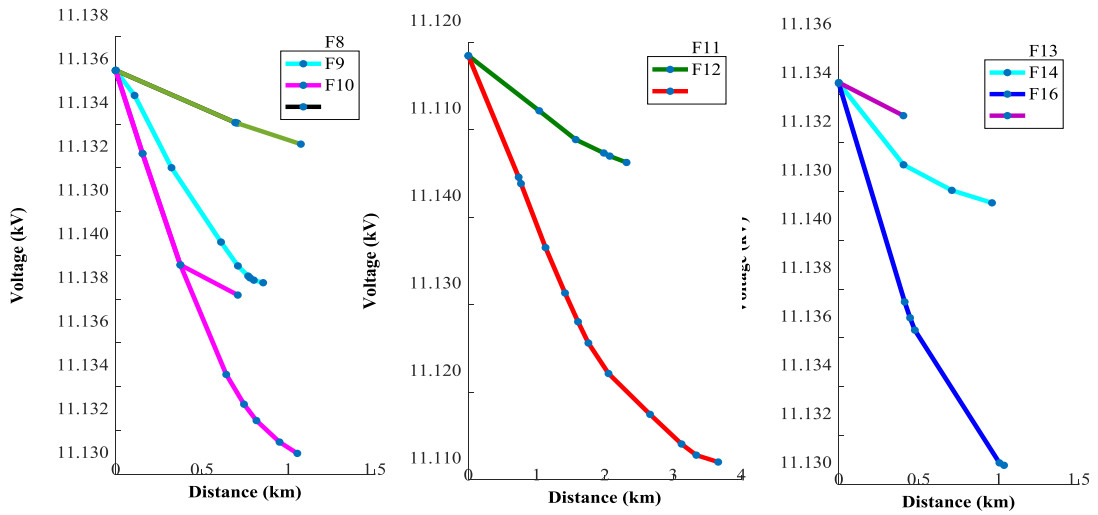


Figure 6-5: Pre-outage voltage profiles for F8 – 14 and F16

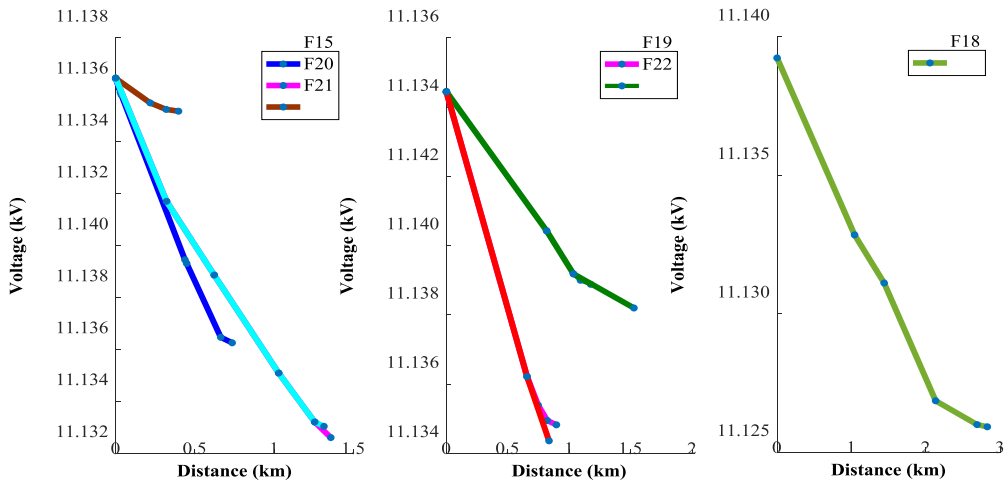


Figure 6-6: Pre-outage voltage profiles for F15 and F18 – 22

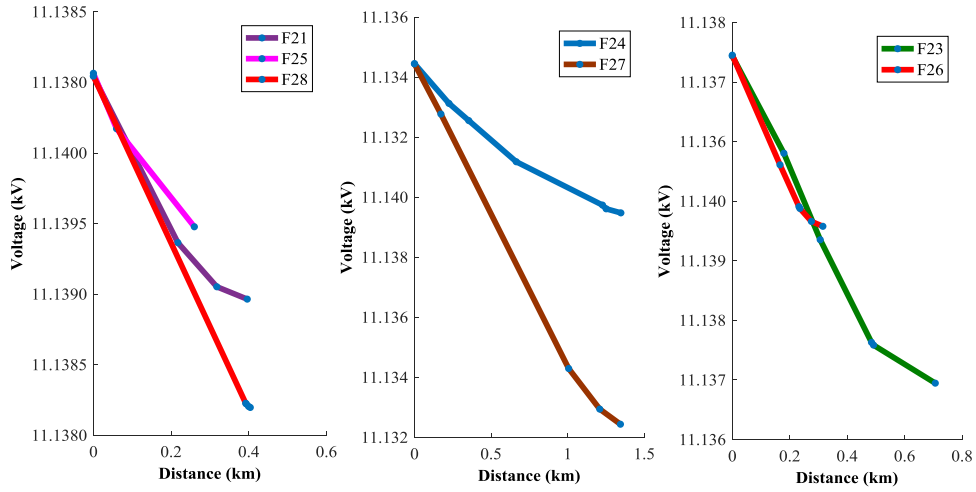


Figure 6-7: Pre-outrage voltage profiles for F21 and F23 – 28

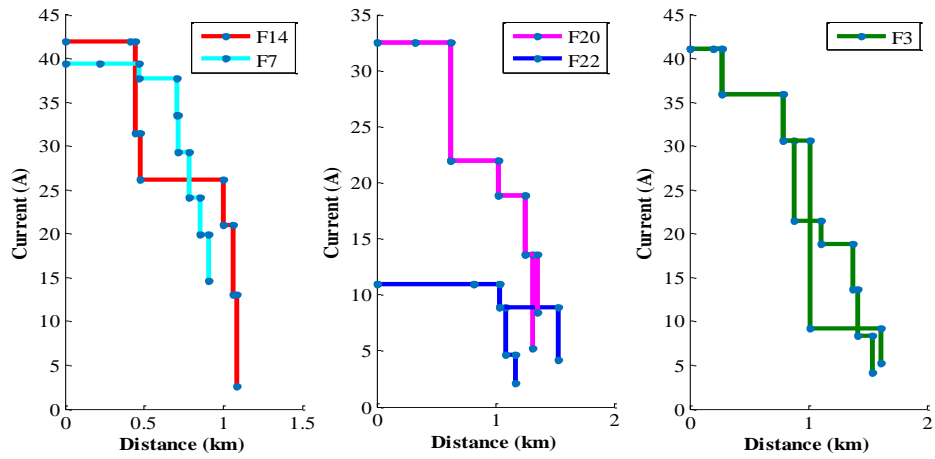


Figure 6-8: Pre-outrage current profiles for F3, F7, F14, F20 and F22

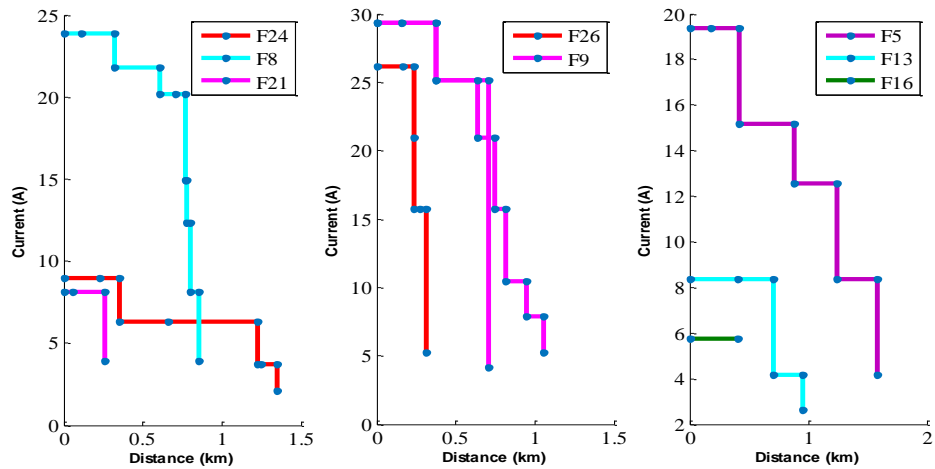


Figure 6-9: Pre-outrage current profiles for F5, F8 – 9, F13, F16, F21, F24 and F26



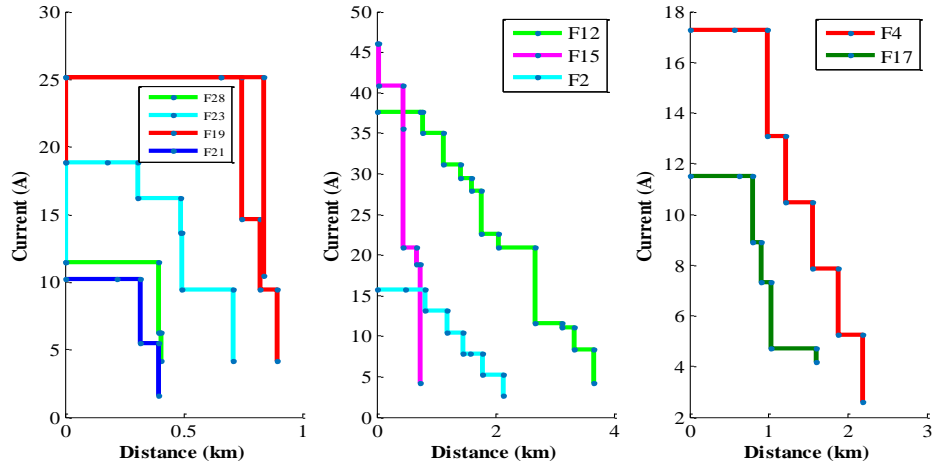


Figure 6-10: Pre-outage current profiles for F2, F4, F12, F15, F17, F19, F21, F23 and F28

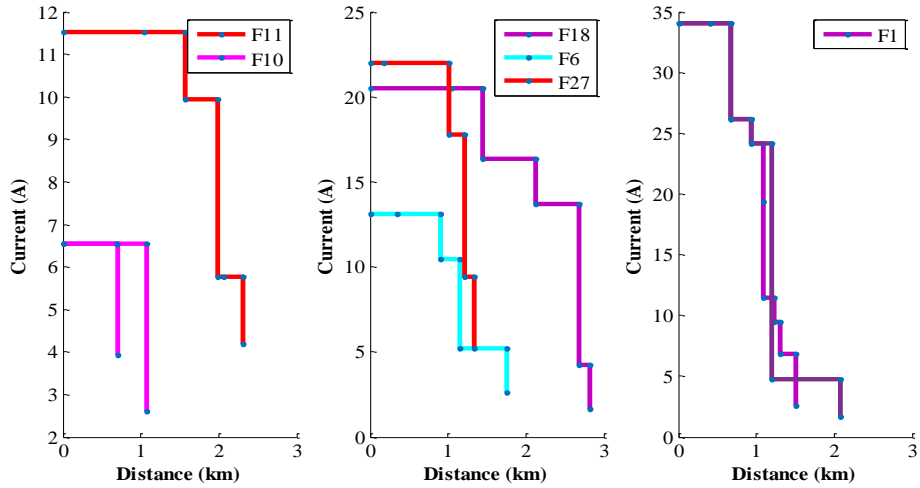


Figure 6-11: Pre-outage current profiles for F1, F6, F10, F11, F18 and F27

All the voltage and current are within limits for all feeders, as expected.

### 6.3 POST-OUTAGE NETWORKS WITH DLR

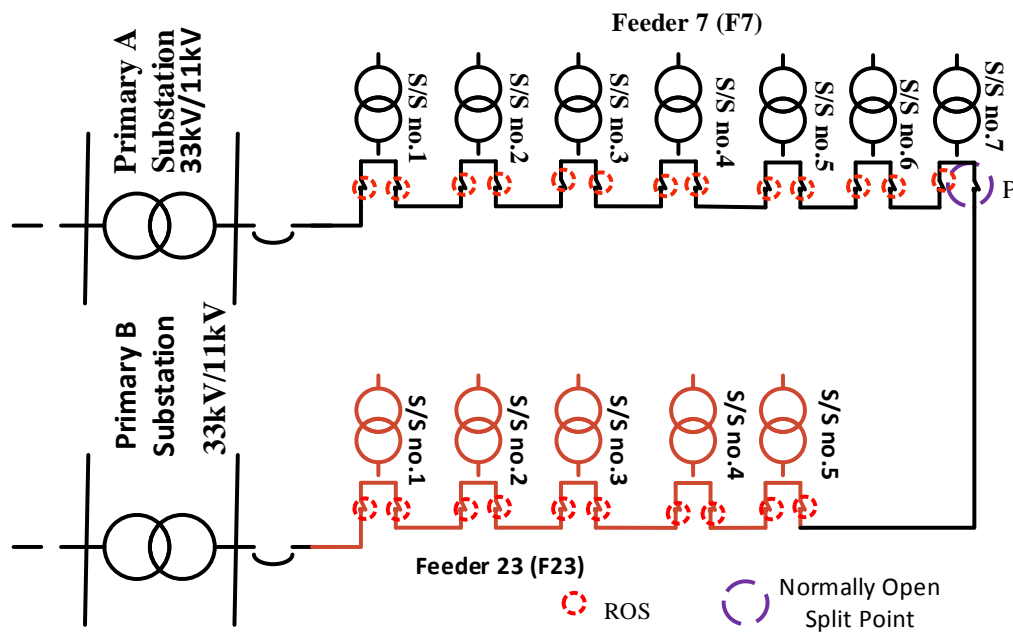
In this section, results from the post-outage calculations are described for two particular feeders. The selected feeders are i) a single feeder without branches, and ii) a single feeder with branches. The results show the number of restored customers, the voltage profiles and the current limit.

### 6.3.1 Fully Automated System

The advantage of the fully automated system is that the ROS have the capacity to respond to fault outage conditions at any locations and are able to restore the maximum number of upstream and downstream customers. The results for the two selected feeders are described in detail in the following subsections:

i) Single feeder without branches

Referring to *Figure 6-12*, both feeders have no branches. Feeder 7 and Feeder 23 comprise 7 and 5 substations respectively. Both cable feeders have total circuit lengths of less than 1km.



*Figure 6-12: Feeder 7 and 23*

*Figure 6-13* shows the voltage profiles during pre-outage and post-outage of F7 for a range of fault locations. As seen from *Figure 6-13* (b), ULR will become effective when an outage occurs at Section (ii) onwards. The results show that there is no voltage violation, as expected for any form of ULR.

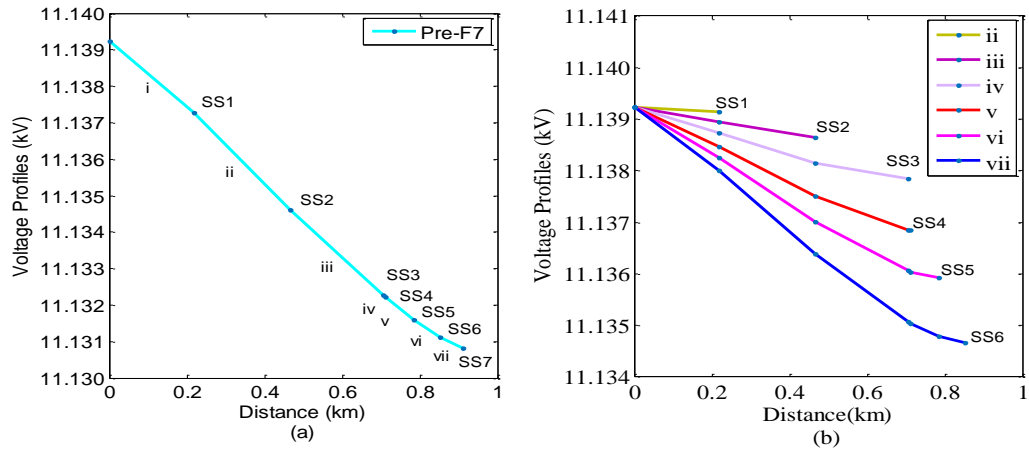


Figure 6-13: Voltage profiles for Feeder 7 (a) pre-outage and (b) post-Outage with ULR for different fault scenarios

Figure 6-14(a) shows the pre-outage voltage profile for the F23 while Figure 6-14(b) shows the voltage profiles of this feeder after DLR, if an outage occurs in Section (i – vii). The substation labelling system is given as:

SSXXY, where XX is the feeder number from the primary substation and Y is the secondary substation number. Figure 6-15 shows the current profiles for F7 and F23 during pre-outage and post-outage. The results demonstrated that F23 has sufficient capability to perform DLR if an outage occurs on any section of the network and without violation of current or voltage limits.

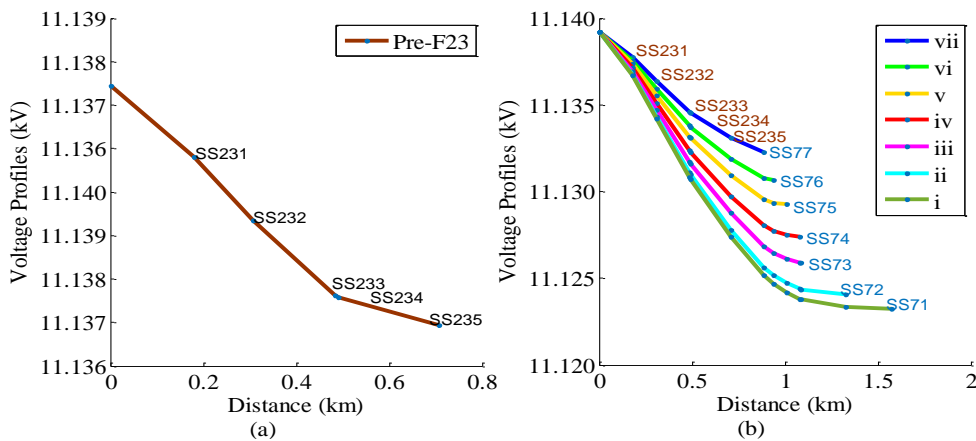


Figure 6-14: Voltage profiles for a) pre-outage F7 and b) post-outage for DLR for F7 by F23 with different section of a fault

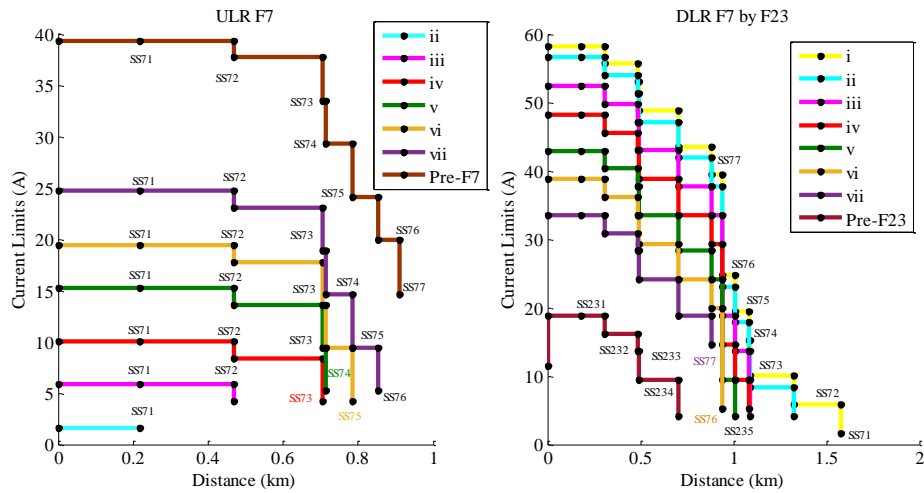


Figure 6-15: Post-outrage current profiles for feeder 7 and feeder 23

ii) Single feeder with branches

The load flow results presented here focus on the post-fault outage restoration for faults occurring on Feeder 14, which has seven sections and six loads. *Figure 6-16* shows F14 connected with F20 and F26 via branches. Feeders 20 and 26 are possible feeders that will be selected to perform DLR. However, from given the total feeder lengths for both feeders, F26 has shorter length compared to F20. Therefore, F26 will be selected for the DLR if an outage occurs between Sections (i) until (v). However, F20 will be used as the DLR option if an outage occurs at Section (vi) or (vii).

The opportunities for this post-fault outage restoration are evaluated by considering all possible fault locations along Feeder 14, occurring at Sections (i) to (vii).

When an outage occurs on Section (i) between the locations of ‘CB B’ and substation B1, there is only DLR available for the restoration of the lost feeder load since all of the secondary substations are downstream.

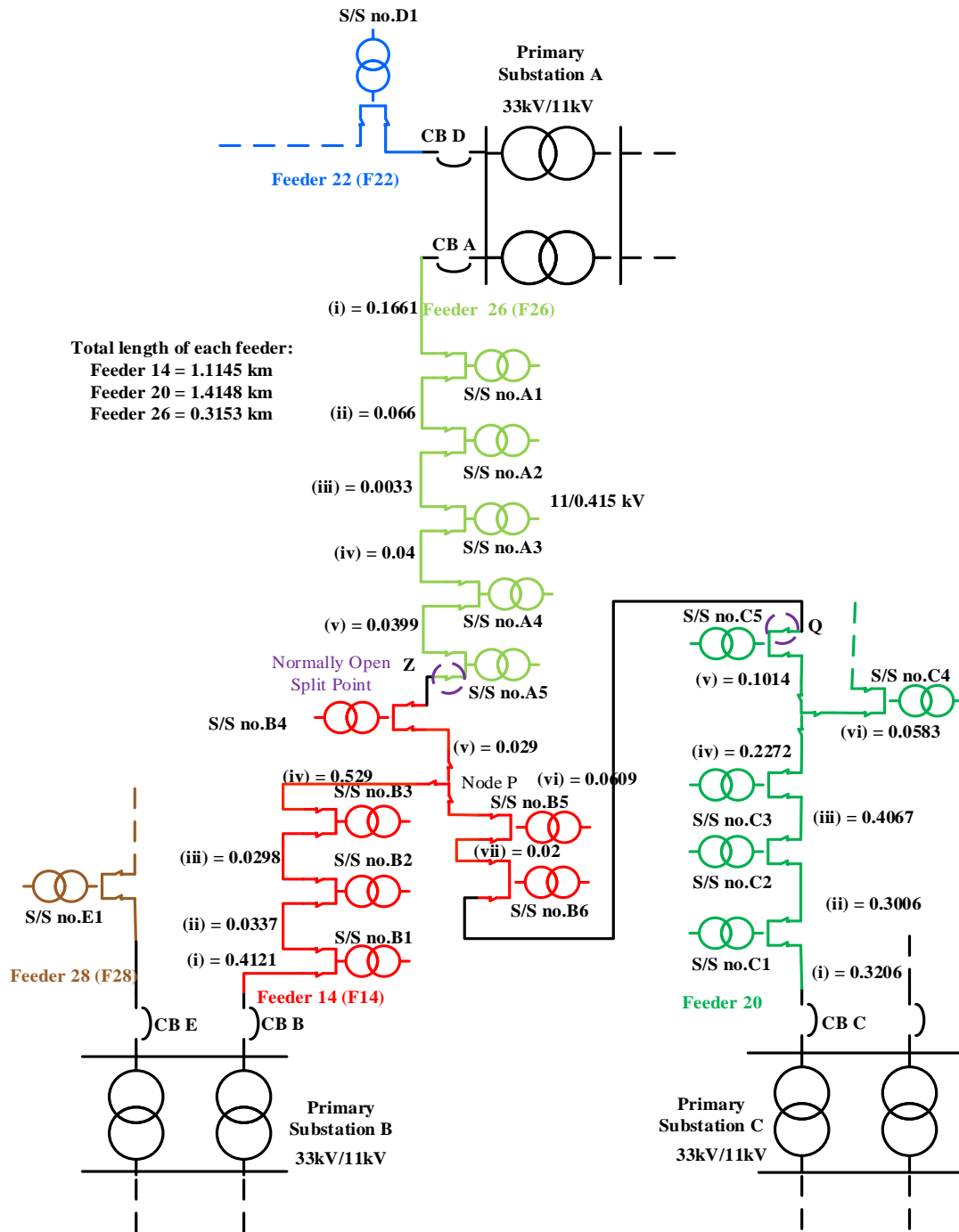


Figure 6-16: Feeder 14 connected with F20 and F26

This condition of a fault occurring close to the feeding supply point represents the most onerous condition in terms of ‘backfeeding’ or downstream load restoration. As described in Section 4.3.1, Feeder 26 was selected as the preferable DLR supply route. Feeder 26 is potentially able to supply Loads B6- B1 by opening the switch at the Primary B substation side of Substation B1, and closing the split point switch Z. Figure

6-17 shows the effect of DLR on the voltage profile along Feeder 26 backfeeding Feeder 14. 14.

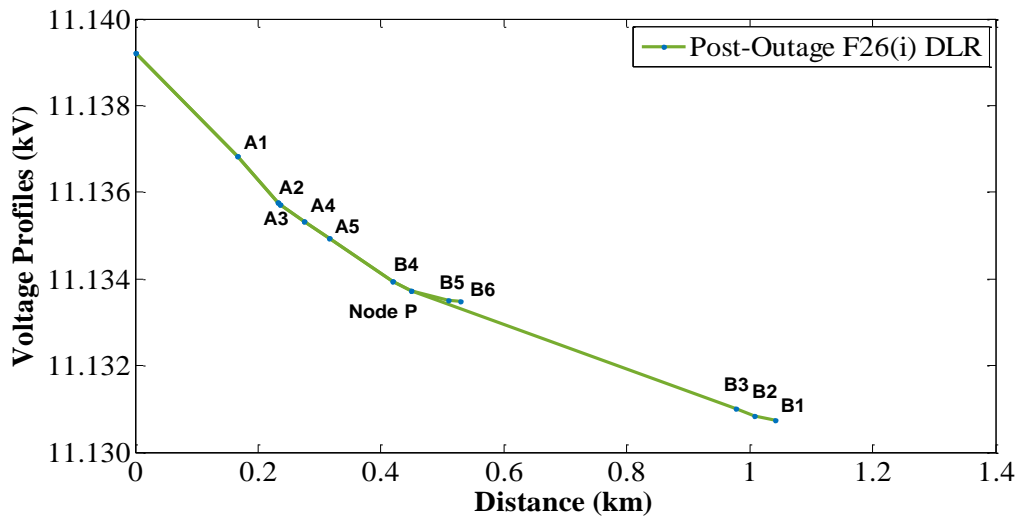


Figure 6-17: Post-outage voltage profile along Feeder 26 supplying 'Feeder 14' lost load at substations B1-B6 via DLR

The corresponding current profiles are shown in Figure 6-18. Based on these two figures, it can be seen that, under the post restoration conditions, the currents magnitudes are increased while the voltage magnitudes are reduced along Feeder 26. Nevertheless, all supplies to substations B1 to B6 are restored along this route without any voltage or current violations.

