Reliability Analysis with Various Transfer Switch Technologies in Open-Ring Distribution Systems

By

Mengwei Wang

McGill University, Montreal

5/8/2013

Thesis submitted to McGill University in partial fulfillment of the requirements of the degree of Master of Engineering in the department of Electrical Engineering.

Abstract

Reliability is a key aspect of power systems. In this research, the minimum cut set method is adapted for assessing the reliability of reconfigurable open-ring distribution networks, where we have considered both sustained and momentary interruptions. Open-ring distribution network topologies can significantly improve system reliability through load transferring, and consequently the outages suffered at load points are reduced. The impact of various transfer switch technologies (i.e. manual or automatic mechanical switches and static switches) on the reliability level is investigated. The placement of the transfer switch and its effect on the reliability level are also evaluated using two open-ring distribution network configurations.

The value of reliability plays an important role in the design and planning of power systems. We present an assessment of the costs and benefits associated with different transfer switch technologies and placements. This assessment incorporates customer concerns in the analysis while responding to economic constraints of the distribution network owner. One of the economic evaluation methods based on customer perception relating the level of system reliability is the customer interruption cost (CIC). The net present value method has been utilized to combine CIC, capital investment in transfer switches, and the impact of lost utility revenues during outages to evaluate the economic viability of switch technologies and placements.

It is found that the application of all transfer switches significantly reduces annual outage time and associated CIC. However, the benefit of using static switches cannot be clearly observed in annual outage reduction compared to automatic mechanical switches. Also, results show that placing a transfer switch at the end of two adjacent radial feeders can contribute to reduce the most the annual outage time suffered by customers. On the other hand, placing

a transfer switch at the feeding bus contributes most to lower the outage frequency seen in the parallel feeders.

Résumé

La fiabilité est un élément clé des réseaux de distribution électriques. Dans cette recherche, la méthode de l'ensemble de coupure minimal est présentée pour l'évaluation de la fiabilité des réseaux de distribution en boucle ouverte. Un réseau de distribution en boucle ouverte en soi peut améliorer considérablement la fiabilité du système en rendant possible le transfert de charge lors de pannes. Dans ces cas, les points normalement ouverts du réseau sont fermés afin d'effectuer ce transfert de charge. Dans cette thèse, on évalue l'impact sur la fiabilité de la technologie utilisée pour le commutateur de transfert (i.e. commutateur mécanique manuel ou automatique et commutateur statique). L'effet du placement du commutateur de transfert sur le niveau de fiabilité est également évalué sur deux configurations de réseau de distribution en boucle ouverte.

On effectue ensuite une analyse coût-bénéfice des différentes technologies de commutateurs de transfert. Cette analyse intègre les préoccupations vis-à-vis la fiabilité des clients tout en répondant aux contraintes économiques du distributeur. Cette évaluation technico-économique est basée sur le coût d'interruption client (CIC), qui mesure l'impact économique équivalent des pannes sur les clients. Le CIC est calculé pour diverses technologies de commutateur de transfert et configurations du réseau de distribution. Simultanément, on calcule la valeur actualisée nette de ses coûts pour chaque cas ainsi que celle des coûts et bénéfices logeant du côté du distributeur, c'est-à-dire le coût d'installation des commutateurs et les réductions dans les ventes d'électricité perdues lors les pannes.

On démontre ainsi que l'application de toutes les technologies de commutateurs de transfert permettent de réduire la durée des pannes et du CIC associé. Cependant, on trouve qu'il y a peu de benefices additionnels à passer d'un commutateur mécanique automatique à un commutateur statique. De plus,

les résultats démontrent que le placement des commutateurs de transfert joue un rôle important dans la fiabilité des réseaux. Ainsi si on place un commutateur de transfert à la fin de deux artères parallèles, on maximise la réduction de la durée des pannes chez les clients. En contrepartie, dans le cas où le commutateur est placé en tête d’artère, ceci permet de maximiser la réduction de la fréquence de défaillance des artères parallèles.

Acknowledgments

The author would like to show her deepest gratitude to her supervisor, Prof F. Bouffard, for giving her the opportunity to work in a very interesting area, and for his support and valuable guidance throughout her graduate studies at McGill University. His keen and vigorous academic observation enlightens her not only in this thesis but also in her future study. She shall extend her thanks Prof. G. Joos for the financial assistance.

The author takes the opportunity to thank her family and friends for their moral support, encouragement and love.

