

**A POWER SUPPLY RELIABILITY ASSESSMENT
MODEL FOR THE COLOMBO SUBURBAN
RAILWAY NETWORK**

D.T. Munasinghe

(168618V)

Degree of Master of Science

Department of Electrical Engineering

University of Moratuwa

Sri Lanka

August 2020

**A POWER SUPPLY RELIABILITY ASSESSMENT
MODEL FOR THE COLOMBO SUBURBAN
RAILWAY NETWORK**

D.T. Munasinghe

(168618V)

Thesis/Dissertation submitted in partial fulfilment of the requirements for the degree
Master of Science in Electrical Installation

Department of Electrical Engineering

University of Moratuwa
Sri Lanka

August 2020

DECLARATION

I declare that this is my own work and this thesis does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

Also, I hereby grant to University of Moratuwa the non-exclusive right to reproduce and distribute my thesis, in whole or in part in print, electronic or other medium. I retain the right to use this content in whole or part in future works (such as articles or books).

Signature:

Date:

The above candidate has carried out research for the Master thesis under my supervision.

Signature of the supervisors:

Date:

Prof. Ranjith Perera

Signature of the supervisors:

Date:

Dr. Tilak Siyambalapitiya

DEDICATION

I dedicate my M.Sc. research dissertation to my beloved parents and my wife for their guidance given throughout my life.

ACKNOWLEDGMENT

I would like to sincerely thank my internal supervisor, Prof. Ranjith Perera, Department of Electrical Engineering, University of Moratuwa for the continuous support, encouragement and expertise in the field to make this Masters research a success.

I am really grateful to supervisor, Dr. Tilak Siyambalapitiya, Managing Director, Resource Management Associates (Pvt) Ltd. for being the originator of this research idea and for the guidance given to me to make this research a success.

I would like to thank the postgraduate research coordinator of department, Dr. Darshana Prasad for the supervision and management of research evaluation. I would like to pay my sincere appreciation to the academic staff of the Department of Electrical Engineering for their valuable feedback and constructive comments during progress reviews.

I would like to sincerely thank Eng. (Ms.) H.D.K. Herath, Electrical Engineer, Transmission Planning, Ceylon Electricity Board and Eng. (Ms.) Thotagamuwage Sajani, Junior Electrical Engineer, Colombo Suburban Railway Project for providing continuous support to get the required details for the project. I pay my special gratitude to Dr. H.M. Wijekoon Banda, Chief Engineer Transmission Planning, Ceylon Electricity Board and Eng. U.N. Sanjaya, Electrical Engineer, Transmission Planning, Ceylon Electricity Board for their support and guidance.

My heartfelt gratitude shall go to my family and friends who had been caring, supporting and facilitating me throughout the work.

ABSTRACT

An electrified railway network is one of the solutions for Colombo traffic congestion due to high population density and high daily passenger flow into the city from the suburbs. Although the initial cost of a railway electrification project is higher compared with other alternatives such as improvements to bus transport, energy, maintenance and operational costs can be lower if the system is designed, maintained effectively and used efficiently. System failures or, delays in system operations should be minimized to reduce the time wasted in traveling.

Reliability and punctuality are the major factors to attract more passengers to use public electrified transport facilities for their daily travel. Power supply is a critical factor to maintain a higher reliability in an electrified railway system.

Designs to upgrade the 230 km long Colombo suburban railway network commenced in 2017 and currently in progress in four stages. Different options for the power supply configuration and the back-up power systems have been identified, qualitatively evaluated and then recommended for implementation. A quantified reliability assessment has not been reported in the design.

A standardized procedure and a reliability assessment model would be required to evaluate the reliability of each optional configuration to supply power and backup power. In this research, optional configurations to supply power to the future electrified railway system of the Colombo Suburban Railway Project area were developed. Reliability assessment was conducted for each optional configuration using the models developed and simulated using Monte Carlo simulation technique. Reliability worth analysis was done to weigh the costs and benefits of configurations with higher reliability.