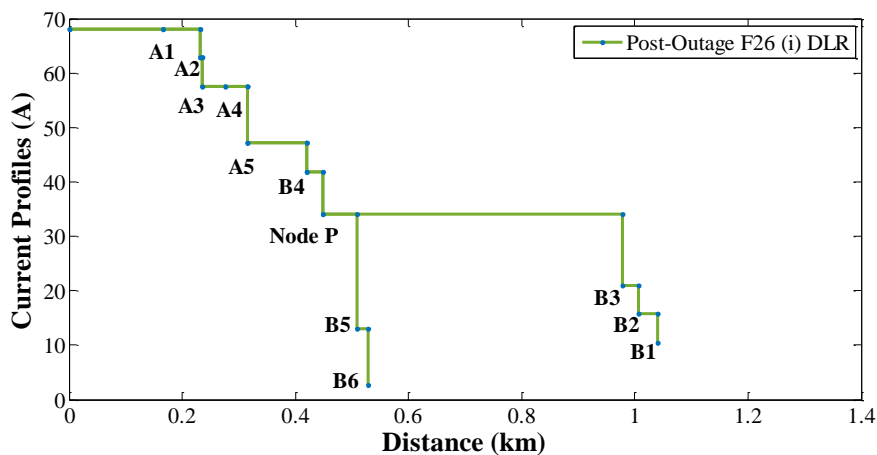
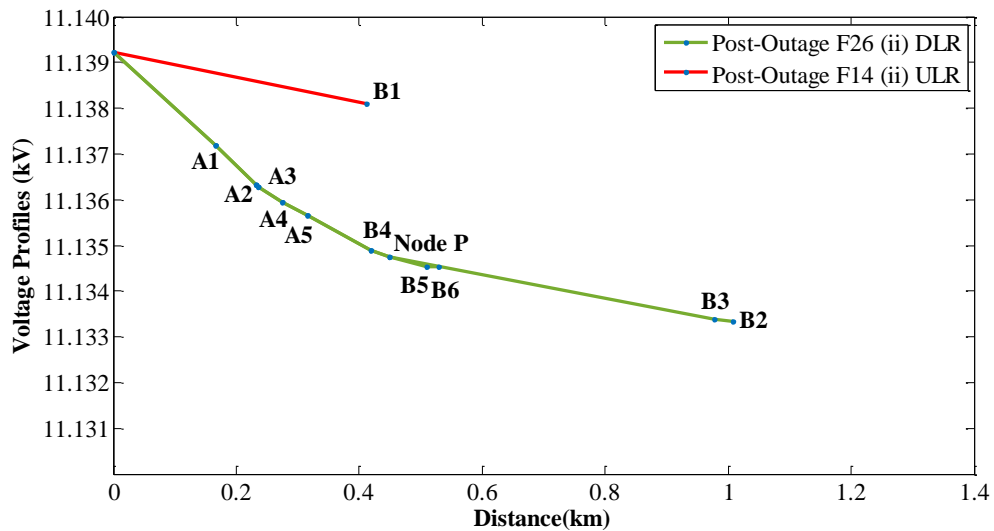


Figure 6-18: Post-outage current profile along Feeder 26 supplying 'Feeder 14' lost load at substations B1-B6 using DLR

It can be seen that the ULR could be performed to restore the supply to S/S B1 while the DLR would be required from Feeder 26 to backfeed S/Ss B6 up to B2 considering an outage occurring on section (ii) of Feeder 14. *Figure 6-19* shows the voltage profile along Feeders 14 and 26 with ULR and DLR implemented.



*Figure 6-19: Post-outage voltage profiles along Feeders 14 and 26 with faulted at section (ii) employing the ULR and DLR*

The corresponding current profiles are shown in *Figure 6-20*. As it can be observed by comparing *Figure 6-17* and *Figure 6-18* with *Figure 6-19* and *Figure 6-20*, the post-outage restoration is less onerous than when the fault that occurs on Section (i) since a direct ULR is applied on S/S B1 to reduce the level of required backfeeding in terms of both distance and load.

*Figure 6-21* and *Figure 6-22* show the voltage and current profiles for a fault occurring on Feeder 14 at Section (iii) via similar restoration strategy with all loads restorable.

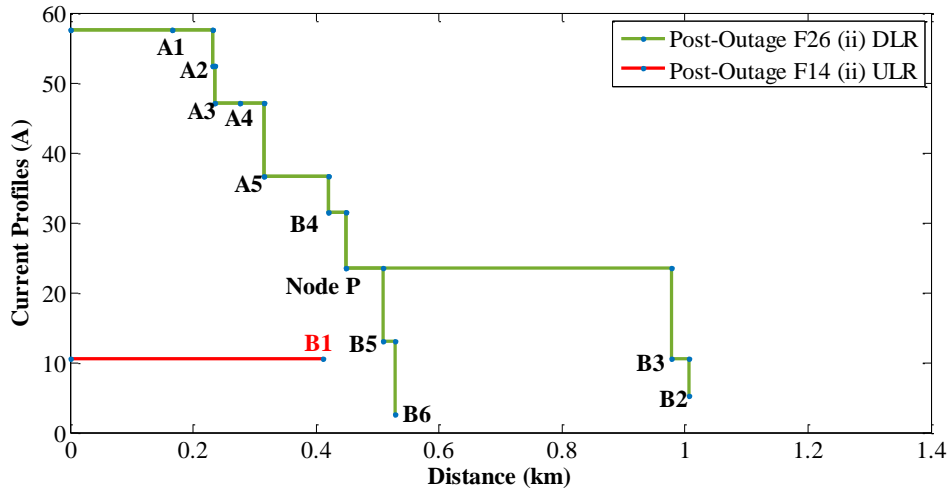


Figure 6-20: Post-outage current profiles via ULR and DLR

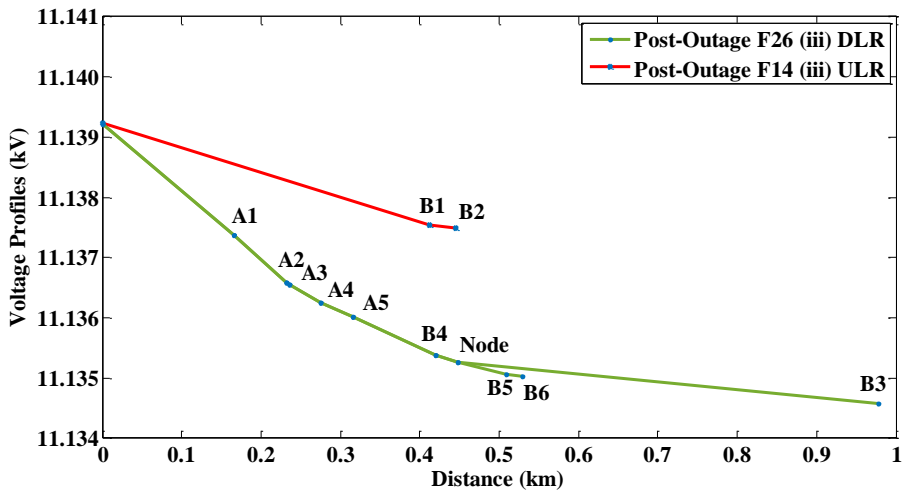


Figure 6-21: Post-outage voltage profiles along the feeder using ULR and DLR

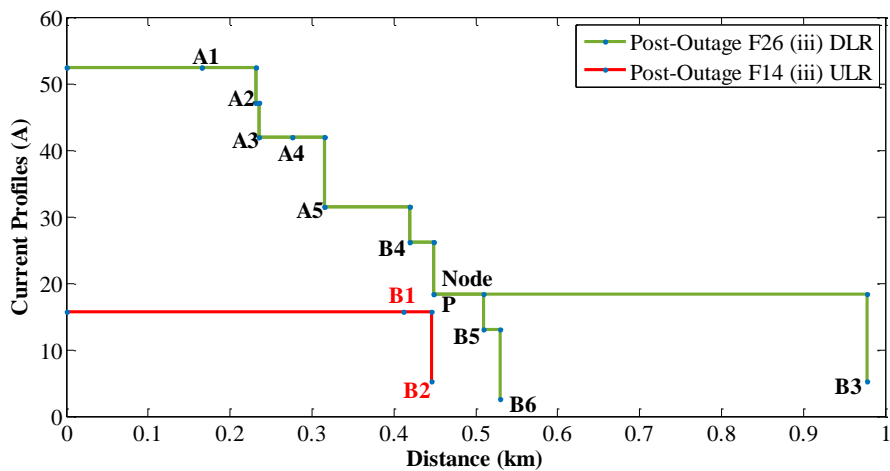
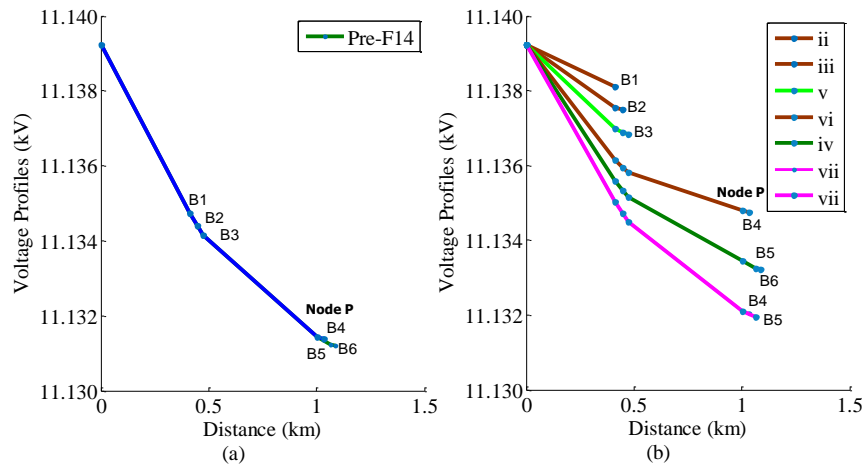


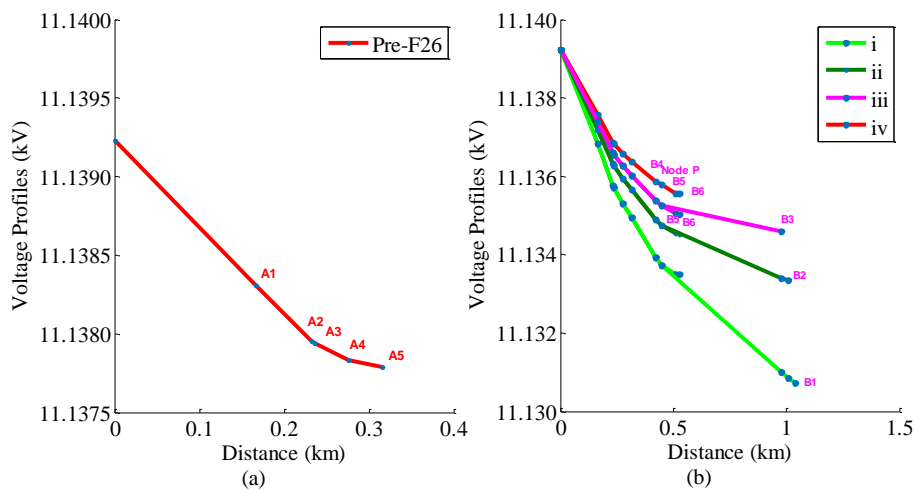
Figure 6-22: Post-outage current profiles following the strategy of the ULR and DLR along Feeders A and B with faulted at section (iii)



A summary of post-outage voltage profiles for F14 during various ULRs is shown in *Figure 6-23*. Feeder 26 performs the DLR for F14, if an outage occurs anywhere between Section (i) and (iv) as shown in *Figure 6-24*. F20 will restore the customers downstream if an outage occurs between Sections (vi) to (vii) as presented in *Figure 6-25*. The DLR option is not available if an outage occurs on Section (v).



*Figure 6-23: a) Pre-outage F14 and b) post-outage voltage profile of F14 if an outage occurs at section (ii/iii/iv/v/vi/vii)*



*Figure 6-24: a) pre-outage F26 b) Post-outage voltage profiles F14 DLR restored by F26 for an outage between (i) to (iv)*

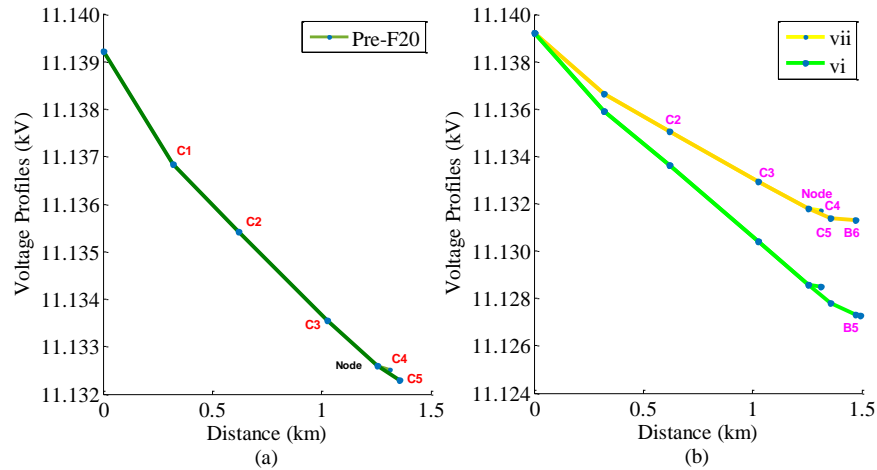


Figure 6-25: a) pre-outage F20 b) post-outage voltage profile F14 for DLR using F20 if an outage occur at section (vi) and (vii)

Table 6-1 provides a comprehensive description of the ULR and DLR restorations for the range of faults occurring at Sections (i) to (vii) together with the corresponding maximum and minimum line section loading.

Table 6-2 shows the number of customers located at each substation on Feeder 14.

Table 6-1: Summary of restoration of the Feeder 14 loads employing the ULR (via Feeder 14) and DLR (via Feeder 20 and Feeder 26)

Feeder	Faulted Section	Current Magnitude (A)		Restored Substation
		Min	Max	
F26 (DLR)	i	2.619	68.09	B1 - B6
	ii	2.619	57.61	B2 - B6
	iii	2.619	52.37	B3 - B6
	iv	2.619	47.13	B4 - B6
	v	-	-	-
F20 (DLR)	vi	10.58	45.58	B5 - B6
	vii	2.619	35.09	B6
F14 (ULR)	i	-	-	-
	ii	10.47	63.96	B1
	iii	5.36	11.7	B1-B2
	iv	5.23	20.94	B1-B3
	v	2.619	34.04	B1-B3, B5 -B6
	vi	7.28	28.8	B1-B4
	vii	10.47	39.28	B1-B5

Table 6-2: Number of customers at each substation on Feeder 14

Feeder 14						
Substations	B1	B2	B3	B4	B5	B6
Customers	59	8	79	4	15	5
Customer failure/year	5.21					

A summary of the number of restored customers through the ULR and DLR for different fault scenarios is shown in *Table 6-3*. From the table, it can be seen that the greater proportion of customers could be restored to supply for any fault scenario along Feeder 14. Only 4 customers will be off supply, corresponding to an outage occurring at Section (v).

Table 6-3: Overall restoration statistics

Feeder	Outage Position	Number of customers lost following initial fault outage	Expected customers restored through; (customer failures/year)		Expected Customers outage following ULR DLR restorations
			ULR	DLR	
Feeder 14	i	170	0.000	1.9265	0.00
	ii	170	0.0547	0.1029	0.00
	iii	170	0.0549	0.0844	0.00
	iv	170	2.124	0.3491	0.00
	v	170	0.1164	0.0191	0.00
	vi	170	0.2512	0.0335	0.00
	vii	170	0.0907	0.0027	0.00

### 6.3.2 Application of ROS Pairs by Brute Force

For this section, results from the application of Brute Force with optimum number of customers restored with optimal locations of ROS pairs to the case study networks is described. To show the difference from the fully automated system, F7 was selected as an example feeder and the characteristic of the feeder shown in *Table 6-4*. The results from the Brute Force for the optimal location of ROS pairs is shown in *Table 6-5*. However, the Brute Force search was carried out until six optimal locations of ROS

pairs were reached corresponding to 99.8% restoration. The number in a column ROS1 to ROS7 represent the locations of ROS pairs on the network. i.e if the ROS1 is equal to 7, it means that the first ROS pair is located at S/S7.

*Table 6-4: Number of customers on each substation for F7*

Feeder 7							
Substation	1	2	3	4	5	6	7
Customers	1	31	12	4	15	4	285
Section length(km)	0.2184	0.249	0.239	0.0061	0.073	0.068	0.0573
Customer failure/year	8.74						

*Table 6-5: Optimal locations of ROS pairs selected by Brute Force for F7*

ROS	#C	% C	ROS1	ROS2	ROS3	ROS4	ROS5	ROS6	ROS7
1	7.14	81.662	7	0	0	0	0	0	0
2	1.18	13.467	7	2	0	0	0	0	0
3	0.28	3.152	7	2	3	0	0	0	0
4	0.10	1.146	7	2	3	5	0	0	0
5	0.03	0.287	7	2	3	5	6	0	0
6	0.00	0.000	7	2	3	5	6	1	0
7	0.03	0.287	All ROS						

*Table 6-6* provides a comprehensive description of the ULR and DLR restorations for the range of faults occurring for Sections (i) to (vii) together with the corresponding maximum and minimum line section loading with different optimal locations and number of ROS pairs.

*Table 6-7* shows the number of customers on each substation on F7. *Table 6-7* shows the number of customers restored corresponding to the number of ROS pairs and the corresponding outage section. Possibilities of restoration are increased if ROS pairs are increased. With only one ROS pair at its optimal location, approximately 82% of customers are restored. However, the effect of diminishing returns may be seen clearly as the number of ROS pair is increased.

Table 6-6: Summary of restoration of the Feeder 7 loads employing the ULR (via Feeder 14) and DLR (via Feeder 23) with optimal locations and number of ROS pairs

Feeder	#ROS	Optimal Locations ROS by Brute Force	Faulted Section	Current Magnitude (A)		Restored Substation
				Min	Max	
F23 (DLR)	1	7	i/ii/iii/iv/v/vi/vii	14.66	33.52	7
F23 (DLR)	2	2,7	i/ii	4.19	56.6	2 - 7
F23 (DLR)			iii/iv/v/vi/vii	14.66	33.52	7
F7 (ULR)			iii/iv/v/vi/vii	4.18	5.83	1 - 2
F23 (DLR)	3	2,3,7	i/ii	4.19	56.6	2 - 7
			iii	4.19	52.4	3 - 7
			iv/v/vi/vii	14.66	33.52	7
F7 (ULR)			iii	4.18	5.83	1 - 2
			iv/v/vi/vii	4.18	10.02	1 - 3
F23 (DLR)	4	2,3,5,7	i/ii	4.19	56.6	2 - 7
			iii	4.19	52.4	3 - 7
			iv/v	4.19	42.96	5 - 7
			vi/vii	14.66	33.52	7
F7 (ULR)			iii	4.18	5.83	1 - 2
			iv/v	4.18	10.02	1 - 3
			vi/vii	4.18	19.45	1 - 5
F23 (DLR)	5	2,3,5,6,7	i/ii	4.19	56.6	2 - 7
			iii	4.19	52.4	3 - 7
			iv/v	4.19	42.96	5 - 7
			vi	5.23	38.76	6 - 7
			vii	14.66	33.52	7
F7 (ULR)			iii	4.18	5.83	1 - 2
			iv/v	4.18	10.02	1 - 3
			vi	4.18	19.45	1 - 5
			vii	5.23	24.69	1 - 6
F23 (DLR)	6	1,2,3,5,6,7	i	1.65	58.25	1 - 7
			ii	4.19	56.6	2 - 7
			iii	4.19	52.4	3 - 7
			iv/v	4.19	42.96	5 - 7
			vi	5.23	38.76	6 - 7
			vii	14.66	33.52	7
F7 (ULR)			ii	1.649	1.649	1
			iii	4.18	5.83	1 - 2
			iv/v	4.18	10.02	1 - 3
			vi	4.18	19.45	1 - 5
			vii	5.23	24.69	1 - 6

Table 6-7: ULR and DLR F7 via F23 by applying the optimal locations of ROS pairs by Brute Force

Feeder	#ROS	Optimal Locations ROS by Brute Force	Outage Position	Expected customers restored through; (customer failures/year)		Expected Customers outage following ULR DLR restorations
				ULR	DLR	
F7	1	7	i/ii/iii/iv/v/vi/vi i	0.00	7.14	1.60
	2	2,7	i/ii	0.00	4.47	0.4047
			iii/iv/v/vi/vii	0.39	3.48	
	3	2,3,7	i/ii	0.00	4.47	0.21
			iii	0.21	2.08	
			iv/v/vi/vii	0.17	1.60	
	4	2,3,5,7	i/ii	0.00	4.47	0.03
			iii	0.21	2.08	
			iv/v	0.10	0.66	
			vi/vii	0.21	0.98	
	5	2,3,5,6,7	i/ii	0	4.47	0.02
			iii	0.21	2.08	
			iv/v	0.10	0.66	
			vi	0.11	0.54	
			vii	0.10	0.45	
	6	1,2,3,5,6,7	i	0	2.09	0.01
			ii	0.01	2.38	
			iii	0.21	2.08	
			iv/v	0.10	0.66	
			vi	0.11	0.54	
			vii	0.10	0.45	

Figure 6-26 illustrates the voltage and current profiles from F7 (SS77) restored by F23. In this case, only one ROS pair is available and located on substation 7 of SS7. However, ULR is not available but DLR is available when an outage occurs at any section on F7.

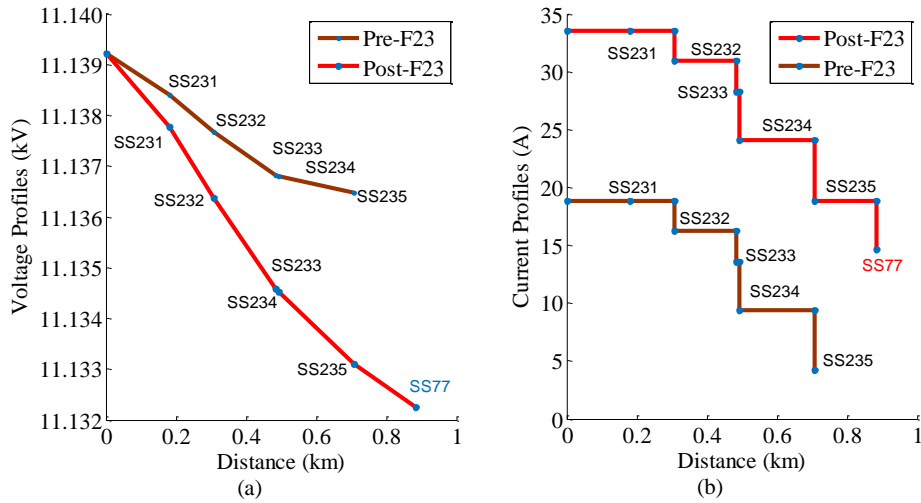


Figure 6-26: Pre and post-outage a) voltage profiles and b) current profiles for one optimal ROS pair by Brute Force (if an outage occurs at section i/ii/iii/iv/v/vi)

Further analysis has been made by adding two ROS pairs at optimal locations. Locations 2 and 7 was selected by Brute Force as optimal locations. Feeder 23 is able to supply load under the DLR option for substations SS72 to SS77 if an outage occurs at Section i or ii and for substation SS77 if outage occurs from Section iii to vii as illustrated in Figure 6-27. ULR is available if an outage happens from Section iii to vii as shown in Figure 6-28.

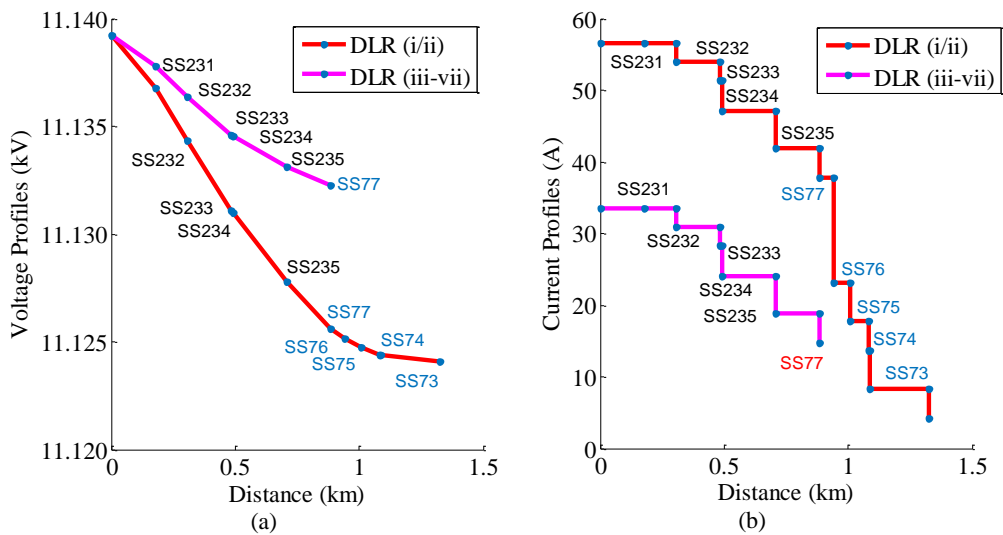


Figure 6-27: Post-outage a) voltage profiles and b) Current profiles for two ROS pairs located on F7 restored by F23 (outage i/ii and iii/iv/v/vi/vii)

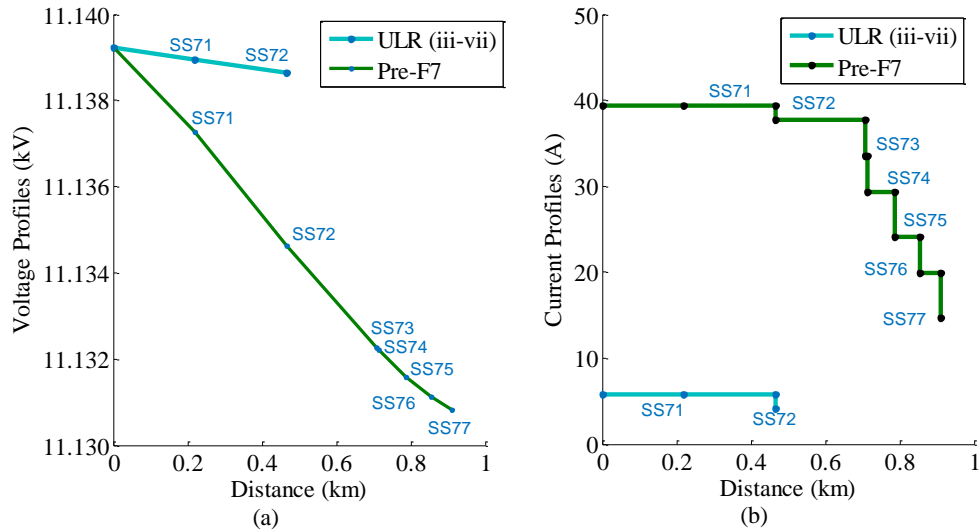


Figure 6-28: Pre and post-outage a) Voltage profiles and b) Current profiles for F7 during with two ROS pairs (outage iii/iv/v/vi/vii)

Further analysis was carried out on a feeder with branches and similar finding was obtained.

## 6.4 CONCLUSION

An analysis of fully automated and Brute Force optimisation location of ROS pairs has been carried out on the case study networks and few feeder using Brute Force method to search optimal number and locations respective to net benefits of adding the ROS pairs. In all cases, restoration with ULR and DLR is possible without voltage and current violations on the networks. The method is also capable of searching suitable DLR options if more than one feeder is available in the network qualified for back-feed restoration. Feeders with branches normally have an option to select the best DLR route for both sides of an NOP at the branches if an outage occurs before the junction node. So, both NOPs from the endings are able to restore the customers on downstream. The results from the proposed algorithm select the options with lower voltage drop and restoration without violations.



Three feeders also are shown for the uniqueness of the results of optimal locations of ROS pairs from Brute Force. Brute Force maintains the previous optimal locations of ROS pairs if more than one ROS pairs are added to it.

## CHAPTER 7

### GENERAL CONCLUSION AND FUTURE WORK

#### 7.1 DPSO ALGORITHM AND BRUTE FORCE METHOD FOR OPTIMAL LOCATIONS OF ROS PAIRS

A DPSO algorithm was successfully developed and applied to 11 kV urban, semi-urban and rural networks in the UK to determine optimum locations of automatically and ROS pairs. The optimisation was based on achieving the maximum number of customers that can be restored. In the current work, the implementation of automation to successively increase the number of applied switch pairs has been extensively studied, and it was found that very high percentages of restorations are achievable with relatively few automated switches. The developed algorithm is also able to prioritise the implementation of automation carried out by the feeder. In addition, it was discovered that there was no current or voltage violation found in the selected the DLR during the investigation, although this may be expected due to the fact that it is an urban network comprising relatively short sections of high capacity cable.

This research has demonstrated that it is not necessary to deploy a fully automated system in order to achieve significant improvement in the network reliability. The result shows that the proposed algorithm is capable of selecting the most suitable feeder for the downstream restoration. The codes developed in MATLAB and NPL (NEPLAN) have been designed such that they can be applied to any type of network, and there is no limitation to apply the algorithm on any radial network. One of the most promising features of the proposed algorithm is the unlimited number of ROS pairs that are to be studied within practically advisable times.