Contents

Abstract i

Résumé iii

Acknowledgments v

List of Figures ix

List of Tables x

List of Acronyms xiii

List of Main Symbols xv

1. Introduction .... - 1 -

1.1. Introduction .... - 1 -

1.2 Definition of Power System Reliability .... - 1 -

1.3 Objective of the Research .... - 3 -

1.3.1 Introduction .... - 3 -

1.3.2 Reliability Improvement with Open-Ring Distribution Network .... - 4 -

1.3.3 Analysis of Transfer Switch Technology Impacts .... - 5 -

1.3.4 Cost-Benefit Assessment .... - 6 -

1.4 Literature Review .... - 6 -

1.4.1 Introduction .... - 6 -

1.4.2 Impact of Different Transfer Switches on Reliability Level .... - 7 -

1.4.3 Method of Momentary Interruption Measurement .... - 9 -

1.4.4 Reliability-Cost Evaluation .... - 11 -

1.5 Methodology .... - 13 -

1.6 Thesis Outline .... - 14 -

1.7 Thesis contributions .... - 14 -

2. Introduction to Distribution System Reliability Indices .... - 16 -

2.1 Introduction .... - 16 -

2.2 System Reliability Indices .... - 16 -

2.2.1 Primary Indices .... - 16 -

2.2.2 Customer-Oriented Indices .... - 17 -

2.3 Summary .... - 19 -
3 Reliability Analysis of Ring-Structured Distribution Networks .... - 20 -
3.1 Introduction .... - 20 -
3.2 Validation of Reliability Assessment Method with IEEE-Gold Book Test System . - 23 -
3.3 Case Study – Assessing Impact of Transfer Switch Technology .... - 30 -
3.3.1 Case Studies for IEEE-Gold Book Test System .... - 31 -
3.3.2 Modified RBST Open Ring Distribution Network with One Supply Source .. - 34 -
3.3.3 Modified RBST Open Ring Distribution Network with Two Supply Sources - 40 -
3.4 Summary .... - 43 -
4. Evaluation of Economic Benefit Worth .... - 44 -
4.1 Introduction .... - 44 -
4.2 Customer Interruption Cost .... - 44 -
4.2.1 IEEE Gold Book Ring Configuration .... - 47 -
4.2.2 Modified RBST Ring with Two Supply Sources .... - 48 -
4.2.3 Summary .... - 50 -
4.3 Lost-Utility Sales Revenue .... - 50 -
4.4 Net Present Value .... - 52 -
4.5 Combined Benefit Assessment for Customer and Utility .... - 56 -
4.6 Summary .... - 60 -
5. Conclusion and Future Work .... - 62 -
5.1 Conclusion .... - 62 -
5.2 Future Work .... - 64 -
Appendices .... - 65 -
Appendix A: Classic Distribution Reliability Evaluation Methodologies .... - 66 -
A.1 Introduction .... - 66 -
A.2 Classic Analytical Reliability Evaluation Methodology .... - 66 -
Appendix B: Minimum Cut Set Method .... - 71 -
B.1 Reliability Evaluation for Ring Structured Distribution Network based on Minimum Cut Set Method (Sustained Interruption) .... - 71 -

B.2 Reliability Evaluation for Ring Structured Distribution Network based on Minimum Cut Set Method (Momentary Interruption) ....- 79 -

Appendix C: Code Listings ....- 82 -

function parallel network_ring(lambda, r, N) ....- 82 -

function cost_calculation(lambda,r,L,type_user) ....- 85 -

function interruption_cost(type_TS, type_user) ....- 87 -

function economy_eval(STS_Pr,i,L_growth,n) ....- 88 -

References ....- 90 -

List of Figures

Figure 1.1 Subdivision of System Reliability [3] ....- 2 -
Figure 1.2 Simplified Open-ring Distribution Network ....- 5 -
Figure 3.1 IEEE Gold Book Test System [31] ....- 21 -
Figure 3.2 Modified Roy Billinton Test System (RBTS) [23] ....- 22 -
Figure 3.3 Equivalent circuit of the secondary selective system ....- 25 -
Figure 3.4 Modified open ring distribution system of Figure 3.2 ....- 34 -
Figure 3.5 Expanded load point potential failure components ....- 35 -
Figure 3.6 Modified RBST ring network with two supply sources ....- 40 -
Figure 4.1 2nd order polynomial interpolation of sustained interruption for customer types...- 45 -
Figure 4.2 Incremental cost of investment versus cost per kWh saved for customers during interruption ....- 60 -
Figure A.1 State space diagram for a component has two states [34] ....- 68 -
Figure A.2 State space diagram for active and passive failures [34] ....- 69 -
Figure B.3 Simplified open ring network...- 73 -
Figure B.4 Reliability diagram for Load Point 1 (L1)..- 75 -

List of Tables

Table 3.1 Failure rate and repair time for components .... - 24 -
Table 3.2 IEEE survey of reliability of electric utility power supplies........................... - 24 -
Table 3.3 Failure rate and repair time for corresponding components in Figure 3.3 (Assuming supply source branch 1 and 2 are completely independent)..................... - 26 -
Table 3.4 Minimum cut sets for one LP (Assuming NO transfer switch ideal.) .... - 26 -
Table 3.5 Short duration interruption data for one LP (Assuming NO transfer switch ideal.) .... - 26 -
Table 3.6 Failure rate and repair time for corresponding components in Figure 3.3 (Assuming supply source branch 1 and 2 are dependent and NO switch ideal) .... - 27 -
Table 3.7 Summary of reliability data for LP 1, assuming a 9 min manual switchover time to source 2. .... - 27 -
Table 3.8 Summary of reliability data for LP 1, assuming a 5 s automatic switchover time to source 2. .... - 28 -
Table 3.9 Failure rate and repair time for corresponding components in Figure 3.3 (Assuming supply source branch 1 and 2 are indep. and NO switch ideal) .... - 29 -
Table 3.10 Summary of reliability data for LP 1, assuming a 9 min manual switchover time to source 2. .... - 29 -
Table 3.11 Summary of reliability data for LP 1, assuming a 5 s automatic switchover time to source 2. .... - 29 -
Table 3.12 Failure rate and annual outage time dependency ratio in scale between dependent and independent cases .... - 30 -
Table 3.13 Summary of reliability data for LP 1, assuming a 9 min manual switchover time to source 2. .... - 31 -
Table 3.14 Summary of reliability data for LP 1, assuming a 5s automatic switchover time to source 2. .... - 31 -
Table 3.15 Summary of reliability data for LP 1, assuming a 5 ms switchover time to source 2 (interruption less than 1 cycle considered). .... - 32 -
Table 3.16 Summary of reliability data for LP 1, assuming a 5 ms switchover time to source 2 (interruption less than 1 cycle not considered). .... - 32 -
Table 3.17 Summary of customer-oriented indices for three cases........................... - 33 -
Table 3.18 Difference in customer-oriented indices .... - 33 -
Table 3.19 Failure rate and repair time for corresponding components in Figure. 3.4 (assuming NO switch ideal)... - 35 -
Table 3.20 Failure rate and repair time for corresponding components in Figure. 3.5- 35 -
Table 3.21 Minimum cut sets for LP L1-L3 (assuming NO ideal.)................................ - 36 -
Table 3.22 Short duration interruption data for LP 1-3 .... - 36 -
Table 3.23 Summary of reliability data for LP 1, assuming a 9 min manual switchover for reconfiguration. .... - 37 -