The model developed can be used for reliability assessment of the power supply to any suburban electrified railway system in Sri Lanka.

Keywords: Electrified Railway, Monte Carlo simulation, Reliability Assessment Model, Reliability Worth

Table of Contents

DECLARATION	i
DEDICATION	ii
ACKNOWLEDGMENT	iii
ABSTRACT	iv
Table of Contents	v
List of Figures	viii
List of Tables	ix
List of Abbreviations	xi
1. INTRODUCTION.....	15
1.1 Electrification of Sri Lanka Railway system.....	15
1.2 Power System Reliability	17
1.3 Research Motivation.....	18
1.4 Objectives of the study	19
1.5 Thesis outline.....	19
2. LITERATURE REVIEW	20
2.1 Power System Reliability Evaluation.....	20
2.2 Reliability Evaluation of Traction substations	20
2.3 Monte Carlo Simulation	21
2.4 Reliability Worth Assessment	22
3. PROPOSED METHODOLOGY FOR RELIABILITY EVALUATION	23
3.1 Power Supply Configuration	23
3.1.1 Sri Lanka Transmission Network.....	24
3.1.2 Selection Criteria for Power Supply Feeding Points.....	25
3.1.3 Power Supply Feeding Options for CSRP	25
3.1.4 Options for Back-up Power.....	27

3.2 Establishment of Reliability Assessment Models	29
3.2.1 Power System Reliability Evaluation techniques	30
3.2.2 Power System Hierarchical Levels	31
3.2.3 Reliability Assessment Indices	32
3.3.4 Reliability Assessment Model	33
3.3 Reliability Assessment of each Power Supply Configuration.....	35
3.4 Monte Carlo Simulation	37
3.4.1 Concept of Monte Carlo Simulation	38
3.4.2 Random Variates.....	39
3.4.3 Simulation Output	40
3.4.4 Reliability Evaluation of repairable systems.....	40
3.5 Reliability Worth Analysis	42
3.5.1 Customer Surveys and Customer Damage Function	43
3.5.2 Reliability Worth Assessment Techniques	43
4. DEVELOPMENT OF THE RELIABILITY EVALUATION MODEL	45
4.1 Grid Substation Modeling	45
4.2 Sub-Transmission System Modeling.....	47
4.3 Traction Substation Modelling	48
4.4 Establishment of an Integrated Reliability Assessment Model	51
4.5 Simplified Reliability Assessment Model	51
5. ASSESSMENT OF RELIABILITY INDICES AND WORTH ANALYSIS	54
5.1 Reliability Data and IEEE Standards.....	54
5.2 Transmission Network for CSRFP Feeding Options.....	55
5.3 Reliability Block Diagram of CSRN Feeding Options	57
5.4 Assessment of Reliability Indices.....	58

5.4.1 Reliability Assessment of CSRP feedings Options using Analytical Method	58
5.5.2 Monte Carlo Simulation.....	64
5.5 Reliability Worth Analysis	68
5.5.1 Optimized Power Supply Configuration.....	68
5.5.2 Blackout Relief Options.....	75
5.5.3 Reliability Benchmark for Power Supply Configuration of Electrified Railway in Sri Lanka.....	77
6. CONCLUSIONS AND FUTURE DIRECTIONS.....	82
6.1 Conclusions	82
6.2 Future Directions	82
REFERENCES.....	84
ANNEX A - SINGLE LINE DIAGRAM OF TRACTION SUBSTATION.....	88
ANNEX B - SUBSTATION LAYOUT FOR PROPOSED TRACTION SUBSTATION.....	89
ANNEX C - SRI LANKA TRANSMISSION SYSTEM IN YEAR 2018.....	90
ANNEX D - SCHEMATIC DIAGRAM OF 2017 TRANSMISSION SYSTEM...	91
ANNEX E - COLOMBO SUBURBAN RAILWAY NETWORK AND PROPOSED FEEDING SUBSTATION.....	92
ANNEX F - CSRP FEEDING OPTIONS FROM SCHEMATIC DIAGRAM OF THE 2022 TRANSMISSION SYSTEM.....	93
ANNEX G - RELIABILITY DIAGRAM OF CSRP FEEDING OPTIONS.....	94
ANNEX H - RELIABILITY INDICES EVALUATION OF KV LINE FEEDING OPTION ONE AND TWO.....	95
ANNEX I - RELIABILITY INDICES EVALUATION OF COASTAL LINE FEEDING OPTION THREE, FOUR AND FIVE.....	99
ANNEX J - RELIABILITY INDICES EVALUATION OF MAIN & PUTTALAM LINE FEEDING OPTION SIX, SEVEN AND EIGHT.....	109
ANNEX K - MONTE CARLO SIMULATION RESULT OF KV, COASTAL AND MAIN & PUTTALAM LINE.....	117