Even the optimal locations of the ROS pairs found and restored a higher number of customers on the respective feeder, but the results not such a promised to DNO to install the switch until the net benefits of adding the ROS pairs is calculated. So, one further step of improvement of the algorithm has been made, rather than only searching for optimal locations of ROS pairs, the proposed algorithm also capable to calculate the beneficial cost of adding ROS pair on a network respective to the number of customer failures per year. The proposed algorithm also help DNO to decide the optimal number, location and beneficial of investment with adding the ROS pair on the different types of network with higher number of substations. The results from this analysis was also compared with the Brute Force method and validated the proposed output achieving the objective function.

## **7.2 RESTORATION ALGORITHM**

The algorithm was developed to carry out predictive supply restoration of the ULR and DLR for 11 kV distribution networks. Based on the standard load flow model (Newton Raphson Method) of the network, the code written in NPL is able to identify the fault locations in three types of network (urban, semi-urban and rural network). The algorithm also determines options available for ULR and DLR via a logical approach and noting the availability of automatic switches in the network. The information helps further analysis of multiple load flow calculations for any fault scenario and every possible level of restoration and considering alternative DLR options. The best option is selected for restoration, and this is identified as the maximum level of restoration without violating voltage or current limits, and it is based on the results from the load flow calculations. The final output from the algorithm produce statistics of the amount of the restored customers and kWhr that can be saved. Successful preliminary tests of

the algorithm were carried out on three types of 11 kV distribution networks which are urban, semi-urban and rural networks.

### **7.3 FUTURE WORK**

It is proposed that a detailed cost benefit analysis is carried out to examine the likely option number of applied ROS to a range of case study networks. The current method calculating the net benefits installation of ROS pairs within a year. An improvement on the analysis can be made by calculating the net benefits if installation has been made for more than one year. This can be applied on feeder with less number of customers such as Rural network. Normally, for feeders with less number of expected customers restored, adding even one ROS pair has positive net benefits. So, rather than only calculating net benefits within one year, the calculation of the net benefits can also be performed for more than one year because, in electrical systems, the expected life time of an equipment is given by manufacturers. If the return of investment is still positive within the equipment lifetime, the installation of the equipment is assumed to be not economical and vice versa.

The second factor influence the decision to install the switch is outage cost considering the true cost to the DNO of locating and clearing the cost. This cost will be higher in rural than in urban networks.

## REFERENCES

- [1] A. Chowdhury and D. Koval, *Power Distribution System Reliability: Practical Methods and Applications*. John Wiley & Sons, 2011.
- [2] R. N. Allan and R. Billinton, “Probabilistic methods applied to electric power systems—are they worth it?,” *Power Eng. J.*, vol. 6, no. 3, p. 121-129, May 1992.
- [3] S. Golestani and M. Tadayon, “Optimal switch placement in distribution power system using linear fragmented particle swarm optimization algorithm preprocessed by GA,” *8th International Conference on the European Energy Market (EEM)*, pp. 537–542, May 2011.
- [4] E. (Erkki) Lakervi, E. J. Holmes, and Institution of Electrical Engineers., *Electricity distribution network design*. P. Peregrinus on behalf of the Institution of Electrical Engineers (IET), 1995.
- [5] J. Northcote-Green and R. Wilson, *Control and automation of electrical power distribution systems*. Taylor & Francis, 2007.
- [6] J. M. Gers and E. J. Holmes, *Protection of Electricity Distribution Networks, 2nd Edition (IEE Power and Energy Series)* Institution of Electrical Engineers (IET), 2004.
- [7] OFGEM UK, “Strategy decision for RIIO-ED1 - Overview” [Online]. Available: <https://www.ofgem.gov.uk/publications-and-updates/strategy-decision-riio-ed1-overview>. [Accessed: 27-Nov-2015].
- [8] OFGEM, “Minutes of the Gas and Electricity Markets Authority - 16 November 2017,” 2017. [Online]. Available: <https://www.ofgem.gov.uk/about-us/who-we-are/gas-and-electricity-markets-authority>. [Accessed: 29-Dec-2017].
- [9] Y. Chollot, J.-M. Biasse, and A. Malot, “Feeder automation improves medium voltage network operating efficiency.” *22<sup>nd</sup> International Conference and Exhibition on Electricity Distribution (CIRED 2013)*, pp. 1–4, June 2008.
- [10] A. Haddad, D. F. Warne, and Institution of Electrical Engineers., *Advances in high voltage engineering*. Institution of Electrical Engineers, 2004.
- [11] “RIIO electricity distribution annual report 2015-16 | Ofgem.” [Online]. Available: <https://www.ofgem.gov.uk/publications-and-updates/riio-electricity-distribution-annual-report-2015-16>. [Accessed: 23-Jun-2017].
- [12] “The Electricity (Standards of Performance) Regulations 2015 and Electricity (Connection Standards of Performance) Regulations 2015 | Ofgem.” [Online]. Available: <https://www.ofgem.gov.uk/publications-and-updates/electricity-standards-performance-regulations-2015-and-electricity-connection-standards-performance-regulations-2015>. [Accessed: 06-May-2015].
- [13] Westinghouse Electric Corporation, *Electrical Transmission and Distribution Reference Book*, 4th ed. East Pittsburgh, 1950.
- [14] P. M. S. Carvalho, L. A. F. M. Ferreira, and A. J. CerejodaSilva, “A Decomposition Approach to Optimal Remote Controlled Switch Allocation in

- Distribution Systems,” *IEEE Trans. Power Deliv.*, vol. 20, no. 2, pp. 1031–1036, Apr. 2005.
- [15] A. A. Chowdhury, “Distribution feeder reliability assessment,” *IEEE Power Engineering Society General Meeting*, pp. 2179–2184, 2005.
- [16] G. V Roberts, R. Owen, and D. Rigler, “Automation strategies and solutions,” *Trends in Distribution Switchgear: 400V-145kV for Utilities and Private Networks, Fifth International Conference on (Conf. Publ. No. 459)*, pp. 96–101, London(UK), Nov 10-12, 1998.
- [17] M. R. Elkadeem, M. A. Alaam, and A. M. Azmy, “Improving performance of underground MV distribution networks using distribution automation system: A case study,” *Ain Shams Eng. J.*, 2016.
- [18] “RIIO-ED1 regulatory instructions and guidance: Annex F – Interruptions.” | Ofgem.” [Online]. Available: <https://www.ofgem.gov.uk/ofgem-publications/95354/annexfinterruptions-pdf> . [Accessed: 06-Apr-2018].
- [19] R. Perez-Guerrero, G. T. Heydt, N. J. Jack, B. K. Keel, and A. R. Castelhana, “Optimal Restoration of Distribution Systems Using Dynamic Programming,” *IEEE Trans. Power Deliv.*, vol. 23, no. 3, pp. 1589–1596, Jul. 2008.
- [20] K. M. Kyusyu E. P. C. L. Ikuo Kurihara ( Research Institute of Electric Power Industry), “Reliability Analysis of Sub-transmission Network: A New Loss of Load Minimization Algorithm In Radial Network,” *13th Power System Computation Conference*, pp. 201–207, 1999.
- [21] W. Li, P. Wang, Z. Li, and Y. Liu, “Reliability Evaluation of Complex Radial Distribution Systems Considering Restoration Sequence and Network Constraints,” *IEEE Trans. Power Deliv.*, vol. 19, no. 2, pp. 753–758, Apr. 2004.
- [22] S. Dimitrijevic and N. Rajakovic, “Service Restoration of Distribution Networks Considering Switching Operation Costs and Actual Status of the Switching Equipment,” *IEEE Trans. Smart Grid*, vol. 6, no. 3, pp. 1227–1232, May 2015.
- [23] M. R. Kleinberg, K. Miu, and H.-D. Chiang, “Improving Service Restoration of Power Distribution Systems Through Load Curtailment of In-Service Customers,” *IEEE Trans. Power Syst.*, vol. 26, no. 3, pp. 1110–1117, Aug. 2011.
- [24] J. W. Feltes, C. Grande-Moran, P. Duggan, S. Kalinowsky, M. Zamzam, V. C. Kotecha, and F. P. deMello, “Some Considerations in the Development of Restoration Plans for Electric Utilities Serving Large Metropolitan Areas,” *IEEE Trans. Power Syst.*, vol. 21, no. 2, pp. 909–915, May 2006.
- [25] W. R. D. Tarnate, I. B. N. C. Cruz, R. D. del Mundo, and B. M. Malquisto, “Maximizing service restoration in reliability optimization of radial distribution systems,” *TENCON 2012 IEEE Region 10 Conference*, pp. 1–6, Cebu(Phillipines), Nov 19-22, 2012.
- [26] laila zemite, J. Gerhards, M. Gorobeas, and A. Levchenkons, “Optimization of Switch Allocation in Power Distribution Systems,” *Engineering and Industry Series*, pp. 166-174, Sept 24-25, 2015.
- [27] T. Jen-Hao and L. Chan-Nan, “Feeder-switch relocation for customer interruption cost minimization,” *Power Deliv. IEEE Trans.*, vol. 17, no. 1, pp. 254–259, Aug 2002.

- [28] I. Lim, T. S. Sidhu, M. S. Choi, S. J. Lee, and B. N. Ha, "An Optimal Composition and Placement of Automatic Switches in DAS," *IEEE Trans. Power Deliv.*, vol. 28, no. 3, pp. 1474–1482, Jul. 2013.
- [29] G. D. Ferreira *et al.*, "Multiobjective MILP model for optimal allocation of automated switching devices in electric power distribution systems," *IEEE Eindhoven PowerTech*, pp. 1–6, Eindhoven(Netherlands), Jun 29 - July 2, 2015.
- [30] F. B. Hasanvand H., Bakhshideh Zad B., Mozafari B., "Damping of low-frequency oscillations using an SVC-based supplementary controller," *IEEEJ Trans. Electr. Electron. Eng.*, vol. 8, no. 6, pp. 550–556, 2013.
- [31] A. A. Mousa, M. A. El-Shorbagy, and W. F. Abd-El-Wahed, "Local search based hybrid particle swarm optimization algorithm for multiobjective optimization," *Swarm Evol. Comput.*, vol. 3, pp. 1–14, Apr. 2012.
- [32] V. Kachitvichyanukul, "Comparison of Three Evolutionary Algorithms: GA, PSO, and DE," *Ind. Eng. Manag. Syst.*, vol. 11, no. 3, pp. 215–223, Sep. 2012.
- [33] J. B. (Janaka B. . Ekanayake and Wiley InterScience (Online service), *Smart grid : technology and applications*. Wiley, 2012.
- [34] J. Valtari, P. Verho, A. Hakala-Ranta, and J. Saarinen, "Increasing cost-efficiency of substation automation systems by centralised protection functions," *IET Conference Publications*, 2009, pp. 764–764, Praque (Chech Republic), Sept 22, 2009.
- [35] F. Mekic, Z. Wang, V. Donde, F. Yang, and J. Stoupis, "Distributed automation for back-feed network power restoration," *62nd Annual Conference for Protective Relay Engineers*, pp. 1–7, Austin(Texas), 2009.
- [36] T. Newman, "System automation in power distribution," *IEE North Eastern Centre Power Section Symposium on the Reliability, Security and Power Quality of Distribution Systems*, pp.9/1–9/6, Durham(UK), 1995.
- [37] P. Reis, C. Cndido, F. Campos, C. Fortunato, F. Melo, and N. Silva, "Distribution automation on LV and MV using distributed intelligence," *22nd International Conference and Exhibition on Electricity Distribution (CIRED 2013)*, pp.750–750, Stockholm(UK), 2013.
- [38] M. Theil and G. Theil, "Reliability Assessment of Medium Voltage Networks With Simulation of the Restoration Process." *Power System Computation Conference* pp. 1, Sevilla, June 24-28, 2002.
- [39] R. E. Brown, "Distribution reliability assessment and reconfiguration optimization," *IEEE/PES Transmission and Distribution Conference and Exposition. Developing New Perspectives (Cat. No.01CH37294)*, Vol. 2, pp. 994–999, Atlanta (USA), Aug 2001.
- [40] A. Gonzalez, F. M. Echavarren, L. Rouco, and T. Gomez, "A Sensitivities Computation Method for Reconfiguration of Radial Networks," *IEEE Trans. Power Syst.*, vol. 27, no. 3, pp. 1294–1301, Aug. 2012.
- [41] A. Botea, J. Rintanen, and D. Banerjee, "Optimal Reconfiguration for Supply Restoration With Informed A\*Search," *IEEE Trans. Smart Grid*, vol. 3, no. 2, pp. 583–593, Jun. 2012.

- [42] Y. Xu, C.-C. Liu, K. P. Schneider, and D. T. Ton, "Placement of Remote-Controlled Switches to Enhance Distribution System Restoration Capability," *IEEE Trans. Power Syst.*, vol. 31, no. 99, pp. 1–12, Apr. 2015.
- [43] G. I. Mazilu, S. Coculescu, M. Conu, and A. I. Mazilu, "Implementation of distribution automation systems (DAS) in the 'Electrica' company — Romania." *18<sup>th</sup> International Conference and Exhibition on Electricity Distribution*, pp. 1–5, Turin(Italy), 2005.
- [44] Xuejing Dong and Qian Sun, "The discussion about the application and development for the distribution automation system in Jinan Power Supply Company," *China International Conference on Electricity Distribution*, pp.1–7, Shanghai(China), Apr 2012.
- [45] L. Kurihara and K. Matsumoto, "Reliability analysis of sub-transmission network: A new loss-of-load minimization algorithm in radial network," unpublished, presented at the 13th Power System Computation Conference, Trondheim, 1999.
- [46] "Strategy decision for RIIO-ED1 - Overview" [Online]. Available: <https://www.ofgem.gov.uk/publications-and-updates/strategy-decision-riio-ed1-overview>. [Accessed: 27-Nov-2015].
- [47] P. Ravibabu, K. Venkatesh, and C. S. Kumar, "Implementation of genetic algorithm for optimal network reconfiguration in distribution systems for load balancing," *IEEE Region 8 International Conference on Computational Technologies in Electrical and Electronics Engineering*, pp. 124–128, July 2008.
- [48] K. S. Kumar, K. Rajalakshmi, and S. P. Karthikeyan, "A modified artificial neural network based Distribution System reconfiguration for loss minimization," *International Conference on Advances in Electrical Engineering (ICAEE)*, pp. 1–5, Vellore( India), Jan 2014.
- [49] Zhijian Hu, Xixiong He, Yang Gao, and Dong Liu, "Distribution network reconfiguration based on ant colony system algorithm," *3rd IEEE Conference on Industrial Electronics and Applications*, pp. 2470–2474, June 2008.
- [50] L. C. Daniel, I. H. Khan, and S. Ravichandran, "Distribution Network Reconfiguration For Loss Reduction Using Ant Colony System Algorithm," *Annual IEEE India Conference (INDICON)*, pp. 619–622, Dec 2005.
- [51] P. R. Babu, M. P. R. Vanamali, M. P. V. V. R. Kumar, and V. S. Hemachandra, "Network reconfiguration in distribution systems using L-E method," *Annual IEEE India Conference (INDICON)*, pp. 1–4, Dec 2010.
- [52] R. B. Rolim *et al.*, "Challenges in the implementation of a distribution automation project in a model with decentralized operation centers," *22nd International Conference and Exhibition on Electricity Distribution (CIRED 2013)*, pp. 0630–0630, Stockholm (Sweden), Jun 10-13, 2013.
- [53] D. P. Bernardon, M. Sperandio, V. J. Garcia, L. N. Canha, A. da Rosa Abaide, and E. F. B. Daza, "AHP Decision-Making Algorithm to Allocate Remotely Controlled Switches in Distribution Networks," *IEEE Trans. Power Deliv.*, vol. 26, no. 3, pp. 1884–1892, Jul. 2011.
- [54] R. Billinton and S. Jonnavithula, "Optimal switching device placement in radial



- distribution systems,” *IEEE Trans. Power Deliv.*, vol. 11, no. 3, pp. 1646–1651, Jul. 1996.
- [55] R. N. Allan, R. Billinton, I. Sjarief, L. Goel, and K. S. So, “A reliability test system for educational purposes-basic distribution system data and results,” *Power Syst. IEEE Trans.*, vol. 6, no. 2, pp. 813–820, 1991.
- [56] A. Moradi and M. Fotuhi-Firuzabad, “Optimal Switch Placement in Distribution Systems Using Trinary Particle Swarm Optimization Algorithm,” *IEEE Trans. Power Deliv.*, vol. 23, no. 1, pp. 271–279, Jan. 2008.
- [57] F. Soudi and K. Tomsovic, “Optimized distribution protection using binary programming,” *IEEE Trans. Power Deliv.*, vol. 13, no. 1, pp. 218–224, Aug. 1998.
- [58] R. E. Brown, “Distribution reliability assessment and reconfiguration optimization,” *IEEE/PES Transmission and Distribution Conference and Exposition. Developing New Perspectives (Cat. No.01CH37294)*, Vol. 2, pp. 994–999, Atlanta (USA), Aug. 2001.
- [59] Jen-Hao Teng and Chan-Nan Lu, “Feeder-switch relocation for customer interruption cost minimization,” *IEEE Trans. Power Deliv.*, vol. 17, no. 1, pp. 254–259, Aug. 2002.
- [60] L. G. W. Da Silva, R. A. F. Pereira, and J. R. S. Mantovani, “Optimised allocation of sectionalising switches and protection devices in distribution networks by using a reactive tabu search algorithm,” *18th International Conference and Exhibition on Electricity Distribution (CIRED 2005)*, vol. 38, no. 1, pp. 1–21, Dec. 2009.
- [61] J.-M. Sohn, S.-R. Nam, and J.-K. Park, “Value-Based Radial Distribution System Reliability Optimization,” *IEEE Trans. Power Syst.*, vol. 21, no. 2, pp. 941–947, May 2006.
- [62] C. S. Chen, C. H. Lin, H. J. Chuang, C. S. Li, M. Y. Huang, and C. W. Huang, “Optimal Placement of Line Switches for Distribution Automation Systems Using Immune Algorithm,” *IEEE Trans. Power Syst.*, vol. 21, no. 3, pp. 1209–1217, Aug. 2006.
- [63] L. G. W. da Silva, R. A. Fernandes Pereira, J. R. Abbad, and J. R. Sanches Mantovani, “Optimised placement of control and protective devices in electric distribution systems through reactive tabu search algorithm,” *Electr. Power Syst. Res.*, vol. 78, no. 3, pp. 372–381, Mar. 2008.
- [64] L. G. Wesz Da Silva, R. A. Fernandes Pereira, J. R. Abbad, and J. R. Sanches Mantovani, “Optimized Allocation of Control and Protective Devices in Electric Distribution Systems,” *Electr. Power Components Syst.*, vol. 38, no. 1, pp. 1–21, Dec. 2009.
- [65] E. Zambon, Dé. Z. Bossois, B. B. Garcia, and E. F. Azeredo, “A Novel Nonlinear Programming Model for Distribution Protection Optimization,” *IEEE Trans. Power Deliv.*, vol. 24, no. 4, pp. 1951–1958, Oct. 2009.
- [66] H. Falaghi, M.-R. Haghifam, and C. Singh, “Ant Colony Optimization-Based Method for Placement of Sectionalizing Switches in Distribution Networks Using a Fuzzy Multiobjective Approach,” *IEEE Trans. Power Deliv.*, vol. 24,

no. 1, pp. 268–276, Jan. 2009.

- [67] A. Abiri-Jahromi, M. Fotuhi-Firuzabad, M. Parvania, and M. Mosleh, “Optimized Sectionalizing Switch Placement Strategy in Distribution Systems,” *IEEE Trans. Power Deliv.*, vol. 27, no. 1, pp. 362–370, Jan. 2012.
- [68] H. Dezaki, H. Abyaneh, A. Agheli, and K. Mazlumi, “Optimized Switch Allocation to Improve the Restoration Energy in Distribution Systems,” *J. Electr. Eng.*, vol. 63, no. 1, pp. 47–52, Jan. 2012.
- [69] A. Shahsavari, A. Fereidunian, and S. M. Mazhari, “A joint automatic and manual switch placement within distribution systems considering operational probabilities of control sequences,” *Int. Trans. Electr. Energy Syst.*, vol. 25, no. 11, pp. 2745–2768, Nov. 2015.
- [70] Z. Popovic, S. Knezevic, and B. Brbaklic, “Optimal number, type and location of remotely controlled and supervised devices in distribution networks,” *IEEE Eindhoven PowerTech*, pp. 1–6, July 2015.
- [71] B. Baruah, S. Das, and M. Ghosh, “Optimal placement of protective devices in a distributed power system,” *Annual IEEE India Conference (INDICON)*, pp. 1–6, Dec 2015.
- [72] H. H. Dezaki, H. . Abyaneh, M. R. Yaghubinia, M. Zanganeh, and K. Mazlumi, “Protective and switching devices allocation according to total cost minimization by genetic algorithm in distribution systems,” *7<sup>th</sup> International Conference on Electrical and Electronics Engineering (ELECO)*, pp. 376-380, Bursa(Turkey), Dec. 1-4, 2011.
- [73] I. Watanabe and M. Nodu, “A genetic algorithm for optimizing switching sequence of service restoration in distribution systems,” *Proceedings of the 2004 Congress on Evolutionary Computation (IEEE Cat. No.04TH8753)*, Vol. 2, pp. 1683–1690, Portland (USA), June 2004.
- [74] B. Baruah, S. Das, and M. Ghosh, “Optimal placement of protective devices in a distributed power system,” *Annual IEEE India Conference (INDICON)*, pp. 1–6, New Delhi (India), Dec 17-20, 2015.
- [75] A. Coelho, A. Rodrigues, R. B. Prada, and M. G. Silva, “Reliability Evaluation of Distribution Networks Considering Optimization Models in the Restoration Process,” *10<sup>th</sup> International conference on Probabilistic Methods Applied to power Systems*, pp. 1–7, Rincon(Puerto Rico), May 25-29, 2008.
- [76] M. Silva, A. Coelho, R. Prada, and A. Rodrigues, “Impact of Voltage and Reactive Power Control Devices On The Reliability Assessment of Radial Distribution Networks,” *16<sup>th</sup> Power System Computation Conference (PSCC)*, pp. 1–6, Galsgow(Scotland), July 14-18, 2008.
- [77] P. Wang and W. Li, “Reliability evaluation of distribution systems considering optimal restoration sequence and variable restoration times,” *IET Gener. Transm. Distrib.*, vol. 1, no. 4, p. 688, July 2007.
- [78] E. M. Davidson, M. J. Dolan, G. W. Ault, and S. D. J. McArthur, “AuRA-NMS: An autonomous regional active network management system for EDF energy and SP energy networks,” *IEEE PES General Meeting*, , pp. 1–6, Providence( USA), July 25-29, 2010.

- [79] “IFI/LCNF 2012,” [Online]. Available: <http://www.energynetworks.org/electricity/engineering/engineering-documents/engineering-documents-overview.html>. [Accessed: 27-Nov-2015].
- [80] U.S Department of Energy, “Fault Location, Isolation, and Service Restoration Technologies Reduce outage Impact and Duration.” American Recovery and Reinvestment Act of 2009, SmartGrid.Gov, US, Tech. Rep, Dec 2014.
- [81] Western Power Distribution, “Distributed generation and demand study - Technology growth scenarios to 2030 Final version-Revision A,” Jan 2016 [Online]. Available: <https://www.westernpower.co.uk/docs/About-us/Our-business/Our-network/Strategic-network-investment/WPD-Regen-DG-Growth-Scenario-Report-RevisionA.aspx> Accessed on: Jan. 1, 2017.
- [82] S. Gludpetch and T. Tayjasant, “Optimal placement of protective devices for improving reliability indices in Microgrid system,” *IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC)*, pp. 1–6, Kowloon (Hong Kong), Dec 2013
- [83] M. A. Velasquez, A. Cadena, and C. Tautiva, “Optimal planning of recloser-based protection systems applying the economic theory of the firm and evolutionary algorithms,” *IEEE PES ISGT Europe 2013*, pp. 1–5, Lyngby (Denmark), Oct. 6-8, 2013.
- [84] M. T. Doyle, “Reviewing the impacts of distributed generation on distribution system protection,” *IEEE Power Engineering Society Summer Meeting*, vol. 1, pp. 103–105, Chicago(USA), July 21-25, 2002.
- [85] A. Girgis and S. Brahma, “Effect of distributed generation on protective device coordination in distribution system,” *LESCOPE 01. 2001 Large Engineering Systems Conference on Power Engineering. Conference Proceedings. Theme: Powering Beyond 2001 (Cat. No.01ex490)*, pp. 115–119, Halifax(Canada), July 11-13, 2001.
- [86] L. M. Cipcigan and P. C. Taylor, “Investigation of the reverse power flow requirements of high penetrations of small-scale embedded generation,” *IET Renew. Power Gener.*, vol. 1, no. 3, p. 160-166, Sept. 2007.
- [87] T. G. M. Alvin, I. Z. Abidin, and H. Hashim, “Changes in fault current levels due to renewable embedded generation in a distribution network,” *IEEE Conference on Clean Energy and Technology (CEAT)*, 2013, pp. 254–258, Langkawi (Malaysia), Nov 18-20, 2013.
- [88] Yu Xiaodan, Jia Hongjie, Wang Chengshan, Wei Wei, Zeng Yuan, and Zhao Jinli, “Network reconfiguration for distribution system with micro-grids,” *International Conference on Sustainable Power Generation and Supply*, pp. 1–4, Nanjing(China), Apr. 6-7, 2009.
- [89] A. Castillo, “Risk analysis and management in power outage and restoration: A literature survey,” *Electr. Power Syst. Res.*, vol. 107, pp. 9–15, Feb. 2014.
- [90] N. Balijepalli, S. S. Venkata, C. W. Richter, R. D. Christie, and V. J. Longo, “Distribution System Reliability Assessment Due to Lightning Storms,” *IEEE Trans. Power Deliv.*, vol. 20, no. 3, pp. 2153–2159, Jul. 2005.
- [91] D. Zhu, D. Cheng, R. P. Broadwater, and C. Scirbona, “Storm modeling for

- prediction of power distribution system outages,” *Electr. Power Syst. Res.*, vol. 77, no. 8, pp. 973–979, Jun. 2007.
- [92] R. (Rafael C. Martí and G. (Gerhard) Reinelt, *The linear ordering problem : exact and heuristic methods in combinatorial optimization*. Springer, 2011.
- [93] S. Salhi, *Heuristic Search*. Cham: Springer International Publishing, 2017.
- [94] R. Martí and G. Reinelt, *Heuristic Methods*, Springer Science, 2011.
- [95] A. M. S. (Ali M. S. . Zalzal and P. J. (Peter J. . Fleming, *Genetic algorithms in engineering systems*. Institution of Electrical Engineers, 1997.
- [96] A. P. Engelbrecht, *Fundamentals of computational swarm intelligence*. Wiley, 2005.
- [97] S. Talukder, *Mathematical Modelling and Applications of Particle Swarm Optimization*, 2011.
- [98] X. Cai, Z. Cui, J. Zeng, and Y. T, “Individual Parameter Selection Strategy for Particle Swarm Optimization,” in *Particle Swarm Optimization*, InTech, 2009.
- [99] Y. Shi and R. Eberhart, “A modified particle swarm optimizer,” *IEEE International Conference on Evolutionary Computation Proceedings. IEEE World Congress on Computational Intelligence (Cat. No.98TH8360)*, pp. 69–73, Anchorage (USA), May 4-9, 1998.
- [100] P. N. Suganthan, “Particle swarm optimiser with neighbourhood operator,” in *Proceedings of the 1999 Congress on Evolutionary Computation-CEC99 (Cat. No. 99TH8406)*, pp. 1958–1962, Washington(USA), July 6-9, 1999.
- [101] Y. Shi and R. C. Eberhart, *Parameter selection in particle swarm optimization*, Springer, Berlin, Heidelberg, 1998.
- [102] F. Van Den Bergh, “An Analysis of Particle Swarm Optimizations.” [Online]. Available: <http://repository.up.ac.za/bitstream/handle/2263/24297/00thesis.pdf>. [Accessed: 14-Jan-2016].
- [103] S. Nanchian, A. Majumdar, and B. C. Pal, “Three-Phase State Estimation Using Hybrid Particle Swarm Optimization,” *IEEE Trans. Smart Grid*, vol. 8, no. 99, pp. 1035–1045, May 2015.
- [104] S. Elsaiah, M. Benidris, and J. Mitra, “Reliability improvement of power distribution system through feeder reconfiguration,” *International Conference on Probabilistic Methods Applied to Power Systems (PMAPS)*, pp. 1–6, Durham (UK), July 7-10, 2014.
- [105] W.-C. Wu and M.-S. Tsai, “Application of Enhanced Integer Coded Particle Swarm Optimization for Distribution System Feeder Reconfiguration,” *IEEE Trans. Power Syst.*, vol. 26, no. 3, pp. 1591–1599, Aug. 2011.
- [106] R. Rajendra and D. K. Pratihari, “Particle Swarm Optimization Algorithm vs Genetic Algorithm to Develop Integrated Scheme for Obtaining Optimal Mechanical Structure and Adaptive Controller of a Robot,” *Intell. Control Autom.*, vol. 2, pp. 430–449, 2011.
- [107] A. Engelbrecht, *Computational intelligence: an introduction*. John Wiley & Son, 2007.