Table 3.24 Summary of reliability data for LP 2, assuming a 9 min manual switchover for reconfiguration. ....- 37 -
Table 3.25 Summary of reliability data for LP 3, assuming a 9 min manual switchover for reconfiguration. ....- 37 -
Table 3.26 Summary of reliability data for LP 1, assuming a 5 s automatic switchover for reconfiguration. ....- 38 -
Table 3.27 Summary of reliability data for LP 2, assuming a 5 s automatic switchover for reconfiguration. ....- 38 -
Table 3.28 Summary of reliability data for LP 3, assuming a 5 s automatic switchover for reconfiguration. ....- 38 -
Table 3.29 Summary of reliability data for LP 1, assuming a 5 ms switchover time to source 2....- 39 -
Table 3.30 Summary of reliability data for LP 2, assuming a 5ms switchover time to source 2....- 39 -
Table 3.31 Summary of reliability data for LP 3, assuming a 5ms switchover time to source 2....- 39 -
Table 3.32 Summary of reliability data for LP 1....- 41 -
Table 3.33 Summary of reliability data for LP 2....- 41 -
Table 3.34 Summary of reliability data for LP 3....- 41 -
Table 3.35 Failure frequency result comparison for Figure 3.1 and Figure 3.6....- 42 -
Table 3.36 Annual outage result comparison for Figure 3.1 and Figure 3.6....- 42 -
Table 4.37 Customer interruption cost $/kW for various customer types and interruption durations....- 45 -
Table 4.38 2nd order polynomial interpolation equations for customer types....- 46 -
Table 4.39 Customer load level....- 47 -
Table 4.40 CIC - no load transfer....- 47 -
Table 4.41 CIC - Manual....- 48 -
Table 4.42 CIC - ATS....- 48 -
Table 4.43 CIC - STS....- 48 -
Table 4.44 CIC - no load transfer....- 49 -
Table 4.45 CIC - Manual....- 49 -
Table 4.46 CIC - ATS....- 49 -
Table 4.47 CIC - STS....- 49 -
Table 4.48 CMI summary for IEEE Gold Book case....- 51 -
Table 4.49 CMI summary for modified ring with two supply sources....- 51 -
Table 4.50 ΔE for IEEE Gold Book Test System, modified ring with two sources based on Manual Switchover....- 51 -
Table 4.51 Present value conversion formulas [2]....- 53 -
Table 4.52 Equipment prices [33]....- 53 -
Table 4.53 Annual CIC per load point ($)....- 54 -
Table 4.54 Cumulative present value of CIC over 20 years per load point ($)....- 54 -

Table 4.55 Probability for system in operation mode for Modified ring with 2 sources - 55 -
Table 4.56 NPV equations - 55 -
Table 4.57 Summary of cumulative present value of loss-sale over 20 years per load point - 57 -
Table 4.58 Change in customer side - $\Delta CICavoided$ per load point - 58 -
Table 4.59 Summary of equipment cost ($) vs corresponding interruption cost charge based on CIC ($) - 59 -
Table B.60 Minimum paths for load points of Figure B.3 - 73 -
Table B.61 Minimum paths for load point 1 - 74 -
Table B.62Minimum cut sets for load points - 74 -
Table B.63 Component failure data for the example - 79 -
Table B.64 Independent minimum cut sets for Load Point 1 - 79 -

List of Acronyms

In alphabetical order:

ATS	Automatic transfer switch
ASAI	Average service availability index
ASUI	Average service unavailability index
CAIFI	Customer average interruption frequency index
CAIDI	Customer average interruption duration index
CB	Circuit breaker
CI	Customers interrupted
CIC	Customer interruption cost
CIPKW	Cost of interruption per kW for a period of duration
CMI	Customer minutes of interruption
LP	Load point
MAIFI	Momentary average interruption frequency index
NC	Normally closed
NO	Normally open
NOP	Normally open point
NPV	Net present value
RBTS	Roy Billinton test system
SAIDI	System average interruption duration index

SAIFI	System average interruption frequency index
STS	Static transfer switch

List of Main Symbols

i	Load point i
U	Annual outage time
λ	Failure frequency
μ	Repair rate
r	Repair time
L_{avg}	Average load level
N_T	Total number of customer served
N_i	Total number of interrupted customers at load point i for each sustained interruption event

1. Introduction

1.1. Introduction

As technology develops, so does the demand for energy. In 2011, the world's total energy consumption increased by 4.9%, and the world's electricity consumption rose by an average of 3.5% as a result of rapid economic growth [1]. Electricity, our primary energy source, has become indispensable in our daily lives – for transportation, lighting, cooling, heating, and various electronic applications.

In present, much attention is focused on delivering reliable, high-quality, and inexpensive electricity from decentralized sources to dispersed loads. This can only be achieved if both system adequacy and security are enforced within reasonable budgetary restrictions.