List of Figures

	Page
Figure 1-1 Proposed Colombo suburban electrified railway network	16
Figure 1-2 Subdivision of system reliability	17
Figure 3-1 Transmission network in CSRP area.....	24
Figure 3-2 GSS with proposed electrified railway network.....	26
Figure 3-3 Selected CSRP feeding arrangements	27
Figure 3-4 Power system hierarchical levels.....	32
Figure 3-5 Sub-transmission system	32
Figure 3-6 Series system with repairable components.....	34
Figure 3-7 Parallel system with repairable components	34
Figure 3-8 Sub-transmission network	36
Figure 3-9 Reduced sub-transmission network.....	37
Figure 3-10 Operating cycles of a two component parallel redundant system	41
Figure 3-11 Incremental reliability cost.....	42
Figure 3-12 Reliability and total system cost.....	42
Figure 4-1 GSS reliability model	45
Figure 4-2 Transmission line reliability model.....	47
Figure 4-3 Single line diagram of a TSS.....	49
Figure 4-4 TSS reliability model	49
Figure 4-5 Integrated power supply reliability model.....	51
Figure 4-6 Simplified reliability diagram of CSRN feeding options.....	53
Figure 5-1 Equivalent power supply configuration for coastal and KV lines.....	56
Figure 5-2 Equivalent power supply configuration of main & Puttalam lines	56
Figure 5-3 Reliability Diagram of CSRN feeding options	57
Figure 5-4 Reliability result of option one	65
Figure 5-5 Reliability result of option thee	66
Figure 5-6 Reliability results of option seven	66
Figure 5-7 Incremental reliability cost of main & Puttalam lines.....	71
Figure 5-8 Expected interruption cost of CSRN	79
Figure 5-9 Reliability worth curve.....	80
Figure 5-10 Minimum total cost analysis of CSRN.....	81

List of Tables

	Page
TABLE 3-1 SUMMARY OF REVISED FEEDING OPTIONS.....	26
TABLE 3-2 OUTAGES OF TRANSMISSION SYSTEM	28
TABLE 3-3 SUMMARY OF ADVANTAGES AND DISADVANTAGES	38
TABLE 4-1 EVALUATION OF LINE BAY IN GSS	46
TABLE 4-2 EVALUATION OF TRANSFORMER BAY IN A GSS	47
TABLE 4-3 EVALUATION OF THE TRANSMISSION LINE.....	48
TABLE 4-4 SYMBOLS OF SLD IN TSS.....	50
TABLE 4-5 EVALUATION OF TSS	50
TABLE 4-6 EVALUATION OF A GSS	52
TABLE 5-1 RELIABILITY DATA	54
TABLE 5-2 POWER SUPPLY FEEDING OPTIONS IN CSR.....	58
TABLE 5-3 RELIABILITY INDICES OF OPTION 1	58
TABLE 5-4 RELIABILITY INDICES OF OPTION 2	59
TABLE 5-5 COMPARISON OF RELIABILITY INDICES OF KV LINE	59
TABLE 5-6 RELIABILITY INDICES OF OPTION THREE.....	60
TABLE 5-7 RELIABILITY INDICES OF OPTION FOUR	60
TABLE 5-8 RELIABILITY INDICES OF OPTIO FIVE	60
TABLE 5-9 RELIABILITY INDICES COMPARISON OF COASTAL LINE.....	60
TABLE 5-10 RELIABILITY INDICES OF OPTION SIX.....	62
TABLE 5-11RELIABILITY INDICES OF OPTION SEVEN	63
TABLE 5-12 RELIABILITY INDICES OF OPTION EIGHT	63
TABLE 5-13 RELIABILITY INDICES COMPARISON OF MAIN & PUTTALAM LINE.....	63
TABLE 5-14 SUMMARY OF RELIABILITY INDICES EVALUATION OF ALL OPTIONS.....	63
TABLE 5-15 MCS SIMULATION RESULT	65
TABLE 5-16 SUMMARY OF EVALUATION OF RELIABILTY INDICES	67
TABLE 5-17 CAPTICAL COST ESTIMATE FOR OF KV LINE	68