- [108] J. Kennedy and R. C. Eberhart, "A discrete binary version of the particle swarm algorithm," *IEEE International Conference on Systems, Man, and Cybernetics. Computational Cybernetics and Simulation*, vol. 5, pp. 4104–4108, Orlando (USA), Oct 12-15, 1997.
- [109] Western Power Distribution, "Long Term Development Statement for Western Power Distribution (East Midlands) plc's Electricity Distribution System," WPD East Midland, UK, Tech. Rep, Nov 2017.
- [110] "What is SCADA? Supervisory Control and Data Acquisition." [Online]. Available: <https://inductiveautomation.com/what-is-scada>. [Accessed: 13-Jul-2017].
- [111] R. L. Alexander, "Intelligent electronic device (IED) technology SCADA and 30 metering," *Rural Electric Power Conference. Papers Presented at the 46th Annual Conference (Cat. No. 02CH37360)*, pp. 1–3, Colorado Spring(USA), May 5-7, 2002.
- [112] C. Wester, N. Engelman, T. Smith, K. Odetunde, B. Anderson, and J. Reilly, "The role of the SCADA RTU in today's substation," *68th Annual Conference for Protective Relay Engineers*, pp. 622–628, College Station (USA), March 30 - Apr. 2, 2015.
- [113] "Distribution Feeder Automation Systems - Smart Grid Solutions - Siemens."
- [114] ABB, "Remote monitoring and control REC615 - Grid automation solutions (Protection and control products for power distribution) | ABB." [Online]. Available: <http://new.abb.com/medium-voltage/distribution-automation/grid-automation-solutions/products/remote-monitoring-and-control-rec615>. [Accessed: 20-Jul-2017].
- [115] V. . Gungor and F. . Lambert, "A survey on communication networks for electric system automation," *Comput. Networks*, vol. 50, no. 7, pp. 877–897, May 2006.
- [116] G. N. Ericsson, "Classification of power systems communications needs and requirements: experiences from case studies at Swedish national grid," *IEEE Trans. Power Deliv.*, vol. 17, no. 2, pp. 345–347, Apr. 2002.
- [117] R. Cohen, "On the establishment of an access VPN in broadband access networks," *IEEE Commun. Mag.*, vol. 41, no. 2, pp. 156–163, Feb. 2003.
- [118] X. Cheng, W.-J. Lee, and X. Pan, "Modernizing Substation Automation Systems: Adopting IEC Standard 61850 for Modeling and Communication," *IEEE Ind. Appl. Mag.*, vol. 23, no. 1, pp. 42–49, Jan. 2017.
- [119] S. Hong, D.-Y. Shin, and M. Lee, "Evaluating Security Algorithms in the Substation Communication Architecture," *International Conference on Scalable Computing and Communications; Eighth International Conference on Embedded Computing* pp. 314–318, Dalian(China), Sept. 25-27, 2009.
- [120] S. Robson, A. Haddad, and H. Griffiths, "An integrated device for optimised power line communication and measurement on smart grids," *IEEE PES T&D Conference and Exposition*, pp. 1–5, Chicago(USA), Apr. 14-17, 2014.
- [121] "RIIO electricity distribution annual report 2015-16 | Ofgem." [Online]. Available: <https://www.ofgem.gov.uk/publications-and-updates/riio-electricity-distribution-annual-report-2015-16>. [Accessed: 23-Jun-2017].

- [122] E. & I. S. Department for Business, “Future electricity networks - GOV.UK,” 2015. [Online]. Available: <https://www.gov.uk/guidance/future-electricity-networks>. [Accessed: 17-Jul-2017].
- [123] A. Apostolov, P. Mysore, T. Sidhu, and C. F. Henville, “An update to protection issues during system restoration,” *IEEE Power and Energy Society General Meeting*, pp. 1–4, San Diego (USA), July 22-26, 2012.
- [124] C. U. Sajjad Ali, Phillip Moseley, Martin Smith, David Tuffery, Sam Donnelly, “Improving Reliability of 11kV Distribution Network,” 2014.
- [125] M. R. Mazidi, M. Aghazadeh, Y. A. Teshnizi, and E. Mohagheghi, “Optimal placement of switching devices in distribution networks using multi-objective genetic algorithm NSGAI,” *21st Iranian Conference on Electrical Engineering (ICEE)*, 2013, pp. 1–6, Mashhad (Iran), May 14-16, 2013.
- [126] A. A. Chowdhury, “Distribution feeder reliability assessment,” *IEEE Power Engineering Society General Meeting, 2005*, pp. 708–713, San Francisco, Jun 16, 2005.
- [127] E. Zamboni, D. Z. Bossois, B. B. Garcia, and E. F. Azeredo, “A Novel Nonlinear Programming Model for Distribution Protection Optimization,” *IEEE Trans. Power Deliv.*, vol. 24, no. 4, pp. 1951–1958, Oct. 2009.
- [128] J.-H. Kim, J.-Y. Kim, J.-T. Cho, I.-K. Song, B.-M. Kweon, I.-Y. Chung, and J.-H. Choi, “Comparison between Underground Cable and Overhead Line for a Low-Voltage Direct Current Distribution Network Serving Communication Repeater,” *Energies*, vol. 7, no. 3, pp. 1656–1672, Mar. 2014.

## APPENDICES

### APPENDIX 1: PROBABILITY LOCATION FOR FEEDER WITH DIFFERENT NUMBER OF TOTAL SUBSTATION

Feeder Length (# S/S)	Number of ROS Pairs					
	1	2	3	4	5	6
2	2					
3	3	3				
4	4	6	4			
5	5	10	10	5		
6	6	15	20	15	6	
7	7	21	35	35	21	7
8	8	28	56	70	56	28
9	9	36	84	126	126	84
10	10	45	120	210	252	210
11	11	55	165	330	462	462
12	12	66	220	495	792	924
13	13	78	286	715	1287	1716
14	14	91	364	1001	2002	3003
15	15	105	455	1365	3003	5005
16	16	120	560	1820	4368	8008
17	17	136	680	2380	6188	12376
18	18	153	816	3060	8568	18564
19	19	171	969	3876	11628	27132
20	20	190	1140	4845	15504	38760
21	21	210	1330	5985	20349	54264
22	22	231	1540	7315	26334	74613
23	23	253	1771	8855	33649	100947
24	24	276	2024	10626	42504	134596
25	25	300	2300	12650	53130	177100
26	26	325	2600	14950	65780	230230
27	27	351	2925	17550	80730	296010
28	28	378	3276	20475	98280	376740
29	29	406	3654	23751	118755	475020
30	30	435	4060	27405	142506	593775
31	31	465	4495	31465	169911	736281
32	32	496	4960	35960	201376	906192
33	33	528	5456	40920	237336	1107568
34	34	561	5984	46376	278256	1344904
35	35	595	6545	52360	324632	1623160
36	36	630	7140	58905	376992	1947792

37	37	666	7770	66045	435897	2324784
38	38	703	8436	73815	501942	2760681
39	39	741	9139	82251	575757	3262623
40	40	780	9880	91390	658008	3838380
41	41	820	10660	101270	749398	4496388
42	42	861	11480	111930	850668	5245786
43	43	903	12341	123410	962598	6096454
44	44	946	13244	135751	1086008	7059052
45	45	990	14190	148995	1221759	8145060
46	46	1035	15180	163185	1370754	9366819
47	47	1081	16215	178365	1533939	10737573
48	48	1128	17296	194580	1712304	12271512
49	49	1176	18424	211876	1906884	13983816
50	50	1225	19600	230300	2118760	15890700
51	51	1275	20825	249900	2349060	18009460
52	52	1326	22100	270725	2598960	20358520
53	53	1378	23426	292825	2869685	22957480
54	54	1431	24804	316251	3162510	25827165
55	55	1485	26235	341055	3478761	28989675
56	56	1540	27720	367290	3819816	32468436
57	57	1596	29260	395010	4187106	36288252
58	58	1653	30856	424270	4582116	40475358
59	59	1711	32509	455126	5006386	45057474
60	60	1770	34220	487635	5461512	50063860
61	61	1830	35990	521855	5949147	55525372
62	62	1891	37820	557845	6471002	61474519
63	63	1953	39711	595665	7028847	67945521
64	64	2016	41664	635376	7624512	74974368
65	65	2080	43680	677040	8259888	82598880
66	66	2145	45760	720720	8936928	90858768
67	67	2211	47905	766480	9657648	99795696
68	68	2278	50116	814385	10424128	109453344
69	69	2346	52394	864501	11238513	119877472
70	70	2415	54740	916895	12103014	131115985
71	71	2485	57155	971635	13019909	143218999
72	72	2556	59640	1028790	13991544	156238908
73	73	2628	62196	1088430	15020334	170230452
74	74	2701	64824	1150626	16108764	185250786
75	75	2775	67525	1215450	17259390	201359550
76	76	2850	70300	1282975	18474840	218618940
77	77	2926	73150	1353275	19757815	237093780
78	78	3003	76076	1426425	21111090	256851595
79	79	3081	79079	1502501	22537515	277962685
80	80	3160	82160	1581580	24040016	300500200
81	81	3240	85320	1663740	25621596	324540216



82	82	3321	88560	1749060	27285336	350161812
83	83	3403	91881	1837620	29034396	377447148
84	84	3486	95284	1929501	30872016	406481544
85	85	3570	98770	2024785	32801517	437353560
86	86	3655	102340	2123555	34826302	470155077
87	87	3741	105995	2225895	36949857	504981379
88	88	3828	109736	2331890	39175752	541931236
89	89	3916	113564	2441626	41507642	581106988
90	90	4005	117480	2555190	43949268	622614630
91	91	4095	121485	2672670	46504458	666563898
92	92	4186	125580	2794155	49177128	713068356
93	93	4278	129766	2919735	51971283	762245484
94	94	4371	134044	3049501	54891018	814216767
95	95	4465	138415	3183545	57940519	869107785
96	96	4560	142880	3321960	61124064	927048304
97	97	4656	147440	3464840	64446024	988172368
98	98	4753	152096	3612280	67910864	1052618392
99	99	4851	156849	3764376	71523144	1120529256
100	100	4950	161700	3921225	75287520	1192052400
101	101	5050	166650	4082925	79208745	1267339920
102	102	5151	171700	4249575	83291670	1346548665
103	103	5253	176851	4421275	87541245	1429840335
104	104	5356	182104	4598126	91962520	1517381580
105	105	5460	187460	4780230	96560646	1609344100
106	106	5565	192920	4967690	101340876	1705904746
107	107	5671	198485	5160610	106308566	1807245622
108	108	5778	204156	5359095	111469176	1913554188
109	109	5886	209934	5563251	116828271	2025023364
110	110	5995	215820	5773185	122391522	2141851635
111	111	6105	221815	5989005	128164707	2264243157
112	112	6216	227920	6210820	134153712	2392407864
113	113	6328	234136	6438740	140364532	2526561576
114	114	6441	240464	6672876	146803272	2666926108
115	115	6555	246905	6913340	153476148	2813729380
116	116	6670	253460	7160245	160389488	2967205528
117	117	6786	260130	7413705	167549733	3127595016
118	118	6903	266916	7673835	174963438	3295144749
119	119	7021	273819	7940751	182637273	3470108187
120	120	7140	280840	8214570	190578024	3652745460
121	121	7260	287980	8495410	198792594	3843323484
122	122	7381	295240	8783390	207288004	4042116078

**APPENDIX 2: DATA FOR 122 FEEDERS AND THREE NETWORKS**

Customer on each S/S			Type of Line (UG or OH)			Section length (km)		
Urban	Rural	Semi-Urban	Urban	Rural	Semi-Urban	urban	rural	Semi-Urban
1	1	0	0	1	0	0.611	0.1093	0.13
3	1	17	0	1	0	0.05	0.214	0.4
0	0	0	0	0	0	0.284	0.287	0.21
173	5	17	0	1	0	0.313	0.098	0.11
1	180	39	0	1	0	0.198	0.0593	0.04
1	2	4	0	1	0	0.282	0.0108	0.03
4	43	8	1	0	1	0.458	0.0221	0.09
123	2	2	0	1	0	0.47	0.054	0.09
1	3	0	0	0	0	0.237	0.1093	0.19
3	14	4	0	1	0	0.041	0.214	0.15
0	0	1	0	1	0	0.107	0.287	0.15
173	16	2	0	1	0	0.15	0.098	0.34
1	1	1	0	1	0	0.371	0.0593	0.09
1	3	2	0	1	0	0.076	0.0108	0.09
4	3	19	0	1	0	0.125	0.0221	0.15
123	1	9	0	1	0	0.367	0.054	0.61
1	1	16	0	1	0	0.587	0.1093	0.15
3	1	3	0	1	0	0.174	0.214	0.17
0	2	1	0	1	0	0.285	0.287	0.33
173	1	4	0	1	0	0.061	0.098	0.155
1	9	18	0	0	0	0.05	0.0593	0.54
1	0	1	0	1	0	0.175	0.0108	0.15
4	3	19	0	0	0	0.132	0.0221	0.66
123	1	19	0	1	0	0.207	0.054	0.85
3	2	9	0	1	0	0.048	0.214	0.72
0	1	9	0	1	0	0.486	0.287	0.18
173	1	15	0	1	0	0.611	0.098	0.09
1	1	3	0	1	0	0.05	0.0593	0.05
1	0	18	0	0	0	0.284	0.0108	0.08
4	5	0	0	1	0	0.313	0.0221	0.04
123	1	0	0	1	0	0.198	0.054	0.13
1	2	17	0	1	0	0.282	0.1093	0.4
3	43	0	0	1	0	0.458	0.214	0.21
0	2	17	0	0	0	0.47	0.287	0.11
173	3	39	0	1	0	0.237	0.098	0.04
1	14	4	0	1	0	0.041	0.0593	0.03
1	0	8	0	1	0	0.107	0.0108	0.09
4	16	2	0	0	0	0.15	0.0221	0.09

123	1	0	0	1	0	0.371	0.054	0.19
1	3	4	0	1	0	0.076	0.0108	0.15
4	3	1	0	0	0	0.125	0.0221	0.15
123	1	2	0	1	0	0.367	0.054	0.34
1	1	1	0	1	0	0.587	0.1093	0.09
3	1	2	0	1	0	0.174	0.214	0.09
0	2	19	0	1	0	0.285	0.287	0.15
173	1	9	0	0	0	0.061	0.098	0.61
1	9	16	0	1	0	0.05	0.0593	0.15
1	0	3	0	1	0	0.175	0.0108	0.17
4	3	1	0	1	0	0.132	0.0221	0.33
123	1	4	0	1	0	0.207	0.054	0.155
3	2	18	0	0	0	0.048	0.214	0.54
0	1	1	0	1	0	0.486	0.287	0.15
173	0	19	0	1	0	0.284	0.098	0.66
1	5	19	0	1	0	0.313	0.0593	0.85
1	165	9	0	1	0	0.198	0.0108	0.72
4	2	9	0	0	0	0.282	0.0221	0.18
123	43	15	0	1	0	0.458	0.054	0.09
1	2	3	0	1	0	0.47	0.1093	0.05
3	3	18	0	0	0	0.237	0.214	0.08
0	14	0	0	1	0	0.041	0.287	0.04
173	0	0	0	1	0	0.107	0.098	0.13
1	16	17	0	1	0	0.15	0.0593	0.4
1	1	0	0	1	0	0.371	0.0108	0.21
4	3	17	0	1	0	0.076	0.0221	0.11
123	3	39	0	1	0	0.125	0.054	0.04
3	1	4	0	1	0	0.367	0.214	0.03
0	1	8	0	1	0	0.587	0.287	0.09
173	1	2	0	1	0	0.174	0.098	0.09
1	2	0	0	0	0	0.285	0.0593	0.19
1	1	4	0	1	0	0.061	0.0108	0.15
4	9	1	0	1	0	0.05	0.0221	0.15
123	0	2	0	1	0	0.175	0.054	0.34
1	3	1	0	1	0	0.132	0.1093	0.09
3	1	2	0	1	0	0.207	0.214	0.09
0	2	19	0	1	0	0.048	0.287	0.15
173	1	9	0	1	0	0.486	0.098	0.61
1	43	16	0	0	0	0.458	0.0593	0.15
1	2	3	0	1	0	0.47	0.0108	0.17
4	3	1	0	1	0	0.237	0.0221	0.33
123	14	4	0	1	0	0.041	0.054	0.155
3	0	18	0	1	0	0.107	0.214	0.54
0	16	1	0	1	0	0.15	0.287	0.15
173	1	19	0	1	0	0.371	0.098	0.66

1	3	19	0	1	0	0.076	0.0593	0.85
1	3	9	0	1	0	0.125	0.0108	0.72
4	1	9	0	0	0	0.367	0.0221	0.18
123	1	15	0	1	0	0.587	0.054	0.09
1	1	3	0	1	0	0.174	0.1093	0.05
3	2	18	0	1	0	0.285	0.214	0.08
0	1	0	0	1	0	0.061	0.287	0.04
173	9	0	0	1	0	0.05	0.098	0.13
1	0	17	0	1	0	0.175	0.0593	0.4
1	3	0	0	1	0	0.132	0.0108	0.21
4	1	17	0	1	0	0.207	0.0221	0.11
123	2	39	0	1	0	0.048	0.054	0.04
123	1	4	0	0	0	0.486	0.054	0.03
3	1	8	0	1	0	0.587	0.214	0.09
0	1	2	0	1	0	0.174	0.287	0.09
173	2	0	0	1	0	0.285	0.098	0.19
1	1	4	0	1	0	0.061	0.0593	0.15
1	9	1	0	1	0	0.05	0.0108	0.15
4	0	2	0	1	0	0.175	0.0221	0.34
123	3	1	0	1	0	0.132	0.054	0.09
1	1	2	0	0	0	0.207	0.1093	0.09
3	2	19	0	1	0	0.048	0.214	0.15
0	1	9	0	1	0	0.486	0.287	0.61
173	9	16	0	1	0	0.05	0.098	0.15
1	0	3	0	1	0	0.175	0.0593	0.17
1	3	1	0	1	0	0.132	0.0108	0.33
4	1	4	0	1	0	0.207	0.0221	0.155
123	2	18	0	1	0	0.048	0.054	0.54
1	1	1	0	1	0	0.486	0.0593	0.15
1	2	19	0	1	0	0.048	0.0108	0.66
4	1	19	0	0	0	0.486	0.0221	0.85
123	2	9	0	1	0	0.048	0.054	0.72
1	1	9	0	1	0	0.486	0.1093	0.18
3	2	15	0	1	0	0.048	0.214	0.09
0	1	3	0	1	0	0.486	0.287	0.05
173	2	18	0	1	0	0.048	0.098	0.08
1	1	0	0	1	0	0.486	0.0593	0.04
1	2	18	0	1	0	0.048	0.0108	0.08
4	1	0	0	1	0	0.486	0.0221	0.04

DATA FOR 13 FEEDERS (Urban, Semi-urban and Rural Network)

%F1 (Semi-urban)

B1 =[17 19 4 4 3 3];

len1 =[0.2100,0.3100,0.8200,1.2600,2.1400,1.3100];

type\_of\_line1=[0;0;0;0;0;0];

%F5 (Urban)

```

B2 =[243  229  311  264  1];

len2 =[0.1810  0.2412  0.4590  0.3660  0.3390];

type_of_line2=[0;0;0;0;0];

%F4 (URBAN)

B3 =[406  75  269  265  279  1];

len3 =[0.5610  0.4220  0.2295  0.3436  0.3230  0.3050];

type_of_line3=[0;0;0;0;0;0];

% F17 (Urban)
B4 =[189  2  27  1  1];
len4 =[0.5610  0.4220  0.2295  0.3436  0.3230  0.3050];
type_of_line4=[0;0;0;0;0];

%F7 (URBAN)

B5 =[1  31  12  1  15  4  285];

len5 =[0.2184  0.2490  0.2390  0.0061  0.0730  0.0680  0.0573];

type_of_line5=[0;0;0;0;0;0;0];

% F8 (Urban)

B6 =[1  3  0  173  1  1  4  123];

len6 =[0.1093  0.2140  0.2870  0.0980  0.0593  0.0108  0.0221
0.0540];

type_of_line6=[0;0;0;0;0;0;0;0];

%F24 (urban)

B7 =[15  0  1  0  1  1];

len7 =[0.2251  0.1293  0.3100  0.5630  0.0240  0.0960];

type_of_line7=[0;0;0;0;0;0];

%%F26 (Urban)
B8 =[5  4  0  8  3];
len8 =[0.1661  0.0660  0.0033  0.0400  0.0399];
type_of_line8=[0;0;0;0;0];
% F23 (Urban)

```

```

B9 =[3      3      15      4      1];

len9 =[0.1796      0.1265      0.1786      0.0070      0.2150];

type_of_line9=[0;0;0;0;0];

%F6 (urban)

B10 =[159      395      141      282];

len10 =[0.3410      0.5645      0.2529      0.5912];

type_of_line10=[0;0;0;0];

% Rural
% F1
B11 =[14      2      1      64      1      4      1];
len11 =[0.3550      0.7850      0.3730      0.0070      0.5870      0.8900      0.3230];
type_of_line11=[1;1;1;1;1;1;1];

F8 Semi -urban

B =[1,1,0,5,165,2,43,2,3,14,0,16,1,3,3,1,1,1,2,1,9,0,3,1,2,1];

len
=[0.611,0.05,0.284,0.313,0.198,0.282,0.458,0.47,0.237,0.041,0.107,0.15,0.371,
0.076,0.125,0.367,0.587,0.174,0.285,0.061,0.05,0.175,0.132,0.207,0.048,0.486]
;

type_of_line=[1;1;1;1;1;1;1;1;1;1;1;1;1;1;1;1;1;1;1;1;1;1;1;1;1;1];

F2 Rural

B =[1      1      34      4      3      0      163      2      0      0      3      19];

len
=[ [0.388,0.081,0.365,0.041,0.076,0.486,0.199,0.13,0.277,0.313,0.36700,0.625];

type_of_line=[1;1;1;1;1;1;1;1;1;1;1;1];

```

## Data for All Networks (Urban, Semi-urban and Rural)

```
%***** URBAN NETWORK*****
```

```

%% F5
busdata1=[1 0 1 0 0.181 0 3.998 2.488 0
0 0 243
2 0 0.9961 0 0.2412 0.0006 0 0 0
0 0 229
3 0 0.9954 0 0.459 0.0004 0 0 0
0 0 311
4 0 0.9907 0 0.366 0.0004 0 0 0
0 0 264
5 0 0.9897 0 0.339 0.0004 0 0 0
0 0 1];

```

```

linedata=[ 1 2 0 0.057553059 0.029338327 0.000222 0.9033
2 3 0 0.102372035 0.097690387 0.000222 1
3 4 0 0.938951311 0.846067416 0.00023 1
4 5 0 0.255617978 0.298626717 0.00023 1];

```

```

%% F4
busdata=[1 0 1 0 0.561 0 3.998 2.488
0 0 0 406
2 0 0.9961 0 0.422 0.0006 0 0 0
0 0 75
3 0 0.9954 0 0.2295 0.0004 0 0 0
0 0 269
4 0 0.9907 0 0.3436 0.0004 0 0 0
0 0 265
5 0 0.9897 0 0.323 0.0004 0 0 0
0 0 279
6 0 0.9889 0 0.305 0.0004 0 0 0
0 0 1
];

```

```

linedata=[ 1 2 0 0.057553059 0.029338327 0.000222 0.9033
2 3 0 0.102372035 0.097690387 0.000222 1
3 4 0 0.938951311 0.846067416 0.00023 1
4 5 0 0.255617978 0.298626717 0.00023 1
5 6 0 0.442509363 0.585081149 0.00024 1
];

```

```

%% F17
busdata=[1 0 1 0 0.329 0 3.998 2.488
0 0 0 189
2 0 0.9961 0 0.255 0.0006 0 0 0
0 0 2
3 0 0.9954 0 0.198 0.0004 0 0 0
0 0 27
4 0 0.9907 0 0.327 0.0004 0 0 0
0 0 1
5 0 0.9897 0 0.359 0.0004 0 0 0
0 0 1
];

```

```

linedata=[ 1 2 0.057553059 0.029338327 0.000222 0.9033
2 3 0.102372035 0.097690387 0.000222 1
3 4 0.938951311 0.846067416 0.00023 1
4 5 0.255617978 0.298626717 0.00023 1
];

```

```

%% F2

```

```

busdata=[1      0  1      0      0.336      0      3.998  2.488
0      0      0      246
      2  0  0.9961  0      0.078      0.0006  0      0      0
0      0      445
      3  0  0.9954  0      0.268      0.0004  0      0      0
0      0      119
      4  0  0.9907  0      0.246      0.0004  0      0      0
0      0      0
      5  0  0.9897  0      0.015      0.0004  0      0      0
0      0      142
      6  0  0.9889  0      0.026      0.0004  0      0      0
0      0      263
      7  0  0.9889  0      0.146      0.0004  0      0      0
0      0      1
];

```

```

linedata=[ 1  2      0.057553059      0.029338327  0.000222      0.9033
2  3      0.102372035      0.097690387  0.000222      1
3  4      0.938951311      0.846067416  0.00023      1
4  5      0.255617978      0.298626717  0.00023      1
5  6      0.442509363      0.585081149  0.00024      1
6  7      0.442509363      0.585081149  0.00024      1
];

```

%% F11

```

busdata5=[1      0  1      0      0      0      3.998  2.488  0
0      0      306
      2  0  0.9961  0      0.263  0.0006  0      0      0
0      0      1
      3  0  0.9954  0      0.375  0.0004  0      0      0
0      0      0
      4  0  0.9907  0      0.105  0.0004  0      0      0
0      0      1
      5  0  0.9897  0      0.284  0.0004  0      0      0
0      0      262
];

```

```

linedata=[ 1  2      0.057553059      0.029338327  0.000222      0.9033
2  3      0.102372035      0.097690387  0.000222      1
3  4      0.938951311      0.846067416  0.00023      1
4  5      0.255617978      0.298626717  0.00023      1
];

```

%% F7

```

busdata=[1      0  1      0      0.2184      0      3.998  2.488  0
0      0      1
      2  0  0.9961  0      0.249      0.0006  0      0      0
0      0      31
      3  0  0.9954  0      0.239      0.0004  0      0      0
0      0      12
      4  0  0.9907  0      0.0061      0.0004  0      0      0
0      0      1
      5  0  0.9897  0      0.073      0.0004  0      0      0
0      0      15
      6  0  0.9889  0      0.068      0.0004  0      0      0
0      0      4
      7  0  0.9889  0      0.0573      0.0004  0      0      0
0      0      285
];