As an integral part of an electric power system, a power distribution network connects electric power generation and electricity consumers. The reliability of the distribution network has always been important. The continuity and consistency of electricity delivery are among the most important factors in its performance. However, according to utility statistics, approximately 80% of all power outages that a customer experiences are caused by faults in the distribution network [2]. The economic loss incurred due to noncontinuous electricity service has a significant impact on both utility providers and customers. In an effort to reduce this loss and guarantee power supply levels, this research will focus on specific ways of improving the reliability of distribution networks.

1.2 Definition of Power System Reliability

The power system reliability assessment describes the ability of the system to provide an electrical energy supply with acceptable and affordable continuity and quality, while meeting the system load requirement. The power system reliability can be subdivided into two main categories: adequacy and security [3], as shown in the Figure 1.1 below.

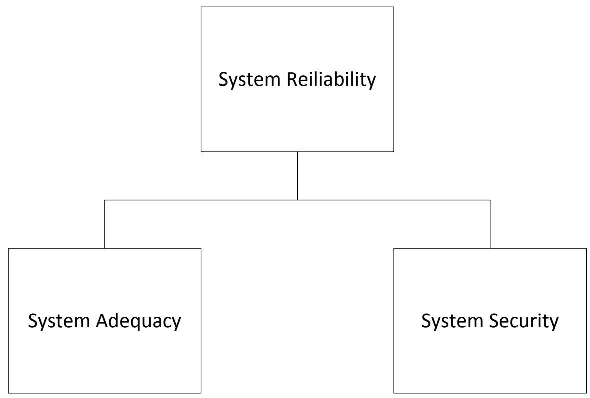

Figure 1.1 Subdivision of System Reliability [3]

Adequacy assessment involves the evaluation of the sufficiency of system facilities (equipment, services, etc.) and the determination of whether the system can satisfy customer load requirements. It takes into account component failures and component outages. It relates the evaluation of the system to steady-state conditions and mainly focuses on the long-term analysis of the system.

Security assessment involves evaluating the ability of the system to respond while undergoing disturbances. It also evaluates the system's ability to tolerate sudden perturbations. Therefore, it mainly focuses on the transient stability of the system and on short-term analysis.

This thesis mainly deals with the power distribution and the system reliability evaluation within the adequacy domain.

1.3 Objective of the Research

1.3.1 Introduction

In today's society, customers and utility providers are dependent on high-quality electricity with as few power interruptions as possible. However, under the constraints of economic investment, environment conservation, and other associated technical factors, an uninterrupted power supply cannot be guaranteed. It is common practice to lessen the duration of interruptions in a power system by increasing its reliability, by means of asset and practices quality improvement and redundancy incrementation. Both of these measures require additional capital investment [3].

The quality factor involves not only the performance of the various pieces of equipment employed in the system, but also other factors including operator activities and working environment constraints. The later terms, relating to human intervention, play a significant role in the reliability level of the system, which is normally very difficult to quantify [2]. Therefore, the main focus here, regarding the quality factor, is to improve the quality of the equipment employed.

The second factor is based on the assumption that the quality of the components erodes as time goes by, leading to occasional and temporary equipment failures, which are characterized within an acceptable time range. When such faults occur, there should be a back-up state, known as redundancy, to enable the system to recover from a failure mode. In a repairable system, the failed components are either repaired or replaced; however, the components will remain out of commission in a non-repairable system.

There are two types of redundancies that help prevent a decline in system performance: standby redundancy and active redundancy. Standby redundancy exists in systems where the redundant components and sources remain in a standby state and can only be activated when there is a failure on the main operating branch. Therefore, a standby system uses extra capacity to reduce the interruption duration and can provide service temporarily for the customers while the failed components on main branches are being repaired or replaced. This type of redundant system is utilized in situations where the quality and reliability of the power supply are crucial, such as at hospitals and in the financial sector [4].

The second type is active redundancy. This type of redundancy exists when system components share functions. When a fault is detected, protective devices disconnect the failed components and reconfigure the network. Power is then redistributed across the remaining components [2].

1.3.2 Reliability Improvement with Open-Ring Distribution Network

In an effort to fulfill the redundancy requirement, one cost-effective reliable option is the application of an open-ring structured distribution network. The simple configuration of such a distribution network contains two independent and adjacent radial feeders, connected by a normally-open transfer switch, as shown in Figure 1.2. In this configuration, during interruptions, faulted sections can be isolated, and unfaulted downstream sections can be tied to the adjacent feeder through the normally-open transfer switch, which is then closed, so that customer interruption cost and interruption duration can be reduced.

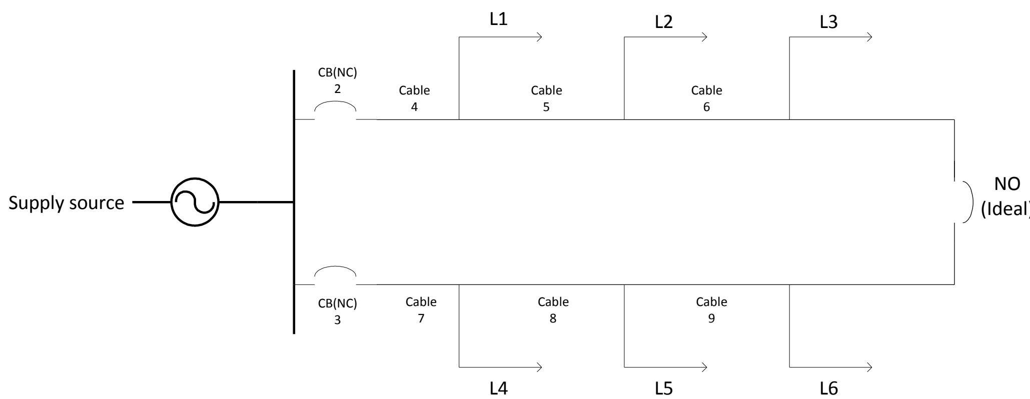

Figure 1.2 Simplified Open-ring Distribution Network

One objective of this research is to evaluate reliability improvements for the power distribution system by considering the application of an open-ring structured distribution network, comparing this network type to a simple radial distribution network.