TABLE 5-18 CAPITAL COST ESTIMATE FOR COASTAL LINE	69
TABLE 5-19 CAPITAL COST ESTIMATE FOR MAIN & PUTTALAM LINE	70
TABLE 5-20 REVENUE LOSS CALCULATION OF MAIN & PUTTALAM LINES	72
TABLE 5-21 FUEL COST AT INTERRUPTION DURATION.....	73
TABLE 5-22 EXPECTED INTERRUPTION COST USING CCDF.....	73
TABLE 5-23 EXPECTED INTERRUPTION COST USING EENS AND IEAR ...	74
TABLE 5-24 COST ANALYSIS OF BOR OPTIONS	76
TABLE 5-25 REVENUE LOSS CALCULATION OF CSRN FEEDING OPTIONS.	77
TABLE 5-26 EXPECTED INTERRUPTION COST OF CSRN USING CCDF	78
TABLE 5-27 EXPECTED INTERRUPTION COST OF CSRN USING EENS AND IEAR	78
TABLE 5-28 AVERAGE INTERRUPTION COST OF CSRN	78
TABLE 5-29 ANNUALIZED COST OF CSRN.....	79
TABLE 5-30 MINIMUM TOTAL COST CALCULATION OF CSRN	80

List of Abbreviations

Abbreviation	Description
AC	Alternative Current
BB	Bus Bar
CB	Circuit Breaker
CEB	Ceylon Electricity Board
CMR	Colombo Metropolitan Region
CSRN	Colombo Suburban Railway Network
CSRP	Colombo Suburban Railway Project
CT	Current Transformer
CVT	Capacitive Voltage Transformer
DMU	Diesel Multiple Unit
ET	Earthing Transformer
EDNS	Expected Demand Not Supplied
EENS	Expected Energy Not Supplied
EMU	Electric Multiple Unit
ES	Earth Switch
ETF	Earthing Transformer
FTA	Fault Tree Analysis
G&T	Generation and Transmission
GSS	Grid Sub Station
HL	Hierarchical Levels
HV	High Voltage
IEC	International Electro technical Commission
IEEE	Institute of Electrical and Electronic Engineering
ISO	Isolator
KV	Kelani Valley
LA	Lightning Arrester
LCC	Life Cycle Cost
LOLF	Loss of Load Frequency

LOLP	Loss of Load Probability
LV	Low Voltage
MCS	Monte Carlo simulation
MTTR	Mean Time to Repair
MV	Medium Voltage
NCRE	Non-Conventional Renewable Energy
NCT	Neutral Current Transformer
O&M	Operation and Maintenance
OCS	Overhead Contact System
PPTA	Project Preparatory Technical Assistance
RSI	Railway System Index
SCADA	Supervisory Control and Data Acquisition
SCC	System Control Centre
SL	Sri Lanka
TSS	Traction Substation
VT	Voltage Transformer