```



```

];

linedata=[ 1 2 0 0.057553059 0.029338327 0.000222 0.9033
           2 3 0 0.102372035 0.097690387 0.000222 1
           3 4 0 0.938951311 0.846067416 0.00023 1
           4 5 0 0.255617978 0.298626717 0.00023 1
           5 6 0 0.442509363 0.585081149 0.00024 1
           6 7 0 0.442509363 0.585081149 0.00024 1
];

%% F16
busdata7=[1 0 1 0 0.4041 0 3.998 2.488 0
           0 0 216
           2 0 0.9961 0 0.659 0.0006 0 0 0
           0 0 204
];

linedata=[ 1 2 0 0.057553059 0.029338327 0.000222 0.9033
];

%% F8
busdata=[1 0 1 0 0.1093 0 3.998 2.488 0 0
          0 1
          2 0 0.9961 0 0.214 0.0006 0 0 0
          0 0 3
          3 0 0.9954 0 0.287 0.0004 0 0 0
          0 0 0
          4 0 0.9907 0 0.098 0.0004 0 0 0
          0 0 173
          5 0 0.9897 0 0.0593 0.0004 0 0 0
          0 0 1
          6 0 0.9889 0 0.0108 0.0004 0 0 0
          0 0 1
          7 0 0.9889 0 0.0221 0.0004 0 0 0
          0 0 4
          8 0 0.9889 0 0.054 0.0004 0 0 0
          0 0 123
];

linedata=[ 1 2 0 0.057553059 0.029338327 0.000222 0.9033
           2 3 0 0.102372035 0.097690387 0.000222 1
           3 4 1 0.938951311 0.846067416 0.00023 1
           4 5 0 0.255617978 0.298626717 0.00023 1
           5 6 0 0.442509363 0.585081149 0.00024 1
           6 7 0 0.442509363 0.585081149 0.00024 1
           7 8 0 0.442509363 0.585081149 0.00024 1
];

%% F24
busdata=[1 0 1 0 0.2251 0 3.998 2.488 0 0
          0 15
          2 0 0.9961 0 0.1293 0.0006 0 0 0
          0 0 0
          3 0 0.9954 0 0.31 0.0004 0 0 0
          0 0 1
          4 0 0.9907 0 0.563 0.0004 0 0 0
          0 0 0
          5 0 0.9897 0 0.024 0.0004 0 0 0
          0 0 1
];

```

```

        6    0    0.9889    0        0.096    0.0004    0        0        0
0        0    1
];

linedata=[ 1    2    0    0.057553059    0.029338327    0.000222    0.9033
           2    3    1    0.102372035    0.097690387    0.000222    1
           3    4    0    0.938951311    0.846067416    0.00023    1
           4    5    1    0.255617978    0.298626717    0.00023    1
           5    6    0    0.442509363    0.585081149    0.00024    1
];

%% F25
busdata10=[1        0    1        0        0.0595        0        3.998
2.488    0    0        0    1
           2    0    0.9961    0        0.2004        0.0006    0        0        0
0        0    34
];

linedata=[ 1    2    0    0.057553059    0.029338327    0.000222    0.9033
];

%% F26
busdata17=[1        0    1        0        0.1661        0        3.998
2.488    0    0        0    5
           2    0    0.9961    0        0.066        0.0006    0        0
0    0        3    0    0.9954    0        0.0033        0.0004    0        0
0    0        4    0    0.9907    0        0.04        0.0004    0        0
0    0        5    0    0.9897    0        0.0399        0.0004    0        0
0    0        0    3
];

linedata=[ 1    2    0    0.057553059    0.029338327    0.000222    0.9033
           2    3    0    0.102372035    0.097690387    0.000222    1
           3    4    1    0.938951311    0.846067416    0.00023    1
           4    5    0    0.255617978    0.298626717    0.00023    1
];

%% F21
busdata11=[1        0    1        0        0.2174    0        3.998    2.488    0
0        0    52
           2    0    0.9961    0        0.1004    0.0006    0        0        0
0        0    13
           3    0    0.9954    0        0.0783    0.0004    0        0        0
0        0    2
];

linedata=[ 1    2    0    0.057553059    0.029338327    0.000222    0.9033
           2    3    0    0.102372035    0.097690387    0.000222    1
];

%% F23
busdata12=[1        0    1        0        0.1796    0        3.998    2.488    0
0        0    3
           2    0    0.9961    0        0.1265    0.0006    0        0        0
0        0    3
];

```

```

0      3      0      0.9954      0      0.1786      0.0004      0      0      0
0      0      15
0      4      0      0.9907      0      0.007      0.0004      0      0      0
0      0      4
0      5      0      0.9897      0      0.215      0.0004      0      0      0
0      0      1
];

linedata=[ 1  2  0  0.057553059  0.029338327  0.000222  0.9033
           2  3  0  0.102372035  0.097690387  0.000222  1
           3  4  0  0.938951311  0.846067416  0.00023  1
           4  5  0  0.255617978  0.298626717  0.00023  1
];

%% F28
busdata13=[1      0      1      0      0.3921      0      3.998      2.488
0      0      0      1
           2      0      0.9961      0      0.0016      0.0006      0      0      0
0      0      0
           3      0      0.9954      0      0.0059      0.0004      0      0      0
0      0      2
           4      0      0.9907      0      0.0043      0.0004      0      0      0
0      0      2
];

linedata=[ 1  2  0  0.057553059  0.029338327  0.000222  0.9033
           2  3  1  0.102372035  0.097690387  0.000222  1
           3  4  0  0.938951311  0.846067416  0.00023  1
];

%% F27
busdata14=[1      0      1      0      0.1725      0      3.998
2.488      0      0      0      2
           2      0      0.9961      0      0.834      0.0006      0      0
0      0      0      2
           3      0      0.9954      0      0.203      0.0004      0      0
0      0      0      1
           4      0      0.9907      0      0.135      0.0004      0      0
0      0      0      1
];

linedata=[ 1  2  0  0.057553059  0.029338327  0.000222  0.9033
           2  3  0  0.102372035  0.097690387  0.000222  1
           3  4  0  0.938951311  0.846067416  0.00023  1
];

%% F6
busdata15=[1      0      1      0      0.341      0      3.998      2.488
0      0      0      159
           2      0      0.9961      0      0.5645      0.0006      0      0      0
0      0      395
           3      0      0.9954      0      0.2529      0.0004      0      0      0
0      0      141
           4      0      0.9907      0      0.5912      0.0004      0      0      0
0      0      282
];

linedata=[ 1  2  0  0.057553059  0.029338327  0.000222  0.9033
           2  3  0  0.102372035  0.097690387  0.000222  1
           3  4  0  0.938951311  0.846067416  0.00023  1
];

```

```

%% F13
busdata16=[1      0      1      0      0.405      0      3.998      2.488
0      0      0      255
           2      0      0.9961      0      0.302      0.0006      0      0
0      0      111
           3      0      0.9954      0      0.2513      0.0004      0      0
0      0      212
];

```

```

linedata=[ 1  2  0  0.057553059  0.029338327  0.000222  0.9033
           2  3  0  0.102372035  0.097690387  0.000222  1
];

```

```

%%F18
busdata1=[1      0      1      0      1.042      0      3.998      2.488      0
0      0      21
           2      0      0.9961      0      0.398      0.0006      0      0
0      0      14
           3      0      0.9954      0      0.692      0.0004      0      0
0      0      1
           4      0      0.9907      0      0.557      0.0004      0      0
0      0      0
           5      0      0.9897      0      0.1384      0.0004      0      0
0      0      1
           6      0      0.9889      0      0.18415      0.0004      0      0
0      0      97];

```

```

linedata=[ 1  2  0  0.057553059  0.029338327  0.000222  0.9033
           2  3  0  0.102372035  0.097690387  0.000222  1
           3  4  0  0.938951311  0.846067416  0.00023  1
           4  5  1  0.255617978  0.298626717  0.00023  1
           4  6  2  0.442509363  0.585081149  0.00024  1];

```

```

%%F1
busdata2=[1      0      1      0      0.406      0      3.998      2.488      0
0      0      10
           2      0      0.9961      0      0.267      0.0006      0      0
0      0      0
           3      0      0.9954      0      0.266      0.0004      0      0
0      0      0
           4      0      0.9907      0      0.257      0.0004      0      0
0      0      321
           5      0      0.9897      0      0.8805      0.0004      0      0
0      0      257
           6      0      0.9889      0      0.1443      0.0004      0      0
0      0      1
           7      0      0.9889      0      0.002      0.0004      0      0
0      0      0
           8      0      0.9889      0      0.1384      0.0004      0      0
0      0      105
           9      0      0.9889      0      0.089      0.0004      0      0
0      0      1
           10     0      0.9889      0      0.191      0.0004      0      0
0      0      122];

```

```

linedata=[ 1  2  0  0.057553059  0.029338327  0.000222  0.9033
           2  3  0  0.102372035  0.097690387  0.000222  1
           3  4  0  0.938951311  0.846067416  0.00023  1
           4  5  0  0.255617978  0.298626717  0.00023  1
           3  6  0  0.442509363  0.585081149  0.00024  1

```

```

        6  7  0  0.442509363  0.585081149  0.00024  1
        7  8  1  0.442509363  0.585081149  0.00024  1
        8  9  0  0.442509363  0.585081149  0.00024  1
        9 10  0  0.442509363  0.585081149  0.00024  1];

%%F10
busdata3=[1  0  1  0  0.693  0  3.998  2.488  0
0  0  0
0  2  0  0.9961  0  0.38  0.0006  0  0  0
0  0  270
0  3  0  0.9954  0  0.013  0.0004  0  0  0
0  0  570];

linedata=[ 1  2  0  0.057553059  0.029338327  0.000222  0.9033
1  3  0  0.102372035  0.097690387  0.000222  1];

%% F3
busdata4=[1  0  1  0  0.199  0  3.998  2.488  0
0  0  1
0  2  0  0.9961  0  0.0762  0.0006  0  0  0
0  0  1
0  3  0  0.9954  0  0.5122  0.0004  0  0  0
0  0  0
0  4  0  0.9907  0  0.223  0.0004  0  0  0
0  0  316
0  5  0  0.9897  0  0.601  0.0004  0  0  0
0  0  222
0  6  0  0.9889  0  0.089  0.0004  0  0  0
0  0  1
0  7  0  0.9889  0  0.236  0.0004  0  0  0
0  0  5
0  8  0  0.9889  0  0.269  0.0004  0  0  0
0  0  10
0  9  0  0.9889  0  0.038  0.0004  0  0  0
0  0  1
0 10  0  0.9889  0  0.1173  0.0004  0  0  0
0  0  10];

linedata=[ 1  2  0  0.057553059  0.029338327  0.000222  0.9033
2  3  0  0.102372035  0.097690387  0.000222  1
3  4  0  0.938951311  0.846067416  0.00023  1
4  5  0  0.255617978  0.298626717  0.00023  1
3  6  0  0.442509363  0.585081149  0.00024  1
6  7  0  0.442509363  0.585081149  0.00024  1
7  8  0  0.442509363  0.585081149  0.00024  1
8  9  0  0.442509363  0.585081149  0.00024  1
9 10  0  0.442509363  0.585081149  0.00024  1];

%% F14
busdata5=[1  0  1  0  0.4121  0  3.998  2.488  0
0  0  59
0  2  0  0.9961  0  0.0337  0.0006  0  0  0
0  0  8
0  3  0  0.9954  0  0.0298  0.0004  0  0  0
0  0  79
0  4  0  0.9907  0  0.529  0.0004  0  0  0
0  0  0
0  5  0  0.9897  0  0.029  0.0004  0  0  0
0  0  4
0  6  0  0.9889  0  0.0609  0.0004  0  0  0
0  0  15
0  7  0  0.9889  0  0.02  0.0004  0  0  0
0  0  5];

```

```

linedata=[ 1 2 0 0.057553059 0.029338327 0.000222 0.9033
           2 3 0 0.102372035 0.097690387 0.000222 1
           3 4 0 0.938951311 0.846067416 0.00023 1
           4 5 0 0.255617978 0.298626717 0.00023 1
           4 6 0 0.442509363 0.585081149 0.00024 1
           6 7 0 0.442509363 0.585081149 0.00024 1];

```

```

%%F22
busdata6=[1 0 1 0 0.8156 0 3.998 2.488 0 0
0 42
           2 0 0.9961 0 0.2183 0.0006 0 0 0 0
0 0
           3 0 0.9954 0 0.4925 0.0004 0 0 0 0
0 1
           4 0 0.9907 0 0.057 0.0004 0 0 0 0
0 9
           5 0 0.9897 0 0.083 0.0004 0 0 0 0
0 21
];

```

```

linedata=[ 1 2 0 0.057553059 0.029338327 0.000222
0.9033
           2 3 0 0.102372035 0.097690387 0.000222 1
           2 4 0 0.938951311 0.846067416 0.00023 1
           4 5 0 0.255617978 0.298626717 0.00023 1
];

```

```

%% F20
busdata7=[1 0 1 0 0.3206 0 3.998 2.488
0 0 0 16
           2 0 0.9961 0 0.3006 0.0006 0 0 0
0 0 1
           3 0 0.9954 0 0.4067 0.0004 0 0 0
0 0 32
           4 0 0.9907 0 0.2272 0.0004 0 0 0
0 0 0
           5 0 0.9897 0 0.0583 0.0004 0 0 0
0 0 1
           6 0 0.9889 0 0.1014 0.0004 0 0 0
0 0 3];

```

```

linedata=[ 1 2 0 0.057553059 0.029338327 0.000222 0.9033
           2 3 0 0.102372035 0.097690387 0.000222 1
           3 4 0 0.938951311 0.846067416 0.00023 1
           4 5 0 0.255617978 0.298626717 0.00023 1
           4 6 0 0.442509363 0.585081149 0.00024 1];

```

```

%%F19
busdata8=[1 0 1 0 0.6563 0 3.998 2.488 0
0 0 0
           2 0 0.9961 0 0.179 0.0006 0 0 0
0 0 2
           3 0 0.9954 0 0.091 0.0004 0 0 0
0 0 1
           4 0 0.9907 0 0.0737 0.0004 0 0 0
0 0 1
           5 0 0.9897 0 0.0745 0.0004 0 0 0
0 0 73];

```

```

linedata=[ 1 2 0 0.057553059 0.029338327 0.000222 0.9033
           1 3 0 0.102372035 0.097690387 0.000222 1
           3 4 0 0.938951311 0.846067416 0.00023 1
           4 5 0 0.255617978 0.298626717 0.00023 1];

```

```
%%F12
```

```

busdata9=[1 0 1 0 0.7369 0 3.998 2.488 0
0 0 8
0 2 0 0.9961 0 0.034 0.0006 0 0
0 0 0
0 3 0 0.9954 0 0.0799 0.0004 0 0
0 0 3
0 4 0 0.9907 0 0.3598 0.0004 0 0
0 0 1
0 5 0 0.9897 0 0.2851 0.0004 0 0
0 0 2
0 6 0 0.9889 0 0.1907 0.0004 0 0
0 0 1
0 7 0 0.9889 0 0.1517 0.0004 0 0
0 0 1
0 8 0 0.9889 0 0.2949 0.0004 0 0
0 0 1
0 9 0 0.9889 0 0.609 0.0004 0 0
0 0 13
0 10 0 0.9889 0 0.4607 0.0004 0 0
0 0 2
0 11 0 0.9889 0 0.216 0.0004 0 0
0 0 116
0 12 0 0.9889 0 0.321 0.0004 0 0
0 0 1];

```

```

linedata=[ 1 2 0 0.057553059 0.029338327 0.000222 0.9033
           2 3 0 0.102372035 0.097690387 0.000222 1
           2 4 0 0.938951311 0.846067416 0.00023 1
           4 5 0 0.255617978 0.298626717 0.00023 1
           5 6 0 0.442509363 0.585081149 0.00024 1
           6 7 0 0.442509363 0.585081149 0.00024 1
           7 8 0 0.442509363 0.585081149 0.00024 1
           8 9 0 0.442509363 0.585081149 0.00024 1
           9 10 0 0.442509363 0.585081149 0.00024 1
           10 11 0 0.442509363 0.585081149 0.00024 1
           11 12 0 0.442509363 0.585081149 0.00024 1];

```

```
%%F9
```

```

busdata10=[1 0 1 0 0.1557 0 3.998 2.488 0
0 0 10
0 2 0 0.9961 0 0.219 0.0006 0 0
0 0 0
0 3 0 0.9954 0 0.3327 0.0004 0 0
0 0 40
0 4 0 0.9907 0 0.2658 0.0004 0 0
0 0 3
0 5 0 0.9897 0 0.103 0.0004 0 0
0 0 1
0 6 0 0.9889 0 0.072 0.0004 0 0
0 0 165
0 7 0 0.9889 0 0.134 0.0004 0 0
0 0 2

```

```

0      8      0      0.9889      0      0.103      0.0004      0      0
0      0      73];

```

```

linedata=[ 1  2  0  0.057553059  0.029338327  0.000222  0.9033
           2  3  0  0.102372035  0.097690387  0.000222  1
           2  4  0  0.938951311  0.846067416  0.00023  1
           4  5  0  0.255617978  0.298626717  0.00023  1
           5  6  0  0.442509363  0.585081149  0.00024  1
           6  7  0  0.442509363  0.585081149  0.00024  1
           7  8  0  0.442509363  0.585081149  0.00024  1];

```

```

%***** SEMI-URBAN NETWORK*****

```

```

%% F8
busdata2=[1  0  1  0  0.13  0  3.998  2.488  0
0  0  0
           2  0  0.9961  0  0.4  0.0006  0  0  0
0  0  17
           3  0  0.9954  0  0.21  0.0004  0  0  0
0  0  0
           4  0  0.9907  0  0.11  0.0004  0  0  0
0  0  17
           5  0  0.9897  0  0.04  0.0004  0  0  0
0  0  39
           6  0  0.9889  0  0.03  0.0004  0  0  0
0  0  4
           7  0  0.9889  0  0.09  0.0004  0  0  0
0  0  8
           8  0  0.9889  0  0.09  0.0004  0  0  0
0  0  2
           9  0  0.9889  0  0.19  0.0004  0  0  0
0  0  0
          10  0  0.9889  0  0.15  0.0004  0  0  0
0  0  4
          11  0  0.9889  0  0.15  0.0004  0  0  0
0  0  1
          12  0  0.9889  0  0.34  0.0004  0  0  0
0  0  2
          13  0  0.9889  0  0.09  0.0004  0  0  0
0  0  1
          14  0  0.9889  0  0.09  0.0004  0  0  0
0  0  2
          15  0  0.9889  0  0.15  0.0004  0  0  0
0  0  19
          16  0  0.9889  0  0.61  0.0004  0  0  0
0  0  9
          17  0  0.9889  0  0.15  0.0004  0  0  0
0  0  16
          18  0  0.9889  0  0.17  0.0004  0  0  0
0  0  3
          19  0  0.9889  0  0.33  0.0004  0  0  0
0  0  1
          20  0  0.9889  0  0.155  0.0004  0  0  0
0  0  4
          21  0  0.9889  0  0.54  0.0004  0  0  0
0  0  18
          22  0  0.9889  0  0.15  0.0004  0  0  0
0  0  1
          23  0  0.9889  0  0.66  0.0004  0  0  0
0  0  19

```



```

0      24  0    0.9889  0      0.85  0.0004  0      0      0
0      0   19
0      25  0    0.9889  0      0.72  0.0004  0      0      0
0      0    9
0      26  0    0.9889  0      0.18  0.0004  0      0      0
0      0    9
0      27  0    0.9889  0      0.09  0.0004  0      0      0
0      0   15
0      28  0    0.9889  0      0.05  0.0004  0      0      0
0      0    3
0      29  0    0.9889  0      0.08  0.0004  0      0      0
0      0   18
0      30  0    0.9889  0      0.04  0.0004  0      0      0
0      0    0
];

```

```

%
%                               Line code
%      Bus bus   R      X      1/2 B   = 1 for lines
%      nl  nr   p.u.  p.u.  p.u.      > 1 or < 1 tr. tap at bus nl
linedata=[  1  2  0  0.057553059  0.029338327  0.000222  0.9033
           1  3  0  0.102372035  0.097690387  0.000222  1
           3  4  0  0.255617978  0.298626717  0.00023  1
           4  5  0  0.442509363  0.585081149  0.00024  1
           5  6  0  0.442509363  0.585081149  0.00024  1
           6  7  0  0.442509363  0.585081149  0.00024  1
           7  8  0  0.442509363  0.585081149  0.00024  1
           8  9  0  0.442509363  0.585081149  0.00024  1
           9 10  0  0.442509363  0.585081149  0.00024  1
          10 11  0  0.442509363  0.585081149  0.00024  1
           8 12  0  0.442509363  0.585081149  0.00024  1
          12 13  0  0.442509363  0.585081149  0.00024  1
          13 14  0  0.442509363  0.585081149  0.00024  1
          14 15  0  0.442509363  0.585081149  0.00024  1
          15 16  0  0.442509363  0.585081149  0.00024  1
          16 17  0  0.442509363  0.585081149  0.00024  1
          17 18  0  0.442509363  0.585081149  0.00024  1
          18 19  0  0.442509363  0.585081149  0.00024  1
          19 20  0  0.442509363  0.585081149  0.00024  1
          20 21  0  0.442509363  0.585081149  0.00024  1
          21 22  0  0.442509363  0.585081149  0.00024  1
          22 23  0  0.442509363  0.585081149  0.00024  1
          23 24  0  0.442509363  0.585081149  0.00024  1
          20 25  0  0.442509363  0.585081149  0.00024  1
          25 26  0  0.442509363  0.585081149  0.00024  1
          26 27  0  0.442509363  0.585081149  0.00024  1
          27 28  0  0.442509363  0.585081149  0.00024  1
          28 29  0  0.442509363  0.585081149  0.00024  1
          29 30  0  0.442509363  0.585081149  0.00024  1
];

```

```

%% F5
%%
busdata3=[1  0  1  0  0.21  0  3.998  2.488  0
0      0  0
0      2  0  0.9961  0  0.3  0.0006  0  0  0
0      0  4
0      3  0  0.9954  0  0.3  0.0004  0  0  0
0      0  19
0      4  0  0.9907  0  0.24  0.0004  0  0  0
0      0  19

```

```

0      5  0  0.9897  0      0.1  0.0004  0      0      0
0      0  9
0      6  0  0.9889  0      0.45  0.0004  0      0      0
0      0  4
0      7  0  0.9889  0      0.27  0.0004  0      0      0
0      0  3
0      8  0  0.9889  0      0.41  0.0004  0      0      0
0      0  9
0      9  0  0.9889  0      0.85  0.0004  0      0      0
0      0  4
0     10  0  0.9889  0      1.25  0.0004  0      0      0
0      0  4
0     11  0  0.9889  0      0.56  0.0004  0      0      0
0      0  1
0     12  0  0.9889  0      1.3   0.0004  0      0      0
0      0  3
0     13  0  0.9889  0      0.16  0.0004  0      0      0
0      0  0
0     14  0  0.9889  0      0.23  0.0004  0      0      0
0      0  11
0     15  0  0.9889  0      0.34  0.0004  0      0      0
0      0  17
0     16  0  0.9889  0      0.34  0.0004  0      0      0
0      0  28
0     17  0  0.9889  0      0.2   0.0004  0      0      0
0      0  3
0     18  0  0.9889  0      0.06  0.0004  0      0      0
0      0  3
];

```

```

%                               Line code
%      Bus bus  R      X      1/2 B  = 1 for lines
%      nl  nr  p.u.  p.u.  p.u.      > 1 or < 1 tr. tap at bus nl
linedata=[ 1  2  0  0.057553059  0.029338327  0.000222  0.9033
           2  3  0  0.102372035  0.097690387  0.000222  1
           1  4  0  0.938951311  0.846067416  0.00023  1
           4  5  0  0.255617978  0.298626717  0.00023  1
           5  6  0  0.442509363  0.585081149  0.00024  1
           6  7  0  0.442509363  0.585081149  0.00024  1
           7  8  0  0.442509363  0.585081149  0.00024  1
           8  9  0  0.442509363  0.585081149  0.00024  1
           9 10  0  0.442509363  0.585081149  0.00024  1
          10 11  0  0.442509363  0.585081149  0.00024  1
          11 12  0  0.442509363  0.585081149  0.00024  1
          12 13  0  0.442509363  0.585081149  0.00024  1
          13 14  0  0.442509363  0.585081149  0.00024  1
          13 15  0  0.442509363  0.585081149  0.00024  1
          15 16  0  0.442509363  0.585081149  0.00024  1
          16 17  0  0.442509363  0.585081149  0.00024  1
          17 18  0  0.442509363  0.585081149  0.00024  1
];

```

```

%% F6
busdata4=[1  0  1      0      0.26  0      3.998  2.488  0
0      0  17
           2  0  0.9961  0      0.3   0.0006  0      0      0
0      0  19
           3  0  0.9954  0      0.12  0.0004  0      0      0
0      0  4
           4  0  0.9907  0      0.72  0.0004  0      0      0
0      0  0

```

```

0      5  0  0.9897  0  1.2  0.0004  0  0  0
0      0  1
0      6  0  0.9889  0  0.4  0.0004  0  0  0
0      0  3
0      7  0  0.9889  0  0.35  0.0004  0  0  0
0      0  1
0      8  0  0.9889  0  0.84  0.0004  0  0  0
0      0  1
0      9  0  0.9889  0  0.14  0.0004  0  0  0
0      0  4
0     10  0  0.9889  0  0.287  0.0004  0  0  0
0      0  9
0     11  0  0.9889  0  0.87  0.0004  0  0  0
0      0  4
0     12  0  0.9889  0  0.21  0.0004  0  0  0
0      0  3
0     13  0  0.9889  0  0.51  0.0004  0  0  0
0      0  43
0     14  0  0.9889  0  0.59  0.0004  0  0  0
0      0  3
0     15  0  0.9889  0  0.5  0.0004  0  0  0
0      0  4
0     16  0  0.9889  0  0.38  0.0004  0  0  0
0      0  9
0     17  0  0.9889  0  1.16  0.0004  0  0  0
0      0  4
0     18  0  0.9889  0  0.61  0.0004  0  0  0
0      0  1
0     19  0  0.9889  0  0.5  0.0004  0  0  0
0      0  4
0     20  0  0.9889  0  1.05  0.0004  0  0  0
0      0  1
0     21  0  0.9889  0  0.42  0.0004  0  0  0
0      0  3
0     22  0  0.9889  0  0.65  0.0004  0  0  0
0      0  17
];

```

```

%
%                               Line code
%      Bus bus   R      X      1/2 B   = 1 for lines
%      nl  nr  p.u.  p.u.  p.u.      > 1 or < 1 tr. tap at bus nl
linedata=[ 1  2  1  0.057553059  0.029338327  0.000222  0.9033
           2  3  0  0.102372035  0.097690387  0.000222  1
           3  4  0  0.938951311  0.846067416  0.00023  1
           4  5  0  0.255617978  0.298626717  0.00023  1
           5  6  0  0.442509363  0.585081149  0.00024  1
           6  7  0  0.442509363  0.585081149  0.00024  1
           7  8  0  0.442509363  0.585081149  0.00024  1
           8  9  0  0.442509363  0.585081149  0.00024  1
           9 10  0  0.442509363  0.585081149  0.00024  1
          10 11  0  0.442509363  0.585081149  0.00024  1
          11 12  0  0.442509363  0.585081149  0.00024  1
          12 13  0  0.442509363  0.585081149  0.00024  1
          13 14  0  0.442509363  0.585081149  0.00024  1
          14 15  0  0.442509363  0.585081149  0.00024  1
          15 16  0  0.442509363  0.585081149  0.00024  1
          16 17  0  0.442509363  0.585081149  0.00024  1
          17 18  0  0.442509363  0.585081149  0.00024  1
          18 19  0  0.442509363  0.585081149  0.00024  1
          19 20  0  0.442509363  0.585081149  0.00024  1
          20 21  0  0.442509363  0.585081149  0.00024  1

```

```

21 22 0 0.442509363 0.585081149 0.00024 1
];