1.3.3 Analysis of Transfer Switch Technology Impacts

Both mechanical and static transfer switches perform power transfer functions. Mechanical transfer switches are traditional transfer switches. The operation of these switches requires an open transition process. An open transaction is a break-before-make operation that requires isolation of the original path before alternative path is closed. Therefore, they cannot provide an uninterrupted power supply. The whole process for mechanical transfer switches to open/close normally takes 0.3 to 3 seconds [5], which is decided by the characteristics of the mechanical transfer switches. Static transfer switches (STS) are solid-state electronic devices. These switches can provide a quasi-uninterrupted power supply by essentially transferring loads to an alternate feeder at ultra-fast rates; normally less than a half cycle. Typically, the core application of such switches are not used in traditional distribution systems, but are used at industry loads which requires fast switchover in order to enhance power quality of critical and sensitive loads.

Researches have shown an interest in replacing mechanically-operated automatic transfer switches (ATS) or manual switches with thyristor-based static transfer switches [5], [6]. Doing so will decrease the amount of interruption time load points (LP) experience [4], resulting in improvements in system reliability.

Despite of the redundancy of supply, the other option for improving distribution network reliability is equipment replacement. The second objective of this research is to evaluate the reliability improvements in the ring structured distribution system after the application of thyristor based static transfer switches. The impact of different transfer switch technologies on the reliability level will also be presented.

1.3.4 Cost-Benefit Assessment

Although meeting the growing requirement for higher reliability can be achieved by various investments, increasing capital investment will result in increasing cost for the service supplier. Therefore, there always exists a conflict between cost and reliability. Investment should be not only technically but also economically viable. Therefore, cost-reliability benefit under a reasonable budgetary restriction is one of the primary considerations as well.

In this thesis, the economic issues related to cost-effectiveness for replacing traditional switches with thyristor-based STSs will be examined. Here, the thesis focuses primarily on the capital investment required to replace switches. Maintenance and end-of-life disposal costs of the switches are neglected.

1.4 Literature Review

1.4.1 Introduction

In today's society, high degree of reliability is one of the primary requirements in power distribution systems. The complexity of the power systems and the ever-growing dependency of customers upon them have led to clear requirements for distribution system reliability improvement [6]. This section presents a review of the current research on reliability assessment for distribution networks. This survey mainly focuses on three parts. The first part involves the analysis of how transfer switches impact distribution networks in terms of reliability level. Of particular interest is the application of the thyristor-based static transfer switch. The second part reviews the impact of inherent momentary interruption caused by load transfer, and a recently proposed method for momentary interruption measurement. The last part mainly concerns recent research on reliability-cost assessment.

1.4.2 Impact of Different Transfer Switches on Reliability Level

Mechanical transfer switches are electrical devices that select between different sources to provide continuous power to the loads. There are two types： manual and automatic. For the manual switch, the transfer activity is determined by the operator, where ATS switches when the loss of the supply sources or other failures are sensed. The selectivity features of ATS, in particular the control technique using a programmable logic controller, are discussed in [7]-[9].

Khan et al. [10] discussed the significant differences in interruption frequency and interruption duration of a load point for two types of mechanical switches: manual switches and automatic transfer switches, which have different failure rates and transferring times. Based on the simulation results for the representative samples presented in their paper, the authors concluded that the duration for repair of components and the switching activities of protective equipment both have a significant impact on the reliability level of the system. The frequency and annual duration of interruptions at a load point is significantly lower when automatic switching restoration procedures are used during outages compared to manual switching procedures. This is due to the fact that automatic switching has a shorter transferring time. Brown and Spare [11] also conducted a series of simulations for a variety of feeder variations for these two types of switches. The results show that a looped feeder topology with automatic switches is less risky than a looped system with manual switches. The system average interruption index ($SAIDI$) is around five times lower for automatic switching cases compared to manual switching cases.

Other than manual and automatic switches, there has been interest in replacing electromechanical transfer switches with faster transfer power-electronic switches (i.e. STSs) to further reduce the interruption duration [5], [6]. Power quality requirements of typical sensitive loads are such that a loss of power longer than half a cycle is unacceptable [12]. Generally, the response time of a STS, including detection time and transfer time, is within that half cycle requirement [5], [13]-[14]. Clearly, STSs could contribute to decrease interruption durations if installed also in traditional distribution networks.

Detailed description of STS configuration and technology can be found in [12], [15]-[16]. Although there are various types of STSs, the thyristor-based static transfer switch is preferred by the industry. It has the following advantages: the setup is most economical and has the largest voltage and current ratings [17]. The evidence in the literature [18], [19] indicates that typically STSs are preferred for their low conduction losses and generally possess a very long service life compared to a mechanical switch. Moreover, further reduction of conduction losses and switching losses can be achieved by application of a hybrid switch device consisting of a mechanical switch and a thyristor based STS [20].