```

```

%% F4
busdata5=[1 0 1 0 0.1 0 3.998 2.488 0 0
0 4
2 0 0.9961 0 0.16 0.0006 0 0 0 0
0 3
3 0 0.9954 0 0.72 0.0004 0 0 0 0
0 0
4 0 0.9907 0 0.13 0.0004 0 0 0 0
0 9
5 0 0.9897 0 1.22 0.0004 0 0 0 0
0 74
6 0 0.9889 0 0.5 0.0004 0 0 0 0
0 4
7 0 0.9889 0 0.5 0.0004 0 0 0 0
0 4
8 0 0.9889 0 0.5 0.0004 0 0 0 0
0 1
9 0 0.9889 0 0.5 0.0004 0 0 0 0
0 0
10 0 0.9889 0 0.5 0.0004 0 0 0 0
0 4
11 0 0.9889 0 0.76 0.0004 0 0 0 0
0 5
12 0 0.9889 0 0.45 0.0004 0 0 0 0
0 3
13 0 0.9889 0 0.45 0.0004 0 0 0 0
0 4
14 0 0.9889 0 0.21 0.0004 0 0 0 0
0 9
15 0 0.9889 0 0.36 0.0004 0 0 0 0
0 5
];

```

```

%
% Line code
% Bus bus R X 1/2 B = 1 for lines
% nl nr p.u. p.u. p.u. > 1 or < 1 tr. tap at bus nl
linedata=[ 1 2 0 0.057553059 0.029338327 0.000222 0.9033
2 3 0 0.102372035 0.097690387 0.000222 1
3 4 0 0.938951311 0.846067416 0.00023 1
3 5 0 0.255617978 0.298626717 0.00023 1
5 6 0 0.442509363 0.585081149 0.00024 1
6 7 0 0.442509363 0.585081149 0.00024 1
7 8 0 0.442509363 0.585081149 0.00024 1
8 9 0 0.442509363 0.585081149 0.00024 1
9 10 0 0.442509363 0.585081149 0.00024 1
4 11 0 0.442509363 0.585081149 0.00024 1
11 12 0 0.442509363 0.585081149 0.00024 1
12 13 0 0.442509363 0.585081149 0.00024 1
13 14 0 0.442509363 0.585081149 0.00024 1
14 15 0 0.442509363 0.585081149 0.00024 1
];

```

```

%% F1
busdata6=[1 0 1 0 0.21 0 3.998 2.488 0
0 0 17
2 0 0.9961 0 0.31 0.0006 0 0 0
0 0 19

```

```

0      3  0  0.9954  0      0.82  0.0004  0      0      0
0      0  4
0      4  0  0.9907  0      1.26  0.0004  0      0      0
0      0  4
0      5  0  0.9897  0      2.14  0.0004  0      0      0
0      0  3
0      6  0  0.9889  0      1.31  0.0004  0      0      0
0      0  3
];

%
%                               Line code
%      Bus bus  R      X      1/2 B  = 1 for lines
%      nl  nr  p.u.  p.u.  p.u.    > 1 or < 1 tr. tap at bus nl
linedata=[ 1  2  0  0.057553059  0.029338327  0.000222  0.9033
           2  3  0  0.102372035  0.097690387  0.000222  1
           3  4  0  0.938951311  0.846067416  0.00023  1
           4  5  0  0.255617978  0.298626717  0.00023  1
           5  6  0  0.442509363  0.585081149  0.00024  1
];

% Kidwelly Main feeder -1 NOP and 2 branches F7
busdata7=[1  0  1  0      0.15  0      3.998  2.488  0
0      0  9
           2  0  0.9961  0      0.15  0.0006  0      0      0
0      0  3
           3  0  0.9954  0      0.13  0.0004  0      0      0
0      0  15
           4  0  0.9907  0      0.09  0.0004  0      0      0
0      0  7
           5  0  0.9897  0      0.35  0.0004  0      0      0
0      0  3
           6  0  0.9889  0      0.06  0.0004  0      0      0
0      0  1
           7  0  0.9889  0      0.213  0.0004  0      0      0
0      0  1
           8  0  0.9889  0      0.07  0.0004  0      0      0
0      0  29
           9  0  0.9889  0      1.101  0.0004  0      0      0
0      0  3
          10  0  0.9889  0      0.63  0.0004  0      0      0
0      0  0
          11  0  0.9889  0      0.17  0.0004  0      0      0
0      0  3
          12  0  0.9889  0      0.343  0.0004  0      0      0
0      0  21
          13  0  0.9889  0      0.47  0.0004  0      0      0
0      0  23
          14  0  0.9889  0      0.83  0.0004  0      0      0
0      0  1
          15  0  0.9889  0      0.04  0.0004  0      0      0
0      0  4
          16  0  0.9889  0      0.38  0.0004  0      0      0
0      0  5
          17  0  0.9889  0      0.144  0.0004  0      0      0
0      0  1
          18  0  0.9889  0      0.667  0.0004  0      0      0
0      0  4
          19  0  0.9889  0      0.535  0.0004  0      0      0
0      0  18
          20  0  0.9889  0      0.42  0.0004  0      0      0
0      0  0

```

```

0      21  0      0.9889  0      0.3      0.0004  0      0      0
0      0      1
0      22  0      0.9889  0      1.04     0.0004  0      0      0
0      0      3
0      23  0      0.9889  0      0.51     0.0004  0      0      0
0      0      3
0      24  0      0.9889  0      0.635    0.0004  0      0      0
0      0      3
0      25  0      0.9889  0      0.11     0.0004  0      0      0
0      0      35
0      26  0      0.9889  0      1.45     0.0004  0      0      0
0      0      19
0      27  0      0.9889  0      0.91     0.0004  0      0      0
0      0      3
];

```

```

%
%                               Line code
%      Bus bus   R      X      1/2 B   = 1 for lines
%      nl  nr   p.u.  p.u.  p.u.      > 1 or < 1 tr. tap at bus nl
linedata=[ 1  2  0  0.057553059 0.029338327 0.000222 0.9033
           2  3  0  0.102372035 0.097690387 0.000222 1
           3  4  0  0.938951311 0.846067416 0.00023 1
           4  5  0  0.255617978 0.298626717 0.00023 1
           5  6  0  0.442509363 0.585081149 0.00024 1
           6  7  0  0.442509363 0.585081149 0.00024 1
           7  8  0  0.442509363 0.585081149 0.00024 1
           8  9  0  0.442509363 0.585081149 0.00024 1
           9 10  0  0.442509363 0.585081149 0.00024 1
          10 11  1  0.442509363 0.585081149 0.00024 1
          11 12  0  0.442509363 0.585081149 0.00024 1
          12 13  0  0.442509363 0.585081149 0.00024 1
          13 14  0  0.442509363 0.585081149 0.00024 1
          14 15  0  0.442509363 0.585081149 0.00024 1
          15 16  0  0.442509363 0.585081149 0.00024 1
          16 17  0  0.442509363 0.585081149 0.00024 1
          17 18  0  0.442509363 0.585081149 0.00024 1
          18 19  0  0.442509363 0.585081149 0.00024 1
          19 20  0  0.442509363 0.585081149 0.00024 1
          20 21  0  0.442509363 0.585081149 0.00024 1
          20 22  0  0.442509363 0.585081149 0.00024 1
          22 23  0  0.442509363 0.585081149 0.00024 1
          23 24  0  0.442509363 0.585081149 0.00024 1
          24 25  0  0.442509363 0.585081149 0.00024 1
          25 26  0  0.442509363 0.585081149 0.00024 1
          26 27  0  0.442509363 0.585081149 0.00024 1];

```

```

%% F3
busdata8=[1  0  1      0      0.11     0      3.998  2.488  0
0      0  55
0      2  0  0.9961  0      0.12     0.0006  0      0      0
0      0  17
0      3  0  0.9954  0      1.3      0.0004  0      0      0
0      0  19
0      4  0  0.9907  0      0.62     0.0004  0      0      0
0      0  15
0      5  0  0.9897  0      0.21     0.0004  0      0      0
0      0  17
0      6  0  0.9889  0      0.64     0.0004  0      0      0
0      0  0
0      7  0  0.9889  0      0.3      0.0004  0      0      0
0      0  1

```

```

0      8  0  0.9889  0      0.3      0.0004  0      0      0
0      0  17
0      9  0  0.9889  0      0.37     0.0004  0      0      0
0      0  15
0     10  0  0.9889  0      0.57     0.0004  0      0      0
0      0  17
0     11  0  0.9889  0      0.44     0.0004  0      0      0
0      0  3
0     12  0  0.9889  0      0.7      0.0004  0      0      0
0      0  4
0     13  0  0.9889  0      0.32     0.0004  0      0      0
0      0  15
];

```

```

%
%           Line code
%      Bus bus  R      X      1/2 B  = 1 for lines
%      nl  nr  p.u.  p.u.  p.u.      > 1 or < 1 tr. tap at bus nl
linedata=[ 1  2  0  0.057553059  0.029338327  0.000222  0.9033
           2  3  0  0.102372035  0.097690387  0.000222  1
           3  4  0  0.938951311  0.846067416  0.00023  1
           4  5  0  0.255617978  0.298626717  0.00023  1
           5  6  0  0.442509363  0.585081149  0.00024  1
           6  7  0  0.442509363  0.585081149  0.00024  1
           7  8  0  0.442509363  0.585081149  0.00024  1
           6  9  0  0.442509363  0.585081149  0.00024  1
           9  10 0  0.442509363  0.585081149  0.00024  1
          10 11 0  0.442509363  0.585081149  0.00024  1
          11 12 0  0.442509363  0.585081149  0.00024  1
          12 13 0  0.442509363  0.585081149  0.00024  1];

```

```

%% F2
busdata9=[1  0  1      0      0.5      0      3.998  2.488  0
0      0  19
0      2  0  0.9961  0      0.3      0.0006  0      0      0
0      0  17
0      3  0  0.9954  0      0.39     0.0004  0      0      0
0      0  19
0      4  0  0.9907  0      0.3      0.0004  0      0      0
0      0  17
0      5  0  0.9897  0      0.51     0.0004  0      0      0
0      0  17
0      6  0  0.9889  0      0.26     0.0004  0      0      0
0      0  17
0      7  0  0.9889  0      0.07     0.0004  0      0      0
0      0  8
0      8  0  0.9889  0      0.5      0.0004  0      0      0
0      0  9
];

```

```

%
%           Line code
%      Bus bus  R      X      1/2 B  = 1 for lines
%      nl  nr  p.u.  p.u.  p.u.      > 1 or < 1 tr. tap at bus nl
linedata=[ 1  2  0  0.057553059  0.029338327  0.000222  0.9033
           2  3  0  0.102372035  0.097690387  0.000222  1
           3  4  0  0.938951311  0.846067416  0.00023  1
           4  5  0  0.255617978  0.298626717  0.00023  1
           5  6  0  0.442509363  0.585081149  0.00024  1
           6  7  0  0.442509363  0.585081149  0.00024  1
           7  8  1  0.442509363  0.585081149  0.00024  1
];

```

```
***** RURAL NETWORK*****
```

```
%% F1
```

```
busdata1=[1 0 1 0 0.355 0 3.998 2.488 0
0 0 14
0 2 0 0.9961 0 0.785 0.0006 0 0 0
0 0 2
0 3 0 0.9954 0 0.373 0.0004 0 0 0
0 0 1
0 4 0 0.9907 0 0.007 0.0004 0 0 0
0 0 64
0 5 0 0.9897 0 0.587 0.0004 0 0 0
0 0 1
0 6 0 0.9889 0 0.89 0.0004 0 0 0
0 0 4
0 7 0 0.9889 0 0.323 0.0004 0 0 0
0 0 1
];
```

```
%
% Line code
% Bus bus R X 1/2 B = 1 for lines
% nl nr p.u. p.u. p.u. > 1 or < 1 tr. tap at bus nl
linedata=[ 1 2 0 0.057553059 0.029338327 0.000222 0.9033
2 3 0 0.102372035 0.097690387 0.000222 1
3 4 0 0.938951311 0.846067416 0.00023 1
4 5 0 0.255617978 0.298626717 0.00023 1
5 6 0 0.442509363 0.585081149 0.00024 1
6 7 0 0.442509363 0.585081149 0.00024 1
];
```

```
%%FEEDER F8
```

```
busdata2=[1 0 1 0 0.611 0 3.998 2.488 0
0 0 1
0 2 0 0.9961 0 0.05 0.0006 0 0 0
0 0 1
0 3 0 0.9954 0 0.284 0.0004 0 0 0
0 0 0
0 4 0 0.9907 0 0.313 0.0004 0 0 0
0 0 5
0 5 0 0.9897 0 0.198 0.0004 0 0 0
0 0 165
0 6 0 0.9889 0 0.282 0.0004 0 0 0
0 0 2
0 7 0 0.9889 0 0.458 0.0004 0 0 0
0 0 43
0 8 0 0.9889 0 0.47 0.0004 0 0 0
0 0 2
0 9 0 0.9889 0 0.237 0.0004 0 0 0
0 0 3
0 10 0 0.9889 0 0.041 0.0004 0 0 0
0 0 14
0 11 0 0.9889 0 0.107 0.0004 0 0 0
0 0 0
0 12 0 0.9889 0 0.15 0.0004 0 0 0
0 0 16
0 13 0 0.9889 0 0.371 0.0004 0 0 0
0 0 1
```



```

0      14 0      0.9889 0      0.076      0.0004 0      0      0
0      0 3
0      15 0      0.9889 0      0.125      0.0004 0      0      0
0      0 3
0      16 0      0.9889 0      0.367      0.0004 0      0      0
0      0 1
0      17 0      0.9889 0      0.587      0.0004 0      0      0
0      0 1
0      18 0      0.9889 0      0.174      0.0004 0      0      0
0      0 1
0      19 0      0.9889 0      0.285      0.0004 0      0      0
0      0 2
0      20 0      0.9889 0      0.061      0.0004 0      0      0
0      0 1
0      21 0      0.9889 0      0.05       0.0004 0      0      0
0      0 9
0      22 0      0.9889 0      0.175      0.0004 0      0      0
0      0 0
0      23 0      0.9889 0      0.132      0.0004 0      0      0
0      0 3
0      24 0      0.9889 0      0.207      0.0004 0      0      0
0      0 1
0      25 0      0.9889 0      0.048      0.0004 0      0      0
0      0 2
0      26 0      0.9889 0      0.486      0.0004 0      0      0
0      0 1
];

```

```

%
%                               Line code
%      Bus bus  R      X      1/2 B  = 1 for lines
%      nl  nr  p.u.  p.u.  p.u.      > 1 or < 1 tr. tap at bus nl
linedata=[ 1  2  0      0.057553059 0.029338327 0.000222 0.9033
           2  3  0      0.102372035 0.097690387 0.000222 1
           3  4  0      0.938951311 0.846067416 0.00023 1
           4  5  0      0.255617978 0.298626717 0.00023 1
           5  6  0      0.442509363 0.585081149 0.00024 1
           6  7  0      0.442509363 0.585081149 0.00024 1
           7  8  0      0.442509363 0.585081149 0.00024 1
           8  9  0      0.442509363 0.585081149 0.00024 1
           9 10  0      0.442509363 0.585081149 0.00024 1
          10 11  0      0.442509363 0.585081149 0.00024 1
          11 12  0      0.442509363 0.585081149 0.00024 1
          12 13  0      0.442509363 0.585081149 0.00024 1
          13 14  0      0.442509363 0.585081149 0.00024 1
          14 15  0      0.442509363 0.585081149 0.00024 1
          15 16  0      0.442509363 0.585081149 0.00024 1
          16 17  0      0.442509363 0.585081149 0.00024 1
          17 18  0      0.442509363 0.585081149 0.00024 1
          18 19  0      0.442509363 0.585081149 0.00024 1
          19 20  0      0.442509363 0.585081149 0.00024 1
          20 21  0      0.442509363 0.585081149 0.00024 1
          21 22  0      0.442509363 0.585081149 0.00024 1
          22 23  0      0.442509363 0.585081149 0.00024 1
          23 24  0      0.442509363 0.585081149 0.00024 1
          24 25  0      0.442509363 0.585081149 0.00024 1
          25 26  0      0.442509363 0.585081149 0.00024 1
];

```

```
%% F9
```

```

busdata3=[1 0 1 0 0.005 0 3.998 2.488 0
0 0 1
0 2 0 0.9961 0 0.373 0.0006 0 0 0
0 0 3
0 3 0 0.9954 0 0.039 0.0004 0 0 0
0 0 18
0 4 0 0.9907 0 0.11415 0.0004 0 0 0
0 0 4
0 5 0 0.9897 0 0.3210 0.0004 0 0 0
0 0 23
0 6 0 0.9889 0 0.65 0.0004 0 0 0
0 0 1
0 7 0 0.9889 0 0.172 0.0004 0 0 0
0 0 2
0 8 0 0.9889 0 0.048 0.0004 0 0 0
0 0 3
0 9 0 0.9889 0 0.0338 0.0004 0 0 0
0 0 1
0 10 0 0.9889 0 0.331 0.0004 0 0 0
0 0 35
0 11 0 0.9889 0 0.039 0.0004 0 0 0
0 0 1
0 12 0 0.9889 0 0.625 0.0004 0 0 0
0 0 6
0 13 0 0.9889 0 0.021 0.0004 0 0 0
0 0 6
0 14 0 0.9889 0 0.227 0.0004 0 0 0
0 0 11
0 15 0 0.9889 0 0.177 0.0004 0 0 0
0 0 2
0 16 0 0.9889 0 0.139 0.0004 0 0 0
0 0 31
0 17 0 0.9889 0 0.259 0.0004 0 0 0
0 0 3
0 18 0 0.9889 0 0.625 0.0004 0 0 0
0 0 4
0 19 0 0.9889 0 0.541 0.0004 0 0 0
0 0 22
0 20 0 0.9889 0 0.336 0.0004 0 0 0
0 0 1
0 21 0 0.9889 0 0.139 0.0004 0 0 0
0 0 5
0 22 0 0.9889 0 0.267 0.0004 0 0 0
0 0 7
0 23 0 0.9889 0 0.57 0.0004 0 0 0
0 0 3
0 24 0 0.9889 0 0.01 0.0004 0 0 0
0 0 1
0 25 0 0.9889 0 0.217 0.0004 0 0 0
0 0 19
0 26 0 0.9889 0 0.37 0.0004 0 0 0
0 0 16
0 27 0 0.9889 0 0.47 0.0004 0 0 0
0 0 28
0 28 0 0.9889 0 0.222 0.0004 0 0 0
0 0 4
0 29 0 0.9889 0 0.508 0.0004 0 0 0
0 0 57
0 30 0 0.9889 0 0.162 0.0004 0 0 0
0 0 1

```

```

0      31 0      0.9889 0      0.1      0.0004 0      0      0
0      0  1
0      32 0      0.9889 0      0.089    0.0004 0      0      0
0      0  2
0      33 0      0.9889 0      0.574    0.0004 0      0      0
0      0  7
0      34 0      0.9889 0      0.36     0.0004 0      0      0
0      0  1
0      35 0      0.9889 0      0.075    0.0004 0      0      0
0      0  4
0      36 0      0.9889 0      0.073    0.0004 0      0      0
0      0  1
0      37 0      0.9889 0      0.331    0.0004 0      0      0
0      0  3
0      38 0      0.9889 0      0.337    0.0004 0      0      0
0      0  2
0      39 0      0.9889 0      0.423    0.0004 0      0      0
0      0  0
0      40 0      0.9889 0      0.65     0.0004 0      0      0
0      0  15
0      41 0      0.9889 0      0.47     0.0004 0      0      0
0      0  2
0      42 0      0.9889 0      0.225    0.0004 0      0      0
0      0  1
];

```

```

%                               Line code
%                               = 1 for lines
%                               > 1 or < 1 tr. tap at bus nl
%                               nl nr R X 1/2 B
linedata=[ 1 2 0 0.057553059 0.029338327 0.000222 0.9033
           2 3 0 0.102372035 0.097690387 0.000222 1
           3 4 0 0.938951311 0.846067416 0.00023 1
           4 5 0 0.255617978 0.298626717 0.00023 1
           5 6 0 0.442509363 0.585081149 0.00024 1
           6 7 0 0.442509363 0.585081149 0.00024 1
           7 8 0 0.442509363 0.585081149 0.00024 1
           8 9 0 0.442509363 0.585081149 0.00024 1
           9 10 0 0.442509363 0.585081149 0.00024 1
          10 11 0 0.442509363 0.585081149 0.00024 1
          11 12 0 0.442509363 0.585081149 0.00024 1
          12 13 0 0.442509363 0.585081149 0.00024 1
          13 14 0 0.442509363 0.585081149 0.00024 1
          14 15 0 0.442509363 0.585081149 0.00024 1
          15 16 0 0.442509363 0.585081149 0.00024 1
          16 17 0 0.442509363 0.585081149 0.00024 1
          17 18 0 0.442509363 0.585081149 0.00024 1
          18 19 0 0.442509363 0.585081149 0.00024 1
          3 20 0 0.442509363 0.585081149 0.00024 1
          20 21 0 0.442509363 0.585081149 0.00024 1
          21 22 0 0.442509363 0.585081149 0.00024 1
          22 23 0 0.442509363 0.585081149 0.00024 1
          23 24 0 0.442509363 0.585081149 0.00024 1
          24 25 0 0.442509363 0.585081149 0.00024 1
          25 26 0 0.442509363 0.585081149 0.00024 1
          26 27 0 0.442509363 0.585081149 0.00024 1
          27 28 0 0.442509363 0.585081149 0.00024 1
          28 29 0 0.442509363 0.585081149 0.00024 1
          29 30 0 0.442509363 0.585081149 0.00024 1
          30 31 0 0.442509363 0.585081149 0.00024 1
          31 32 0 0.442509363 0.585081149 0.00024 1

```

```

32 33 0 0.442509363 0.585081149 0.00024 1
33 34 0 0.442509363 0.585081149 0.00024 1
34 35 0 0.442509363 0.585081149 0.00024 1
35 36 0 0.442509363 0.585081149 0.00024 1
36 37 0 0.442509363 0.585081149 0.00024 1
37 38 0 0.442509363 0.585081149 0.00024 1
38 39 0 0.442509363 0.585081149 0.00024 1
39 40 0 0.442509363 0.585081149 0.00024 1
40 41 0 0.442509363 0.585081149 0.00024 1
41 42 0 0.442509363 0.585081149 0.00024 1
];

%% F2
busdata4=[1 0 1 0 0.388 0 3.998 2.488 0
0 0 1
0 2 0 0.9961 0 0.081 0.0006 0 0 0
0 0 1
0 3 0 0.9954 0 0.365 0.0004 0 0 0
0 0 34
0 4 0 0.9907 0 0.041 0.0004 0 0 0
0 0 4
0 5 0 0.9897 0 0.076 0.0004 0 0 0
0 0 3
0 6 0 0.9889 0 0.486 0.0004 0 0 0
0 0 0
0 7 0 0.9961 0 0.199 0.0006 0 0 0
0 0 163
0 8 0 0.9954 0 0.13 0.0004 0 0 0
0 0 2
0 9 0 0.9907 0 0.277 0.0004 0 0 0
0 0 0
0 10 0 0.9897 0 0.313 0.0004 0 0 0
0 0 0
0 11 0 0.9889 0 0.367 0.0004 0 0 0
0 0 3
0 12 0 0.9889 0 0.625 0.0004 0 0 0
0 0 19
];

linedata=[ 1 2 0 0.057553059 0.029338327 0.000222 0.9033
2 3 0 0.102372035 0.097690387 0.000222 1
3 4 0 0.938951311 0.846067416 0.00023 1
4 5 0 0.255617978 0.298626717 0.00023 1
5 6 0 0.442509363 0.585081149 0.00024 1
6 7 0 0.057553059 0.029338327 0.000222 0.9033
7 8 0 0.102372035 0.097690387 0.000222 1
8 9 0 0.938951311 0.846067416 0.00023 1
9 10 0 0.255617978 0.298626717 0.00023 1
10 11 0 0.442509363 0.585081149 0.00024 1
11 12 0 0.255617978 0.298626717 0.00023 1
];

%% F3
busdata5=[1 0 1 0 0.041 0 3.998 2.488 0
0 0 2
0 2 0 0.9961 0 0.267 0.0006 0 0 0
0 0 5
0 3 0 0.9954 0 0.058 0.0004 0 0 0
0 0 2
0 4 0 0.9907 0 0.205 0.0004 0 0 0
0 0 1

```

```

0      5      0      0.9897      0      0.466      0.0004      0      0
0      0      17
0      6      0      0.9889      0      0.2      0.0004      0      0
0      0      3
0      7      0      0.9961      0      0.076      0.0006      0      0
0      0      0
0      8      0      0.9954      0      0.105      0.0004      0      0
0      0      3
0      9      0      0.9907      0      0.423      0.0004      0      0
0      0      0
0      10     0      0.9897      0      0.386      0.0004      0      0
0      0      0
0      11     0      0.9889      0      0.507      0.0004      0      0
0      0      0
0      12     0      0.9889      0      0.327      0.0004      0      0
0      0      1
0      13     0      0.9889      0      0.076      0.0004      0      0
0      0      0
];

```

```

linedata=[ 1  2  0  0.057553059  0.029338327  0.000222  0.9033
           2  3  0  0.102372035  0.097690387  0.000222  1
           3  4  0  0.938951311  0.846067416  0.00023  1
           4  5  0  0.255617978  0.298626717  0.00023  1
           5  6  0  0.442509363  0.585081149  0.00024  1
           6  7  0  0.057553059  0.029338327  0.000222  0.9033
           7  8  0  0.102372035  0.097690387  0.000222  1
           8  9  0  0.938951311  0.846067416  0.00023  1
           9 10  0  0.255617978  0.298626717  0.00023  1
          10 11  0  0.442509363  0.585081149  0.00024  1
          10 12  0  0.255617978  0.298626717  0.00023  1
          12 13  0  0.442509363  0.585081149  0.00024  1
];

```

```

];
%% F4
busdata6=[1  0  1      0      0.552      0      3.998      2.488      0
0      0      19
0      2      0      0.9961      0      0.331      0.0006      0      0
0      0      50
0      3      0      0.9954      0      0.65      0.0004      0      0
0      0      1
0      4      0      0.9907      0      0.736      0.0004      0      0
0      0      2
0      5      0      0.9897      0      0.835      0.0004      0      0
0      0      13
0      6      0      0.9889      0      0.366      0.0004      0      0
0      0      0
0      7      0      0.9961      0      0.132      0.0006      0      0
0      0      0
0      8      0      0.9954      0      0.073      0.0004      0      0
0      0      1
0      9      0      0.9907      0      0.27      0.0004      0      0
0      0      3
0      10     0      0.9897      0      0.188      0.0004      0      0
0      0      69
0      11     0      0.9889      0      0.458      0.0004      0      0
0      0      1
0      12     0      0.9889      0      0.444      0.0004      0      0
0      0      0
];

```

```

linedata=[ 1  2  0  0.057553059  0.029338327  0.000222  0.9033

```

```

2 3 0 0.102372035 0.097690387 0.000222 1
3 4 0 0.938951311 0.846067416 0.00023 1
4 5 0 0.255617978 0.298626717 0.00023 1
5 6 0 0.442509363 0.585081149 0.00024 1
6 7 0 0.057553059 0.029338327 0.000222 0.9033
7 8 0 0.102372035 0.097690387 0.000222 1
8 9 0 0.938951311 0.846067416 0.00023 1
9 10 0 0.255617978 0.298626717 0.00023 1
10 11 0 0.442509363 0.585081149 0.00024 1
11 12 0 0.255617978 0.298626717 0.00023 1
];