The performance evaluation of STS from the detection time and transfer time point of view has been conducted in several papers [6], [13], [14], [21], [22]. In [21], analytical expressions are derived to estimate the transfer time of thyristor-based STSs under different disturbance conditions, and the system parameters that impact transfer time are identified. Three cases are considered: three-phase under-voltage disturbance, single-phase-to-ground fault, and phase-to-phase fault. Analytical results are validated using Electro-Magnetic Transient for DC (EMTDC) simulation package. Thorough analysis of an STS system using a fast selective gating strategy is presented in [6]. The simulation result is also validated using EMTDC. The results have shown that the transfer time for different types of fault is within a half cycle. A similar simulation is conducted using EMTPWorks RV in [13], and two different simulation strategies for STS performance can be found in [14]. The results are consistent and all show that the maximum transfer time of STS from a fault source to an alternative source under any conditions can be completed within a half cycle. However, the often-claimed 4ms maximum transfer time cannot be guaranteed, while detailed experimental results can be found in [22]. Unlike the mechanical transfer switches cases, simulations of typical looped systems with static transfer switches implemented at the normally open point and evaluation of the reliability level of this topology cannot be found in the literature.

1.4.3 Method of Momentary Interruption Measurement

Nowadays, with the increasing usage of precise electronic devices among customers, attention to the impact of momentary interruptions has grown due to the fact that momentary interruptions occur more frequently than sustained interruptions. Based on the simulation results of the case study in [23], it is clear that momentary interruptions occur more frequently than sustained interruptions, and the interruption cost due to momentary interruptions is higher.

In [23], the authors proposed a reliability evaluation method for a power distribution network, taking into account momentary interruptions caused by the reclosing behavior of circuit breakers (CBs) when a temporary fault is detected. Both analytic and probabilistic evaluation methods are proposed as well. Prior to these proposals, two basic parameters for reliability evaluation regarding momentary interruptions were proposed. One of them is the temporary failure rate, and the other is the duration of momentary interruption. The latter term is directly related to the reclosing time of protective devices. For analytical evaluations, the traditional momentary interruption index ($MAIFI$) now is modified into the following form

$$MAIFI = \frac{\sum_{i=1}^{N_{LP}}\left(\sum_{k=1}^{N_r}\left(\lambda_{Mi}P_{r_k}k\right)\right)NC_i}{\sum_{i=1}^{N_{LP}} NC_i}$$

where λ_{Mi} is the momentary failure rate for load point i and P_{r_k}denotes the probability of successful reclosing for the k^{th} time. NC_i represents the number of customers served at load point i, and N_{LP} represents the number of load points.

The concept and equation derived by the authors in [23] may be applied to static switches. However, further quantification needs to be clarified for P_{r_k}as the turn-on time for thyristors is roughly 10 μs [19]. For $k = 1, \dots, n$, when k is small, the probability of successful reclosing for the k^{th} time is nearly zero. The value of P_{r_k} is expected to be grow slowly over k.

R.E. Brown et al. [24] also presented a method of reliability assessment for momentary interruptions. Unlike in [23], the authors proposed a procedure solely based on analytical evaluations, especially Markov modeling. The calculation of the $MAIFI$ is also modified. They proposed a different way of computing the number of momentary interruptions other than counting the number of reclosing activities of the protective devices until the network is restored. Their paper discussed momentary interruptions in two categories: momentary interruptions due to self-clearing faults and momentary interruptions due to permanent faults. For the first factor, when a self-clearing fault occurs, customers downstream clearly undergo a single momentary interruption without transfer. When a permanent fault occurs, a number of customers undergo a momentary interruption, and the number is based on whether power transfer to an adjacent feeder is possible and which set of customers can be transferred to the nearby alternative source. Therefore, the total number of momentary interruptions that each customer undergoes can be obtained by adding the number of momentary interruptions due to self-clearing faults and the number of momentary interruptions due to permanent faults, if the load of customers can be transferred.

1.4.4 Reliability-Cost Evaluation

Recently there has been increasing interest in reducing the economic losses suffered by customers due to interruptions [11], especially in the field of power quality [25]. Meanwhile, there has been a recognition that momentary interruptions play a significant role in causing customer economic losses [26]. Traditional system performance indices such as system average interruption frequency index ($SAIFI$), system average interruption duration index ($SAIDI$) and customer average interruption duration index ($CAIDI$), and others are not sufficient to provide information representing the cost of reliability. The less widely used index $MAIFI$, along with cost functions based on the cost to customers have been used to provide information to evaluate the reliability level of the distribution system and the demand for new investments.

In reference [27], both analytical techniques and a time sequential Monte Carlo simulation technique are used to evaluate the reliability-cost worth indices of a complex distribution system. One of the indices is the expected interruption cost ($ECOST$). The generalized analytical approach for $ECOST$ computation is summarized below. For each load point i and outage of element j, find the average failure rate λ_{ij} and the average outage time r_{ij}. Then apply the outage time and the customer type at load point i to determine the per unit (kWh) interruption cost c_{ij} using sector customer damage functions (SCDF). SCDF represent the costs incurred during outages as a function of outage duration for different customer types in an affected service area [3]. Therefore, for load point i,

$$ECOST_i = \sum_{j=1}^{N_e} c_{ij} L_i \lambda_{ij}$$

where N_e is the number of elements that may fail and cause interruptions for the load point, and L_i is the average load of load point i.

Repeating the process for every load point, and the total system expected cost can be obtained by taking the sum of the expected cost for each load point.

$$ECOST = \sum_{i=1}^{N_{LP}} L_i \sum_{j=1}^{N_e} c_{ij} \lambda_{ij}$$

Other than reference [27], S. Yeddanapudi et al. [28] presented a new method for evaluating a distribution system project worth, based on failure rates and the consequences of these failures. They proposed a new cost function involving the factors of customer satisfaction, revenue lost by utilities and the cost of equipment failure. However, their work is mainly based on the measurement of sustained interruptions and on the assumption that the network configuration would not change.

S.-Y. Yun et al. [23] proposed a cost function based on the costs to the different customer categories that were originally proposed in [27]. They proposed a unified reliability evaluation method in which the evaluation elements are integrated into the customer interruption cost for both sustained and momentary interruptions. They separate the per unit momentary interruption cost computation into two parts. Specifically, the impacts of the average momentary failure rate of components and the average sustained failure rate of components are taken into account individually.

Unlike those above using a cost function to evaluate the reliability worth of the system design, Ortmeyer et al. [29] developed an incremental cost-based approach that provides linkage between $SAIFI$ and $MAIFI$, where $MAIFI$ is less widely used compared to $SAIFI$. The proposed model is based on the relative cost relationship between sustained and momentary interruptions for different types of customers. They proposed a term called $SAIFI/MAIFI$ relative cost ratio ($SMRCR$). A factor of 2.0 is used in this paper for $SMRCR$. This proposed index provides the relative view of customers who view the impact of having 2 momentary interruptions is similar to the impact of a single 2 hours sustained interruption, whose duration is at the same $CAIDI$ level as the entire system. The final combined sustained momentary average interruption frequency ($SMAIF$) index for the purpose of project design comparison is calculated below.

$$SMAIF = SAIFI + \frac{MAIFI}{SMRCR}$$

Based on the case study, it was shown that the $SMAIF$ index helped in the selection of system designs. Yet, according to the formula, the $SMAIF$ index is mainly based on the $SMRCR$ ratio. The $SMRCR$ ratio is a regional decision that will affect not only the quality of the service but the price as well. It needed to be carefully chosen in order to best represent customer needs. The method for selecting the $SMCRC$ ratio has yet to be discussed.

1.5 Methodology

This research is focused on the comparison of reliability improvement for manual and automatic transfer switches as well as static transfer switches when tying to an adjacent redundancy. The topology of one of the test systems will primarily involve open-ring looped distribution networks, similar to the ones presented in references [11] and [23]. The overall evaluation method will be analytical, especially when based on a path minimization method and on minimum cut set methods. For economic benefit evaluation, this research will mainly focus on the cost recovery issue and the period of pay-back based on net-present value evaluation.

1.6 Thesis Outline

This thesis consists of five chapters. Following the introduction in Chapter 1, Chapter 2 briefly describes concepts generally used in power system reliability evaluation. Specifically, Chapter 2 briefly introduces and defines the most frequently-used distribution system reliability indices. Those indices are used for later assessment of system reliability in Chapter 3 where the contribution of feeder reconfiguration is assessed. Chapter 3 involves the evaluation of the reliability impact related to the placement of normally open (NO) transfer switches and three different types of transfer switches. Chapter 4 extends those results by presenting an economic evaluation of different switch placements and switch technologies. The analysis focuses on customer benefits and utility capital investment. Chapter 5 summarizes the research work and makes general conclusions and future work is proposed.

1.7 Thesis contributions

The thesis contributions can be summarized as follows:

- The thesis generalizes the application of minimum cut set methods for reconfigurable and standard IEEE open-ring distribution networks for reliability evaluation. It takes into account both sustained and momentary interruptions.
- The research demonstrates a reliability improvement through application of advanced transfer switch technologies (i.e., from manual and automatic mechanical transfer switch to static transfer switches).
- Comparisons of placement of the NO transfer switches have been conducted. Results show that placing the transfer switch at the end of two adjacent radial feeders can contribute to reduce the most the annual

outage time suffered by customers, while placing the transfer switch at the feeding bus contributes most to lower the failure frequency seen in the feeders.

- The thesis demonstrates that the application of various transfer switch technologies significantly reduces associated CIC, and CIC can be further reduced when faster switches are applied. The net present value method has been utilized to combine CIC, capital investment in transfer switches, and lost-utility energy sale revenue to evaluate the economic viability of the design.

2. Introduction to Distribution System Reliability Indices

2.1 Introduction

In the electricity supply industry, the weakest link in terms of reliability is the distribution network. Therefore, great attention has been given in the past to the assessment of the reliability of distribution grids. As reliability is generally hard to describe objectively, the power system community has developed a number of reliability indices and techniques to calculate them. For example, the Institute of Electrical and Electronic Engineers (IEEE) has standardized a wide range of reliability indices and reliability calculations for general networks. These standard indices can provide information about the typical frequency and the duration of customer interruptions in any given network [30].

This chapter reviews the concepts behind these commonly applied indices and their calculation. Definitions of these indices are summarized from [3] and [30]. We review those here because they constitute the basis of the research conducted in this thesis.

2.2 System Reliability Indices

In this section, we present the standard definitions for reliability indices most commonly used. We distinguish *Primary* and *Customer-oriented* indices. The primary indices refer to individual components as well as load points. The customer-oriented indices describe the overall performance of the system. Section 2.2.1 reviews the definition and calculation techniques of the three primary indices. Section 2.2.2 presents the description of customer-oriented indices.

2.2.1 Primary Indices

Failure rate: $\lambda_{Li}(freq/year)$, outage/restoration duration: $r_{Li}(h)$, and annual outage time: $U_{Li}(h/year)$ are the three primary indices used for the system reliability evaluation of load point i. They can be obtained based on the following three equations.

$$\lambda_{Li} = \sum_{j \in M} \lambda_j$$

$$U_{Li} = \sum_{j \in M} \lambda_j \, r_j$$

$$r_{Li} = \frac{U_{Li}}{\lambda_{Li}}$$

where M is the set of components that have an impact on load point i, and λ_j is the failure rate of the j^{th} component that belongs to the set M.