```

```
%% F6
```

```

busdata7=[1 0 1 0 0.736 0 3.998 2.488 0
0 0 42
0 2 0 0.9961 0 0.19 0.0006 0 0 0
0 0 1
0 3 0 0.9954 0 0.048 0.0004 0 0 0
0 0 2
0 4 0 0.9907 0 0.674 0.0004 0 0 0
0 0 1
0 5 0 0.9897 0 0.259 0.0004 0 0 0
0 0 1
0 6 0 0.9889 0 0.444 0.0004 0 0 0
0 0 1
0 7 0 0.9961 0 0.213 0.0006 0 0 0
0 0 1
0 8 0 0.9954 0 0.675 0.0004 0 0 0
0 0 3
0 9 0 0.9907 0 0.126 0.0004 0 0 0
0 0 35
0 10 0 0.9897 0 0.174 0.0004 0 0 0
0 0 1
0 11 0 0.9889 0 0.785 0.0004 0 0 0
0 0 155
0 12 0 0.9889 0 0.158 0.0004 0 0 0
0 0 1
0 13 0 0.9889 0 0.222 0.0004 0 0 0
0 0 1
0 14 0 0.9954 0 0.213 0.0004 0 0 0
0 0 2
0 15 0 0.9907 0 0.171 0.0004 0 0 0
0 0 23
0 16 0 0.9897 0 0.03 0.0004 0 0 0
0 0 1
0 17 0 0.9889 0 0.6 0.0004 0 0 0
0 0 8
0 18 0 0.9889 0 0.198 0.0004 0 0 0
0 0 4
0 19 0 0.9889 0 0.061 0.0004 0 0 0
0 0 1
0 20 0 0.9954 0 0.185 0.0004 0 0 0
0 0 1
0 21 0 0.9907 0 0.155 0.0004 0 0 0
0 0 12
0 22 0 0.9897 0 0.184 0.0004 0 0 0
0 0 2
0 23 0 0.9889 0 0.057 0.0004 0 0 0
0 0 1

```

```

0      24  0  0.9889  0      0.504      0.0004  0      0      0
0      0  61
0      25  0  0.9889  0      0.207      0.0004  0      0      0
0      0  0
0      26  0  0.9954  0      0.294      0.0004  0      0      0
0      0  1
0      27  0  0.9907  0      0.327      0.0004  0      0      0
0      0  26
0      28  0  0.9897  0      0.42      0.0004  0      0      0
0      0  2
0      29  0  0.9889  0      0.015      0.0004  0      0      0
0      0  1
0      30  0  0.9889  0      0.569      0.0004  0      0      0
0      0  54
];

```

```

linedata=[ 1  2  0  0.057553059  0.029338327  0.000222  0.9033
2  3  0  0.102372035  0.097690387  0.000222  1
3  4  0  0.938951311  0.846067416  0.00023  1
4  5  0  0.255617978  0.298626717  0.00023  1
5  6  0  0.442509363  0.585081149  0.00024  1
6  7  0  0.057553059  0.029338327  0.000222  0.9033
7  8  0  0.102372035  0.097690387  0.000222  1
8  9  0  0.938951311  0.846067416  0.00023  1
9  10  0  0.255617978  0.298626717  0.00023  1
10 11  0  0.442509363  0.585081149  0.00024  1
11 12  0  0.255617978  0.298626717  0.00023  1
12 13  0  0.442509363  0.585081149  0.00024  1
13 14  0  0.442509363  0.585081149  0.00024  1
14 15  0  0.057553059  0.029338327  0.000222  0.9033
15 16  0  0.102372035  0.097690387  0.000222  1
16 17  0  0.938951311  0.846067416  0.00023  1
17 18  0  0.255617978  0.298626717  0.00023  1
18 19  0  0.442509363  0.585081149  0.00024  1
19 20  0  0.255617978  0.298626717  0.00023  1
20 21  0  0.442509363  0.585081149  0.00024  1
21 22  0  0.442509363  0.585081149  0.00024  1
22 23  0  0.057553059  0.029338327  0.000222  0.9033
23 24  0  0.102372035  0.097690387  0.000222  1
24 25  0  0.938951311  0.846067416  0.00023  1
25 26  1  0.255617978  0.298626717  0.00023  1
26 27  0  0.442509363  0.585081149  0.00024  1
27 28  0  0.255617978  0.298626717  0.00023  1
28 29  0  0.442509363  0.585081149  0.00024  1
29 30  0  0.442509363  0.585081149  0.00024  1
];

```

```

%% F10
busdata8=[1  0  1      0  0.89  0      3.998  2.488  0  0  0
7
0      2  0  0.9961  0  0.236  0.0006  0      0      0  0  0
0      7
0      3  0  0.9954  0  0.107  0.0004  0      0      0  0  0
0      1
0      4  0  0.9907  0  0.217      0.0004  0      0      0
0      0  1
0      5  0  0.9897  0      0.116      0.0004  0      0      0
0      0  6
0      6  0  0.9889  0      0.048      0.0004  0      0      0
0      0  16
0      7  0  0.9961  0      0.08      0.0006  0      0      0
0      0  3

```

0	8	0	0.9954	0	0.271	0.0004	0	0	0
0	0	0							
0	9	0	0.9907	0	0.125	0.0004	0	0	0
0	0	0							
0	10	0	0.9897	0	0.076	0.0004	0	0	0
0	0	1							
0	11	0	0.9889	0	0.217	0.0004	0	0	0
0	0	20							
0	12	0	0.9889	0	0.125	0.0004	0	0	0
0	0	4							
0	13	0	0.9889	0	0.221	0.0004	0	0	0
0	0	166							
0	14	0	0.9954	0	0.42	0.0004	0	0	0
0	0	7							
0	15	0	0.9907	0	0.57	0.0004	0	0	0
0	0	68							
0	16	0	0.9897	0	0.146	0.0004	0	0	0
0	0	0							
0	17	0	0.9889	0	0.4	0.0004	0	0	0
0	0	46							
0	18	0	0.9889	0	0.197	0.0004	0	0	0
0	0	1							
0	19	0	0.9889	0	0.2	0.0004	0	0	0
0	0	6							
0	20	0	0.9954	0	0.225	0.0004	0	0	0
0	0	2							
0	21	0	0.9907	0	0.226	0.0004	0	0	0
0	0	0							
0	22	0	0.9897	0	0.728	0.0004	0	0	0
0	0	2							
0	23	0	0.9889	0	0.26	0.0004	0	0	0
0	0	1							
0	24	0	0.9889	0	0.205	0.0004	0	0	0
0	0	7							
0	25	0	0.9889	0	0.005	0.0004	0	0	0
0	0	23							
0	26	0	0.9954	0	0.386	0.0004	0	0	0
0	0	2							
0	27	0	0.9907	0	0.486	0.0004	0	0	0
0	0	0							
0	28	0	0.9897	0	0.089	0.0004	0	0	0
0	0	2							
0	29	0	0.9889	0	0.08	0.0004	0	0	0
0	0	1							
0	30	0	0.9889	0	0.122	0.0004	0	0	0
0	0	3							
0	31	0	0.9889	0	0.281	0.0004	0	0	0
0	0	66							
0	32	0	0.9889	0	0.089	0.0004	0	0	0
0	0	1							
0	33	0	0.9889	0	0.735	0.0004	0	0	0
0	0	12							
0	34	0	0.9889	0	0.42	0.0004	0	0	0
0	0	1							
0	35	0	0.9889	0	0.173	0.0004	0	0	0
0	0	3							
0	36	0	0.9889	0	0.491	0.0004	0	0	0
0	0	0							
0	37	0	0.9889	0	0.338	0.0004	0	0	0
0	0	1							



```

0      38  0  0.9889  0      0.048  0.0004  0      0      0
0      0  1
0      39  0  0.9889  0      0.367  0.0004  0      0      0
0      0  3
0      40  0  0.9889  0      0.42   0.0004  0      0      0
0      0  0
0      41  0  0.9889  0      0.105  0.0004  0      0      0
0      0  44
0      42  0  0.9889  0      0.037  0.0004  0      0      0
0      0  4
0      43  0  0.9889  0      0.288  0.0004  0      0      0
0      0  0
0      44  0  0.9889  0      0.436  0.0004  0      0      0
0      0  9
0      45  0  0.9889  0      0.177  0.0004  0      0      0
0      0  0
0      46  0  0.9889  0      0.271  0.0004  0      0      0
0      0  35
0      47  0  0.9889  0      0.125  0.0004  0      0      0
0      0  16
0      48  0  0.9889  0      0.099  0.0004  0      0      0
0      0  2
0      49  0  0.9889  0      0.224  0.0004  0      0      0
0      0  3
0      50  0  0.9889  0      0.728  0.0004  0      0      0
0      0  5
0      51  0  0.9889  0      0.222  0.0004  0      0      0
0      0  0
0      52  0  0.9889  0      0.225  0.0004  0      0      0
0      0  4
0      53  0  0.9889  0      0.47   0.0004  0      0      0
0      0  39
0      54  0  0.9889  0      0.287  0.0004  0      0      0
0      0  24
0      55  0  0.9889  0      0.285  0.0004  0      0      0
0      0  0
0      56  0  0.9889  0      0.126  0.0004  0      0      0
0      0  166
0      57  0  0.9889  0      0.105  0.0004  0      0      0
0      0  29
0      58  0  0.9889  0      0.048  0.0004  0      0      0
0      0  29
0      59  0  0.9889  0      0.173  0.0004  0      0      0
0      0  3
0      60  0  0.9889  0      0.199  0.0004  0      0      0
0      0  0
0      61  0  0.9889  0      0.674  0.0004  0      0      0
0      0  2
0      62  0  0.9889  0      0.048  0.0004  0      0      0
0      0  0
];

```

```

%
%                               Line code
%      Bus bus   R      X      1/2 B   = 1 for lines
%      nl  nr  p.u.  p.u.  p.u.      > 1 or < 1 tr. tap at bus nl
linedata=[  1   2   0  0.057553059  0.029338327  0.000222  0.9033
           2   3   0  0.102372035  0.097690387  0.000222  1
           3   4   0  0.938951311  0.846067416  0.00023   1
           4   5   0  0.255617978  0.298626717  0.00023   1
           5   6   0  0.442509363  0.585081149  0.00024   1

```

6	7	0	0.442509363	0.585081149	0.00024	1
7	8	0	0.442509363	0.585081149	0.00024	1
8	9	0	0.442509363	0.585081149	0.00024	1
9	10	0	0.442509363	0.585081149	0.00024	1
10	11	0	0.442509363	0.585081149	0.00024	1
11	12	0	0.442509363	0.585081149	0.00024	1
12	13	0	0.442509363	0.585081149	0.00024	1
13	14	0	0.442509363	0.585081149	0.00024	1
14	15	0	0.442509363	0.585081149	0.00024	1
15	16	0	0.442509363	0.585081149	0.00024	1
8	17	0	0.442509363	0.585081149	0.00024	1
17	18	0	0.442509363	0.585081149	0.00024	1
18	19	0	0.442509363	0.585081149	0.00024	1
19	20	0	0.442509363	0.585081149	0.00024	1
20	21	0	0.442509363	0.585081149	0.00024	1
21	22	0	0.442509363	0.585081149	0.00024	1
22	23	0	0.442509363	0.585081149	0.00024	1
23	24	0	0.442509363	0.585081149	0.00024	1
24	25	0	0.442509363	0.585081149	0.00024	1
25	26	0	0.442509363	0.585081149	0.00024	1
26	27	0	0.442509363	0.585081149	0.00024	1
27	28	0	0.442509363	0.585081149	0.00024	1
28	29	0	0.442509363	0.585081149	0.00024	1
29	30	0	0.442509363	0.585081149	0.00024	1
30	31	0	0.442509363	0.585081149	0.00024	1
31	32	0	0.442509363	0.585081149	0.00024	1
32	33	0	0.442509363	0.585081149	0.00024	1
33	34	0	0.442509363	0.585081149	0.00024	1
34	35	0	0.442509363	0.585081149	0.00024	1
35	36	0	0.442509363	0.585081149	0.00024	1
36	37	0	0.442509363	0.585081149	0.00024	1
37	38	0	0.442509363	0.585081149	0.00024	1
38	39	0	0.442509363	0.585081149	0.00024	1
39	40	0	0.442509363	0.585081149	0.00024	1
40	41	0	0.442509363	0.585081149	0.00024	1
41	42	0	0.442509363	0.585081149	0.00024	1
42	43	0	0.442509363	0.585081149	0.00024	1
43	44	0	0.442509363	0.585081149	0.00024	1
44	45	0	0.442509363	0.585081149	0.00024	1
45	46	0	0.442509363	0.585081149	0.00024	1
46	47	0	0.442509363	0.585081149	0.00024	1
47	48	0	0.442509363	0.585081149	0.00024	1
48	49	0	0.442509363	0.585081149	0.00024	1
49	50	0	0.442509363	0.585081149	0.00024	1
50	51	0	0.442509363	0.585081149	0.00024	1
51	52	0	0.442509363	0.585081149	0.00024	1
52	53	0	0.442509363	0.585081149	0.00024	1
53	54	0	0.442509363	0.585081149	0.00024	1
54	55	0	0.442509363	0.585081149	0.00024	1
55	56	0	0.442509363	0.585081149	0.00024	1
56	57	0	0.442509363	0.585081149	0.00024	1
57	58	0	0.442509363	0.585081149	0.00024	1
58	59	0	0.442509363	0.585081149	0.00024	1
59	60	0	0.442509363	0.585081149	0.00024	1
60	61	0	0.442509363	0.585081149	0.00024	1
61	62	0	0.442509363	0.585081149	0.00024	1

];

```

%% F7
busdata9=[1 0 1 0 0.313 0 3.998 2.488 0
0 0 1
2 0 0.9961 0 0.226 0.0006 0 0 0
0 0 2
3 0 0.9961 0 0.386 0.0006 0 0 0
0 0 2
4 0 0.9954 0 0.08 0 0 0 0
0 0 5
5 0 0.9907 0 0.198 0.0004 0 0 0
0 0 1
6 0 0.9897 0 0.45 0.0004 0 0 0
0 0 6
7 0 0.9889 0 0.107 0.0004 0 0 0
0 0 1
8 0 0.9889 0 0.507 0.0004 0 0 0
0 0 7
9 0 0.9889 0 0.259 0.0004 0 0 0
0 0 5
10 0 0.9889 0 0.076 0.0004 0 0 0
0 0 2
11 0 0.9889 0 0.288 0.0004 0 0 0
0 0 3
12 0 0.9889 0 0.674 0.0004 0 0 0
0 0 3
13 0 0.9889 0 0.835 0.0004 0 0 0
0 0 39
14 0 0.9889 0 0.285 0.0004 0 0 0
0 0 1
15 0 0.9889 0 0.524 0.0004 0 0 0
0 0 1
16 1 0.9889 0 0.345 0.0004 0 0 0
0 0 1
17 0 0.9889 0 0.211 0.0004 0 0 0
0 0 0
18 0 0.9889 0 0.561 0.0004 0 0 0
0 0 1
19 0 0.9889 0 0.835 0.0004 0 0 0
0 0 1
20 0 0.9889 0 0.073 0.0004 0 0 0
0 0 5
21 0 0.9889 0 0.587 0.0004 0 0 0
0 0 29
22 0 0.9889 0 0.405 0.0004 0 0 0
0 0 1
23 0 0.9889 0 0.194 0.0004 0 0 0
0 0 1
24 0 0.9889 0 0.717 0.0004 0 0 0
0 0 1
];

```

```

%
% Line code
% Bus bus R X 1/2 B = 1 for lines
% nl nr p.u. p.u. p.u. > 1 or < 1 tr. tap at bus nl
linedata=[ 1 2 0 0.057553059 0.029338327 0.000222 0.9033
2 3 0 0.102372035 0.097690387 0.000222 1
3 4 0 0.938951311 0.846067416 0.00023 1
4 5 0 0.255617978 0.298626717 0.00023 1
5 6 0 0.442509363 0.585081149 0.00024 1
6 7 0 0.442509363 0.585081149 0.00024 1
7 8 0 0.442509363 0.585081149 0.00024 1

```

8	9	0	0.442509363	0.585081149	0.00024	1
9	10	0	0.442509363	0.585081149	0.00024	1
10	11	0	0.442509363	0.585081149	0.00024	1
11	12	0	0.442509363	0.585081149	0.00024	1
12	13	0	0.442509363	0.585081149	0.00024	1
13	14	0	0.442509363	0.585081149	0.00024	1
14	15	0	0.442509363	0.585081149	0.00024	1
15	16	0	0.442509363	0.585081149	0.00024	1
16	17	1	0.442509363	0.585081149	0.00024	1
17	18	0	0.442509363	0.585081149	0.00024	1
18	19	0	0.442509363	0.585081149	0.00024	1
19	20	0	0.442509363	0.585081149	0.00024	1
20	21	0	0.442509363	0.585081149	0.00024	1
21	22	0	0.442509363	0.585081149	0.00024	1
22	23	0	0.442509363	0.585081149	0.00024	1
23	24	0	0.442509363	0.585081149	0.00024	1

];

%% F5

```
busdata=[1 0 1 0 0.179 0 3.998 2.488 0 0
0 1
2 0 0.9961 0 0.285 0.0006 0 0 0
0 0 1
3 0 0.9954 0 0.199 0.0004 0 0 0
0 0 5
4 0 0.9907 0 0.13 0.0004 0 0 0
0 0 2
5 0 0.9897 0 0.05 0.0004 0 0 0
0 0 2
6 0 0.9889 0 0.287 0.0004 0 0 0
0 0 3
7 0 0.9889 0 0.89 0.0004 0 0 0
0 0 2
8 0 0.9889 0 0.039 0.0004 0 0 0
0 0 1
9 0 0.9889 0 0.26 0.0004 0 0 0
0 0 1
10 0 0.9889 0 0.364 0.0004 0 0 0
0 0 2
11 0 0.9889 0 0.423 0.0004 0 0 0
0 0 12
12 0 0.9889 0 0.259 0.0004 0 0 0
0 0 5
13 0 0.9889 0 0.1 0.0004 0 0 0
0 0 16
14 0 0.9889 0 0.491 0.0004 0 0 0
0 0 3
15 0 0.9889 0 0.03 0.0004 0 0 0
0 0 42
16 0 0.9889 0 0.125 0.0004 0 0 0
0 0 2
17 0 0.9889 0 0.076 0.0004 0 0 0
0 0 4
18 0 0.9889 0 0.075 0.0004 0 0 0
0 0 106
19 0 0.9889 0 0.336 0.0004 0 0 0
0 0 1
20 0 0.9889 0 0.285 0.0004 0 0 0
0 0 2
```

```

0      21  0    0.9889  0      0.381    0.0004  0      0      0
0      0   38
0      22  0    0.9889  0      0.334    0.0004  0      0      0
0      0   1
0      23  0    0.9889  0      0.039    0.0004  0      0      0
0      0   4
0      24  0    0.9889  0      0.048    0.0004  0      0      0
0      0   4
0      25  0    0.9889  0      0.611    0.0004  0      0      0
0      0   1
0      26  0    0.9889  0      0.263    0.0004  0      0      0
0      0   1
0      27  0    0.9889  0      0.295    0.0004  0      0      0
0      0   1
0      28  0    0.9889  0      0.224    0.0004  0      0      0
0      0   6
0      29  0    0.9889  0      0.35     0.0004  0      0      0
0      0   3
0      30  0    0.9889  0      0.09     0.0004  0      0      0
0      0   2
0      31  0    0.9889  0      0.148    0.0004  0      0      0
0      0   1
0      32  0    0.9889  0      0.47     0.0004  0      0      0
0      0   4
0      33  0    0.9889  0      0.321    0.0004  0      0      0
0      0   2
0      34  0    0.9889  0      0.342    0.0004  0      0      0
0      0   2
0      35  0    0.9889  0      0.31     0.0004  0      0      0
0      0   1
0      36  0    0.9889  0      0.55     0.0004  0      0      0
0      0   2
0      37  0    0.9889  0      0.217    0.0004  0      0      0
0      0   2
0      38  0    0.9889  0      0.209    0.0004  0      0      0
0      0  189
0      39  0    0.9889  0      0.217    0.0004  0      0      0
0      0   1
0      40  0    0.9889  0      0.316    0.0004  0      0      0
0      0   2
0      41  0    0.9889  0      0.115    0.0004  0      0      0
0      0   1
0      42  0    0.9889  0      0.557    0.0004  0      0      0
0      0  169
0      43  0    0.9889  0      0.309    0.0004  0      0      0
0      0   1
0      44  0    0.9889  0      0.321    0.0004  0      0      0
0      0   5
0      45  0    0.9889  0      0.259    0.0004  0      0      0
0      0   1
];

```

```

%                               Line code
%      Bus bus   R      X      1/2 B   = 1 for lines
%      nl  nr   p.u.   p.u.   p.u.     > 1 or < 1 tr. tap at bus nl
linedata=[  1   2   0   0.057553059 0.029338327 0.000222  0.9033
           2   3   0   0.102372035 0.097690387 0.000222  1
           3   4   0   0.938951311 0.846067416 0.00023   1
           4   5   0   0.255617978 0.298626717 0.00023   1
           5   6   0   0.442509363 0.585081149 0.00024   1

```

```

6 7 0 0.442509363 0.585081149 0.00024 1
7 8 0 0.442509363 0.585081149 0.00024 1
8 9 0 0.442509363 0.585081149 0.00024 1
9 10 0 0.442509363 0.585081149 0.00024 1
10 11 0 0.442509363 0.585081149 0.00024 1
11 12 0 0.442509363 0.585081149 0.00024 1
12 13 0 0.442509363 0.585081149 0.00024 1
13 14 0 0.442509363 0.585081149 0.00024 1
14 15 0 0.442509363 0.585081149 0.00024 1
15 16 0 0.442509363 0.585081149 0.00024 1
16 17 0 0.442509363 0.585081149 0.00024 1
17 18 0 0.442509363 0.585081149 0.00024 1
18 19 0 0.442509363 0.585081149 0.00024 1
19 20 0 0.442509363 0.585081149 0.00024 1
20 21 0 0.442509363 0.585081149 0.00024 1
21 22 0 0.442509363 0.585081149 0.00024 1
22 23 0 0.442509363 0.585081149 0.00024 1
23 24 0 0.442509363 0.585081149 0.00024 1
24 25 0 0.442509363 0.585081149 0.00024 1
25 26 0 0.442509363 0.585081149 0.00024 1
23 27 0 0.442509363 0.585081149 0.00024 1
27 28 0 0.442509363 0.585081149 0.00024 1
28 29 0 0.442509363 0.585081149 0.00024 1
29 30 0 0.442509363 0.585081149 0.00024 1
30 31 0 0.442509363 0.585081149 0.00024 1
31 32 0 0.442509363 0.585081149 0.00024 1
32 33 0 0.442509363 0.585081149 0.00024 1
33 34 0 0.442509363 0.585081149 0.00024 1
34 35 0 0.442509363 0.585081149 0.00024 1
35 36 0 0.442509363 0.585081149 0.00024 1
36 37 0 0.442509363 0.585081149 0.00024 1
37 38 0 0.442509363 0.585081149 0.00024 1
38 39 0 0.442509363 0.585081149 0.00024 1
39 40 0 0.442509363 0.585081149 0.00024 1
40 41 0 0.442509363 0.585081149 0.00024 1
41 42 0 0.442509363 0.585081149 0.00024 1
42 43 0 0.442509363 0.585081149 0.00024 1
43 44 0 0.442509363 0.585081149 0.00024 1
44 45 0 0.442509363 0.585081149 0.00024 1
];

```

```

%% F11
busdata11=[1 0 1 0 0.211 0 3.998 2.488
0 0 0 1
0 2 0 0.9961 0 0.061 0.0006 0 0 0
0 0 3
0 3 0 0.9954 0 0.209 0.0004 0 0 0
0 0 2
0 4 0 0.9907 0 0.337 0.0004 0 0 0
0 0 4
0 5 0 0.9897 0 0.337 0.0004 0 0 0
0 0 1
0 6 0 0.9889 0 0.01 0.0004 0 0 0
0 0 2
0 7 0 0.9889 0 0.288 0.0004 0 0 0
0 0 0
0 8 0 0.9889 0 0.466 0.0004 0 0 0
0 0 1
0 9 0 0.9889 0 0.277 0.0004 0 0 0
0 0 3

```

0	10	0	0.9889	0	0.185	0.0004	0	0	0
0	0	1							
0	11	0	0.9889	0	0.505	0.0004	0	0	0
0	0	154							
0	12	0	0.9889	0	0.148	0.0004	0	0	0
0	0	0							
0	13	0	0.9889	0	0.336	0.0004	0	0	0
0	0	43							
0	14	0	0.9889	0	0.046	0.0004	0	0	0
0	0	2							
0	15	0	0.9889	0	0.288	0.0004	0	0	0
0	0	39							
0	16	0	0.9889	0	0.08	0.0004	0	0	0
0	0	16							
0	17	0	0.9889	0	0.184	0.0004	0	0	0
0	0	3							
0	18	0	0.9889	0	0.309	0.0004	0	0	0
0	0	3							
0	19	0	0.9889	0	0.172	0.0004	0	0	0
0	0	1							
0	20	0	0.9889	0	0.041	0.0004	0	0	0
0	0	5							
0	21	0	0.9889	0	0.27	0.0004	0	0	0
0	0	1							
0	22	0	0.9889	0	0.561	0.0004	0	0	0
0	0	1							
0	23	0	0.9889	0	0.005	0.0004	0	0	0
0	0	1							
0	24	0	0.9889	0	0.432	0.0004	0	0	0
0	0	8							
0	25	0	0.9889	0	0.99	0.0004	0	0	0
0	0	5							
0	26	0	0.9889	0	0.146	0.0004	0	0	0
0	0	1							
0	27	0	0.9889	0	0.407	0.0004	0	0	0
0	0	1							
0	28	0	0.9889	0	0.42	0.0004	0	0	0
0	0	4							
0	29	0	0.9889	0	0.835	0.0004	0	0	0
0	0	2							
0	30	0	0.9889	0	0.104	0.0004	0	0	0
0	0	9							
0	31	0	0.9889	0	0.287	0.0004	0	0	0
0	0	2							
0	32	0	0.9889	0	0.4	0.0004	0	0	0
0	0	60							
0	33	0	0.9889	0	0.073	0.0004	0	0	0
0	0	1							
0	34	0	0.9889	0	0.434	0.0004	0	0	0
0	0	1							
0	35	0	0.9889	0	0.728	0.0004	0	0	0
0	0	3							
0	36	0	0.9889	0	0.09	0.0004	0	0	0
0	0	19							
0	37	0	0.9889	0	0.061	0.0004	0	0	0
0	0	2							

];

```

%
%                               Line code
%      Bus bus   R      X      1/2 B   = 1 for lines
%      nl  nr  p.u.  p.u.  p.u.      > 1 or < 1 tr. tap at bus nl
linedata=[ 1  2  0  0.057553059 0.029338327 0.000222 0.9033
           2  3  1  0.102372035 0.097690387 0.000222 1
           3  4  0  0.938951311 0.846067416 0.00023 1
           4  5  0  0.255617978 0.298626717 0.00023 1
           5  6  0  0.442509363 0.585081149 0.00024 1
           6  7  1  0.442509363 0.585081149 0.00024 1
           7  8  0  0.442509363 0.585081149 0.00024 1
           8  9  0  0.442509363 0.585081149 0.00024 1
           9 10  0  0.442509363 0.585081149 0.00024 1
          10 11  0  0.442509363 0.585081149 0.00024 1
          11 12  0  0.442509363 0.585081149 0.00024 1
          12 13  0  0.442509363 0.585081149 0.00024 1
          13 14  0  0.442509363 0.585081149 0.00024 1
          14 15  0  0.442509363 0.585081149 0.00024 1
          15 16  0  0.442509363 0.585081149 0.00024 1
          16 17  0  0.442509363 0.585081149 0.00024 1
          13 18  0  0.442509363 0.585081149 0.00024 1
          18 19  0  0.442509363 0.585081149 0.00024 1
          19 20  0  0.442509363 0.585081149 0.00024 1
          20 21  0  0.442509363 0.585081149 0.00024 1
          21 22  0  0.442509363 0.585081149 0.00024 1
          22 23  0  0.442509363 0.585081149 0.00024 1
          23 24  0  0.442509363 0.585081149 0.00024 1
          24 25  0  0.442509363 0.585081149 0.00024 1
          25 26  0  0.442509363 0.585081149 0.00024 1
          26 27  0  0.442509363 0.585081149 0.00024 1
          27 28  0  0.442509363 0.585081149 0.00024 1
          28 29  0  0.442509363 0.585081149 0.00024 1
          29 30  0  0.442509363 0.585081149 0.00024 1
          30 31  0  0.442509363 0.585081149 0.00024 1
          31 32  0  0.442509363 0.585081149 0.00024 1
          32 33  0  0.442509363 0.585081149 0.00024 1
          33 34  0  0.442509363 0.585081149 0.00024 1
          34 35  0  0.442509363 0.585081149 0.00024 1
          35 36  0  0.442509363 0.585081149 0.00024 1
          36 37  0  0.442509363 0.585081149 0.00024 1
];

```

### APPENDIX 3: OBJECTIVE FUNCTION FOR ONE BRANCHES

*j* is the number of the ROS

$N_{ROSj}$  is the total number of the ROS

$N_{ROSj}$  is the number of the *j*th ROS (from 1 to *N*)

$End_1$  is the end of substation on branch 1 of a feeder

$End_2$  or *N* is the end of substation on branch 2 of a feeder

$Node(1)$  is the junction node of the feeder



**a) if  $N_{ROSt} < \text{node}(1)$**

*i) if the  $N_{ROSj}$  equal to final ROS;*

$$N_{Tji} = N_{Tji-1} + \left( \sum_{i=1}^N N_{Si} - \sum_{i=ROS_j+1}^N N_{LSi} \right) \times \sum_{i=ROS_j+1}^N P_{fni} \text{ for } N_{fs} > N_{ROSj} \quad (1)$$

$$N_{Tji} = N_{Tji-1} + \left( \sum_{i=1}^N N_{Si} - \sum_{i=ROS_{(j-1)}+1}^{N_{ROSj}-1} N_{LSi} \right) \times \sum_{i=ROS_{(j-1)}+1}^{N_{ROSj}} P_{fni} \text{ for } N_{ROS(j-1)} < N_{fs} \leq N_{ROSj} \quad (2)$$

*ii) if the  $N_{ROSj}$  equal to  $N_{ROS1}$ ;*

$$N_{Tji} = N_{Tji-1} + \left( \sum_{i=1}^N N_{Si} - \sum_{i=1}^{ROS_j-1} N_{LSi} \right) \times \sum_{i=1}^{ROS_j} P_{fni} \text{ for } N_{fs} \leq N_{ROSj} \quad (3)$$

*iii) Others  $ROS_j$ ;*

*Use equation (2)*

**b) else if  $N_{ROS1} > \text{node}(1)$  and  $N_{ROSt} \leq \text{end}(1)$**

*i) if the  $N_{ROSj}$  equal to  $N_{ROSt}$ ;*

*use equation (2) and (4);*

$$N_{Ti} = \left( \sum_{i=1}^N N_{Si} - \sum_{i=N_{ROSj}+1}^{\text{end}1} N_{LSi} \right) \times \sum_{i=ROS_j+1}^{\text{end}1} P_{fni} \text{ for } N_{ROSj} < N_{fs} \leq N_{\text{end}1} \quad (4)$$

*ii) Others ;*

*use equation (2)*

*iii) if  $N_{ROSj}$  equal to  $N_{ROS1}$*

$$N_{Ti} = \left( \sum_{i=1}^N N_{Si} - \left( \sum_{i=1}^{N_{ROSj}-1} N_{LSi} + \sum_{i=\text{end}1+1}^N N_{LSi} \right) \right) \times \left( \sum_{i=1}^{N_{ROSj}} P_{fni} + \sum_{i=\text{end}1+1}^N P_{fni} \right) \text{ for } N_{ROSj} \geq N_{fs} > N_{\text{end}1} \quad (5)$$

**c) if  $N_{ROS1} > \text{end}(1)$  – used the same equations as (1), (2) and (3)**

**d) if  $N_{ROS1}$  equal to  $\text{node}(1)$  and  $N_{ROSt} \leq \text{end}(1)$**

*i) if the  $N_{ROSj}$  equal to  $N_{ROSt}$*

use equations(2) and (4)

ii) if  $N_{ROSj}$  equal to  $N_{ROS1}$

use equation (3)

iii) Others  $ROS_j$

use equation (2)

**e) if  $N_{ROS1}$  equal to node(1) and  $N_{ROSt}$  larger than end(1)**

i) if the  $N_{ROSj}$  equal to  $N_{ROSt}$  and  $N_{ROS(j-1)}$  larger than end(1)

use equations (1)and (2)

ii) if the  $N_{ROSj}$  equal to  $N_{ROSt}$  and  $N_{ROS(j-1)}$  smaller or equal to end(1)

if  $ROS_{(j-1)}$  smaller or equal to end(1)

use equations (1) and (7)

$$N_{Tji} = \left( \sum_{i=1}^N N_{Si} - \sum_{i=end1+1}^{N_{ROSj}-1} N_{LSi} \right) \times \sum_{i=end1+1}^{ROSj} P_{fni} \text{ for } N_{end1} < N_{fs} \leq N_{ROSj} \quad (7)$$

iii) Others  $N_{ROSj}$  larger than end1

if  $ROS_{(j-1)}$  larger than end(1)

use equation (2)

if  $ROS_{(j-1)}$  less than or equal end(1)

use equation (7)

iv) else if  $ROS_j$  larger than node(1) and less or equal to end1

if  $ROS_{(j+1)}$  larger than end1

use equations (2)and (4)

else

use equation (2)

v) else if  $N_{ROSj}$  equal to  $N_{ROS1}$

use equation (3)

**f) if position  $N_{ROSt}$  equal to node(1)**

i) if the  $N_{ROSj}$  equal to  $N_{ROSt}$

use equations (1) and (4)

ii) if  $N_{ROSj}$  equal to  $N_{ROS1}$

use equation (3)

iii) Others  $N_{ROSj}$

use equation (2)

**g) if any  $N_{ROS(t-1)}$  equal to Node(1) and  $N_{ROS1}$  not equal to node(1) and  $N_{ROSt}$  not equal to node(1) and  $N_{ROSt}$  less or equal to end(1)**

i) if the  $N_{ROSj}$  equal to  $N_{ROSt}$

use equations (1), (2) and (4)

ii) if the  $N_{ROSj}$  equal to  $N_{ROS1}$

use equation (3)

ii) Others

Use equation (2)

**h) if any  $N_{ROSj}$  equal to Node (1) and  $N_{ROS1}$  not equal to Node(1) and  $N_{ROSt}$  not equal to Node(1) and  $N_{ROSt}$  larger than ending (1)**

i) if the  $N_{ROSj}$  equal to  $N_{ROSt}$  and  $N_{ROS(j-1)}$  larger than end(1)

use equations (1) and (2)

ii) if  $N_{ROSj}$  equal to  $N_{ROSt}$  and  $N_{ROS(j-1)}$  equal or less than end1

use equations (1) and (7)

iii) if  $N_{ROSj}$  equal to  $N_{ROS1}$

use equation (3)

iii) Others

a) if  $N_{ROSj}$  larger than  $N_{end1}$

if  $N_{ROS(j-1)}$  less or equal to  $N_{end1}$

Use equation (7)

else

use equation (2)

b) elseif  $N_{ROSj}$  less or equal to  $N_{end1}$

and  $N_{ROSj}$  larger or equal to  $N_{node(1)}$ ;

if  $N_{ROS(j+1)}$  larger than  $N_{end1}$

use equations (2) and (4)

else

use equation (2)

c) elseif  $N_{ROSj}$  less than Node(1)

use equation (2)

**i) elseif any  $N_{ROSj}$  less than node(1) and any  $N_{ROSj}$  larger than node (1) and  $N_{ROSt}$  less or equal to  $N_{end1}$**

i) if the  $N_{ROSj}$  equal to  $N_{ROSt}$

if  $N_{ROSj-1}$  less than node(1)

use equations (4) and (8)

$$N_{Ti} = \left( \sum_{i=1}^N N_{Si} - \left( \sum_{i=N_{ROS(j-1)}+1}^{N_{ROSj}-1} N_{LSi} + \sum_{i=end1+1}^N N_{LSi} \right) \right) \times \left( \sum_{i=N_{ROS(j-1)}+1}^{N_{ROSj}-1} P_{fni} + \sum_{i=end1+1}^N P_{fni} \right) \text{ for } N_{ROSj} \geq N_{fs} > N_{ROS(j-1)} \text{ and } N_{fs} > end1 \quad (8)$$

if  $N_{ROSj-1}$  larger than node(1)

use equations (2) and (4)

ii) if  $N_{ROSj}$  equal to  $N_{ROS1}$

use equation (3)

ii) Others

elseif  $N_{ROSj}$  larger than node(1) and  $N_{ROS(j-1)}$  less than node(1)

use equation (8)

else

use equation (2)

**j) if any  $N_{ROSj}$  lesser than Node(1) and  $N_{ROSt}$  larger than ending (1)**

i) if  $N_{ROSj}$  equal to  $N_{ROSt}$

use equations (1) and (2)

ii) if  $N_{ROSj}$  equal to  $N_{ROS1}$

use equation (3)

iii) Others

use equation (2)

**k) elseif  $N_{ROSj}$  larger than node(1) and  $N_{ROSj}$  less or equal to end1**

and  $N_{ROSj}$  larger than end(1)

i) if  $N_{ROSj}$  equal to  $N_{ROSt}$

if  $N_{ROS(j-1)}$  larger than end(1)

*use equations (1) and (2)*

*if  $N_{ROS(j-1)}$  less or equal to end(1)*

*use equations (1) and (7)*

*ii) if  $N_{ROSj}$  equal to  $N_{ROS1}$*

*use equation (3)*

*iii) else*

*if  $N_{ROSj}$  less or equal to end1*

*if  $N_{ROS(j+1)}$  larger than end(1)*

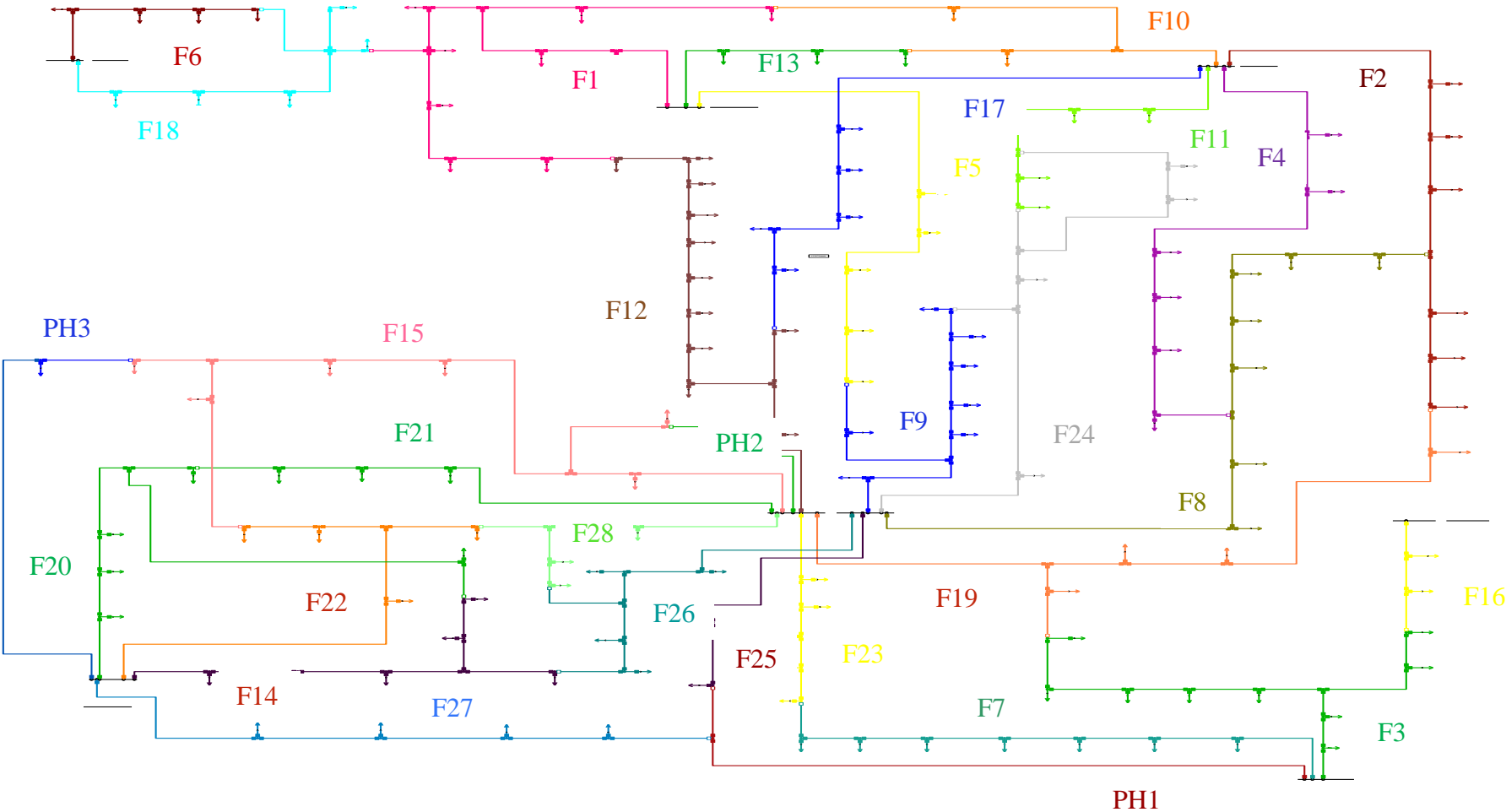
*use equations (2) and (4)*

*else*

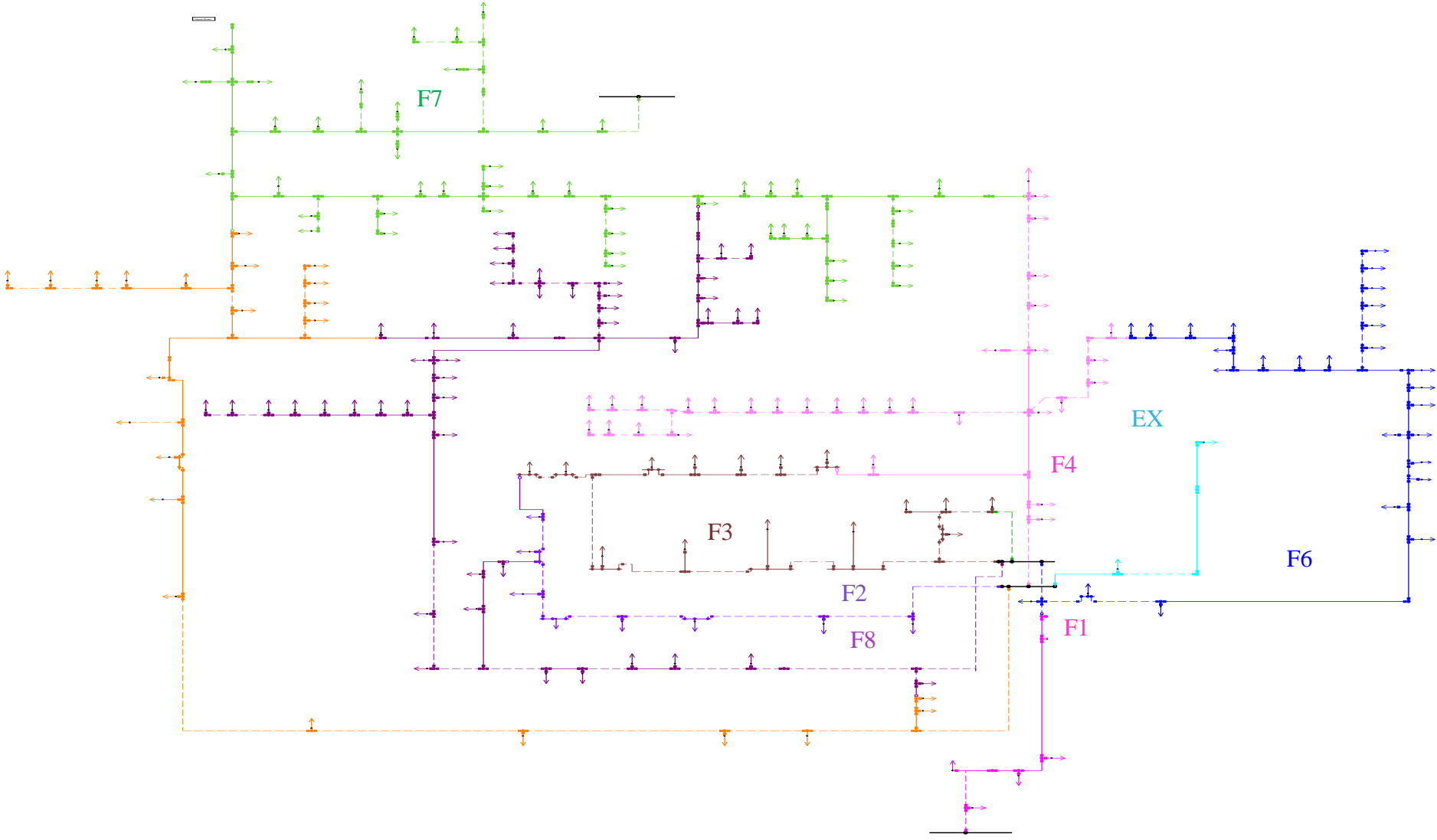
*use equation (2)*

**APPENDIX 4: URBAN, SEMI-URBAN AND RURAL NETWORK**

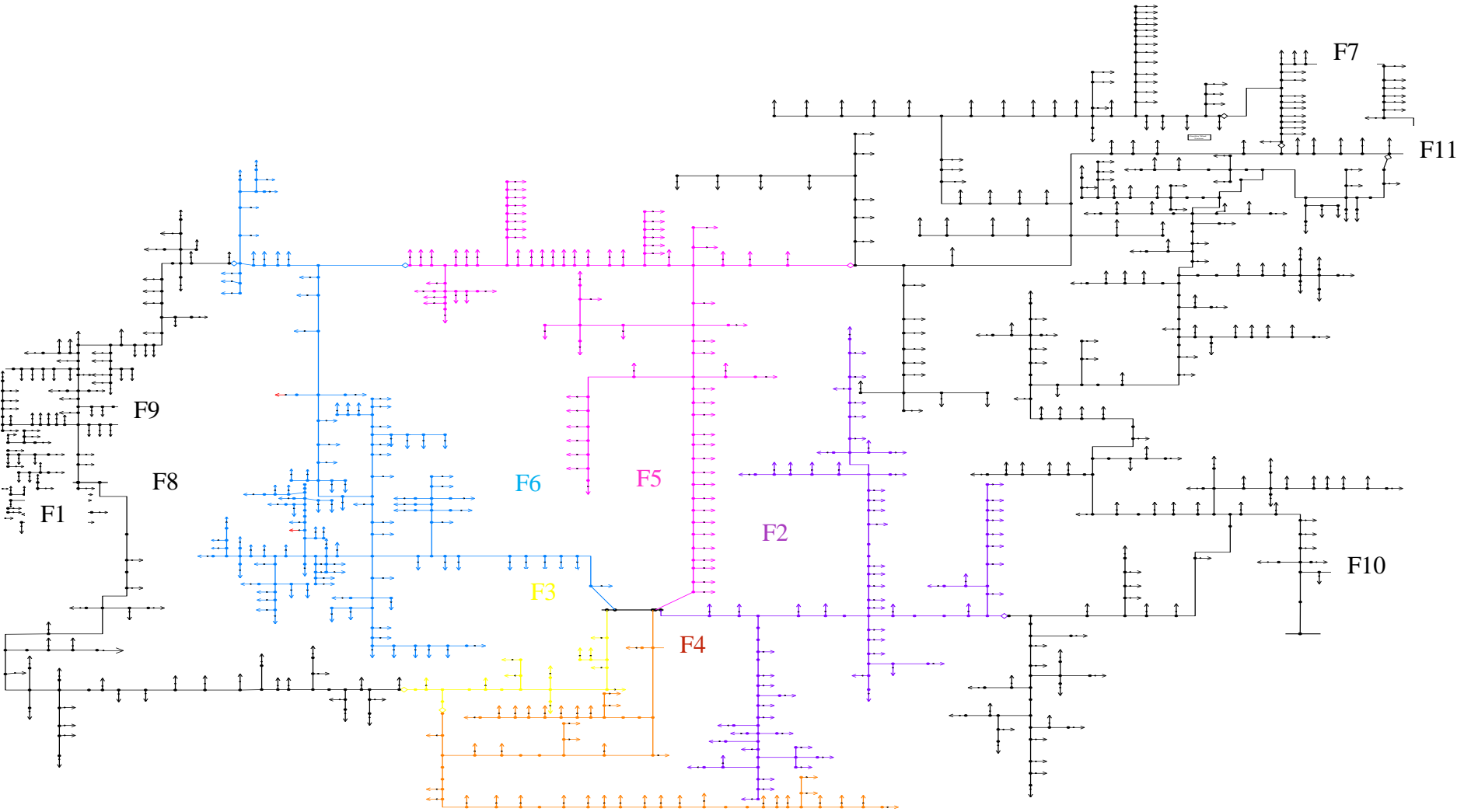
**a) Urban Network**



**b) Semi - Urban Network**



c) Rural Network





## APPENDIX 5: OPTIMAL LOCATIONS FOR CASE STUDY NETWORKS

### a) Urban

Feeder ID	Total S/S	ROS										
		1	2	3	4	5	6	7	8	9	10	11
1	10	4	4,6	4,5,7	1,4,5,8	4,5,6,8,10	1,4,5,7,8,10	1,4,5,7,8,9,10	1,2,4,5,6,8,9,10	1,2,4,5,6,7,8,10		
2	7	2	2,5	1,2,5	1,2,3,6	1,2,3,5,6	1,2,3,5,6,7					
3	10	4	4,5	3,4,5	3,4,5,8	2,4,5,7,8	3,4,5,7,8,10	2,4,5,6,7,8,10	2,3,4,5,6,7,8,10	1,2,3,4,5,6,7,8,10		
4	6	3	1,4	1,3,4	1,3,4,5	1,2,3,4,5						
5	5	3	2,3	2,3,4	1,2,3,4							
6	4	2	2,4	1,2,4								
7	7	7	2,7	2,3,7	2,3,5,7	2,3,5,6,7	1,2,3,5,6,7					
8	8	4	4,8	2,4,8	2,4,7,8	1,2,4,7,8	1,2,4,5,7,8	1,2,4,5,6,7,8				
9	8	6	2,6	2,6,8	1,2,6,8,3	1,2,3,4,6,8	1,2,3,4,6,7,8					
10	3	1	2,3									
11	5	1	1,5	1,4,5	1,2,4,5							
12	12	11	9,11	2,9,11	1,6,9,11	1,4,6,9,11	1,4,5,6,9,11	1,4,5,6,8,9,11	1,4,5,6,8,9,10,11	1,2,4,5,7,9,10,11,12	1,2,4,5,6,7,8,9,10,11	1,2,4,5,6,7,8,9,10,11,12
13	3	1	1,2									
14	7	3	1,3	1,3,4	1,3,4,6	1,2,3,4,6	1,2,3,4,5,6					
15	8	2	2,4	2,4,8	1,3,4,8	1,3,4,7,8	1,3,4,6,7,8	1,3,4,5,6,7,8				
16	2	1										
17	5	1	1,3	1,3,4	1,3,4,5							

18	6	6	1,6	1,2,6	1,2,3,6	1,2,3,4,6						
19	5	5	1,5	1,2,5	1,2,3,5							
20	6	3	1,3	1,3,4	1,2,3,4	1,2,3,4,6						
21	3	1	1,2									
22	5	1	1,4	1,4,5	1,2,4,5							
23	5	3	1,3	1,2,3	1,2,3,4							
24	6	1	1,5	1,3,5	1,3,5,6	1,3,4,5,6						
25	2	2										
26	5	2	1,2	1,2,4	1,2,4,5							
27	4	2	1,2	1,2,3								
28	4	1	1,3	1,3,4								

**b) Semi – urban**

Fee der ID	ROS												
	To tal S/S	1	2	3	4	5	6	7	8	9	10	11	12
1	6	2	2, 4	2,4, 5	1,2,4, 5	1,2,3,4, 5							
2	8	4	3, 5	2,4, 6	1,3,4, 6	1,3,4,5, 6	1,3,4,5,6,7	1,2,3,4,5,6,8					
3	13	6	2, 6	2,3, 6	2,3,6, 10	2,3,4,6, 10	2,3,5,6,10, 12	1,2,3,5,6,10, 12	1,2,3,4,5,6,10 ,12	1,2,3,4,5,6,10, 11,12	1,2,4,5,8,9,18,1 2,16	1,2,3,4,5,6,8,9,1 0,11,12	
4	15	5	5, 13	2,5, 7	4,5,7, 14	2,4,5,7, 14	2,4,5,7,11, 14						
5	18	9	8, 13	5,10 ,13	4,8,12 ,15	4,8,10,1 3,16	4,8,10,14, 15,16	2,4,8,10,13, 15,16	3,4,8,9,10,14, 15,16	3,4,5,9,10,14,1 5,16	3,4,5,8,11,12,1 4,15,16	2,4,6,8,9,10,12,1 4,15,16,18	2,3,4,6,8,9,10,12, 13,14,15,16

6	22	3	3,13	3,13,17	3,9,13,19	3,9,13,16,20	3,5,10,13,16,21	2,6,10,13,16,19,22	2,6,10,11,13,16,19,22	1,3,6,10,11,13,16,19,22	1,3,6,8,10,13,16,17,19,22
7	27	13		13,25	8,13,20,25	8,12,14,19,25	8,12,13,19,25,26	8,12,13,19,22,25,26	4,8,12,13,19,22,25,26		
8	30		8	8,17	1,8,17						

**c) Rural**

Feeder ID	Total S/S	ROS											
		1	2	3	4	5	6	7	8	9	10	11	12
1	7	4	1,4	1,4,6	1,2,4,6	1,2,4,5,6	1,2,3,4,5,6						
2	12	7	3,7	3,7,12	3,7,11,12	3,4,7,11,12	3,5,7,8,11,12	3,5,6,7,8,11,12	1,3,5,7,8,9,11,12	1,2,3,5,6,7,8,11,12	1,2,3,4,5,7,8,9,11,12	1,2,3,4,5,6,7,8,10,11,12	
3	13	5	5,8	2,5,8	2,3,5,8	2,6,8,12	1,2,5,6,8,12	1,2,4,5,6,8,12	1,2,3,4,5,6,8,10	1,2,3,5,6,8,10,12,13	1,2,3,4,5,6,8,9,10,13	1,2,3,4,5,6,7,8,10,12,13	1,2,3,4,5,6,7,8,9,10,12,13
4	12	5	2,10	1,2,10	1,2,5,10	1,2,4,5,10	1,2,4,5,7,10	1,2,4,5,8,10,11	1,2,3,4,5,6,10,11	1,2,4,5,6,7,9,10,12	1,2,3,4,5,7,9,10,11,12	1,2,3,4,5,6,7,8,9,10,11	
5	45	38	18,38	18,38,42	15,21,38,42	11,18,23,38,42							
6	30	11	11,24	9,11,24	9,11,15,24	1,9,11,15,24	1,9,11,15,24,30	1,9,11,15,24,27,30					

7	24	13	13,2 1	8,13 ,21	6,9,13 ,21	6,9,13,2 0,21	4,8,11,13, 19,21	4,6,8,11,1 3,20,21	4,6,8,11,13, 18,20,21	4,6,8,10,12,1 3,18,20,21	
8	26	5	5,12	5,7, 14	5,7,12 ,20	5,7,10,1 3,21	5,7,10,12, 18,21	5,7,10,12, 16,21,24	5,7,10,12,1 5,17,21,23	4,5,7,10,12,1 5,20,21,23	4,5,7,10,12,14, 15,19,21,25
9	42	3	10,2 0	10,1 6,20	10,14, 16,20	10,14,1 6,17,20	10,13,14, 16,18,20				
10	31	11, 17	13,1 5,17								
11	37	14	2,14	2,7, 33							