The repair rate μ of any component can be easily obtained by taking the reciprocal of component repair duration r.

Primary indices are the basis of computing system wide indices.

2.2.2 Customer-Oriented Indices

The three primary indices described previously are very important. They constitute the basis of all distribution network reliability evaluation. However, they cannot fully demonstrate the characteristics for the reliability of a distribution system. In order to reflect the severity and importance of system outages, the IEEE standardized a set of system reliability indices. These indices can provide reliability information for overall system. Through these indices, weaknesses of the system can be identified. The concepts and calculation techniques of those commonly used system performance indices, i.e., $SAIFI, SAIDI, CAIFI, CAIDI, ASAI \text{ and } ASUI$, are presented briefly next.

2.2.2.1 *System Average Interruption Frequency Index (SAIFI)*

This reliability index provides the average number of or frequency of sustained interruption events that each customer would experience on a yearly basis. The mathematical expression for $SAIFI$ is presented below.

$$SAIFI = \frac{total\ number\ of\ customer\ interruptions}{total\ number\ of\ customers\ served} = \frac{\sum_i \lambda_i N_i}{\sum_i N_i} = \frac{CI}{N_T}$$

where CI represents the number of customers interrupted, and N_T is the total number of customers served in the area.

2.2.2.2 *System Average Interruption Duration Index (SAIDI)*

The index indicates the average interruption duration that each customer would experience for a sustained interruption event during the reported period of time (normally on a yearly basis). The mathematical expression for $SAIDI$ is presented below.

$$SAIDI = \frac{\sum customer\ interruption\ duration}{total\ number\ of\ customers\ served} = \frac{\sum_i r_i N_i}{\sum_i N_i} = \frac{CMI}{N_T}$$

where CMI is the customer minutes of interruption. CMI represents the sum of affected customer's service interruption duration for a given outage event.

2.2.2.3 *Customer Average Interruption Frequency Index (CAIFI)*

This index measures the average number of sustained interruptions that the customers would experience on a yearly basis. The mathematical expression for $CAIFI$ is presented below.

$$CAIFI = \frac{\sum Total\ number\ of\ customer\ interruptions}{Total\ number\ of\ customers\ affected}$$

The denominator describes the total number of customers that have experienced at least one sustained interruption. Customers affected should be counted only once regardless of the number of interruptions they might experience.

2.2.2.4 *Customer Average Interruption Duration Index ($CAIDI$)*

This index measures the average outage duration for each interrupted customer during the year. On average, any customer who experienced a sustained outage during the period in question is out of service for $CAIDI$ hours. The mathematical expression for $CAIDI$ is presented below.

$$CAIDI = \frac{\sum Customer\ interruption\ duration}{Total\ number\ of\ customers\ interrupted} = \frac{\sum_i U_i N_i}{\sum_i \lambda_i N_i} = \frac{CMI}{CI} = \frac{SAIDI}{SAIFI}$$

2.2.2.5 *Average Service Availability Index ($ASAI$)*

$ASAI$ measures the ratio of uninterrupted service and customer demanded service on a yearly basis (8760 hours). The mathematical expression for $ASAI$ is presented below.

$$ASAI = \frac{Customer\ \hbar ours\ of\ available\ service}{Customer\ \hbar ours\ demand} = \frac{\sum_i 8760 N_i - \sum_i U_i N_i}{\sum_i 8760 N_i}$$
$$= 1 - \frac{\sum_i U_i N_i}{\sum_i 8760 N_i}$$

2.2.2.6 *Average Service Unavailability Index ($ASUI$)*

$ASUI$ measures the percentage of outage for the system. The mathematical expression for $ASUI$ is presented below.

$$ASUI = 1 - ASAI$$

2.3 Summary

In this chapter, we introduced and defined those commonly used indices for distribution system reliability evaluation. In the next chapter, we will look how to apply these indices to evaluate reliability improvement of reconfigurable open-ring distribution networks as well as various transfer switch technologies using minimum cut set method. A brief introduction of the minimum cut set method as well as traditional analytical evaluation methods can be found in Appendix A. We focus on the minimum cut set method, as it is the method applied in this research. Examples of how to apply the minimum cut set method can be found in Appendix B.

3 Reliability Analysis of Ring-Structured Distribution Networks

3.1 Introduction

The open ring distribution network configuration is one of the most commonly used MV distribution networks topologies for the purpose of decreasing interruption duration [25]. The ring network provides two independent alternative paths for load points at the secondary MV/LV substation, and each load point is radially connected to its primary supply source through the normally-closed load circuit breakers. Thus each sector of the ring can be treated as a purely radial feeder. Both sources are connected through the transfer switch at the normally-open point (NOP), which is normally located at the switchgear bus as shown in Figure 3.1 [31], or at the end of the feeder lines where two individual feeders can be connected, as shown in Figure 3.2 [23]. It is assumed that the failure events undergone in one source do not affect the functioning of the other one. Both sources are assumed to be able to support the entire load capacity of load points connected to them, and the two different utility sources are synchronized.

When a fault is detected along the MV lines, circuit breakers connecting the load to its primary sources will all be disconnected. Faulted sections can be isolated, and unfaulted downstream sections can be tied to the adjacent supply or feeder by closing the NO transfer switches. The restoration process is traditionally achieved through artificial methods, i.e., manual switches which requiring the dispatch of a crew in the field and take minutes or hours to accomplish. Now the restoration of the supply can be further reduced by the application of mechanical automatic transfer switches and static transfer switches.

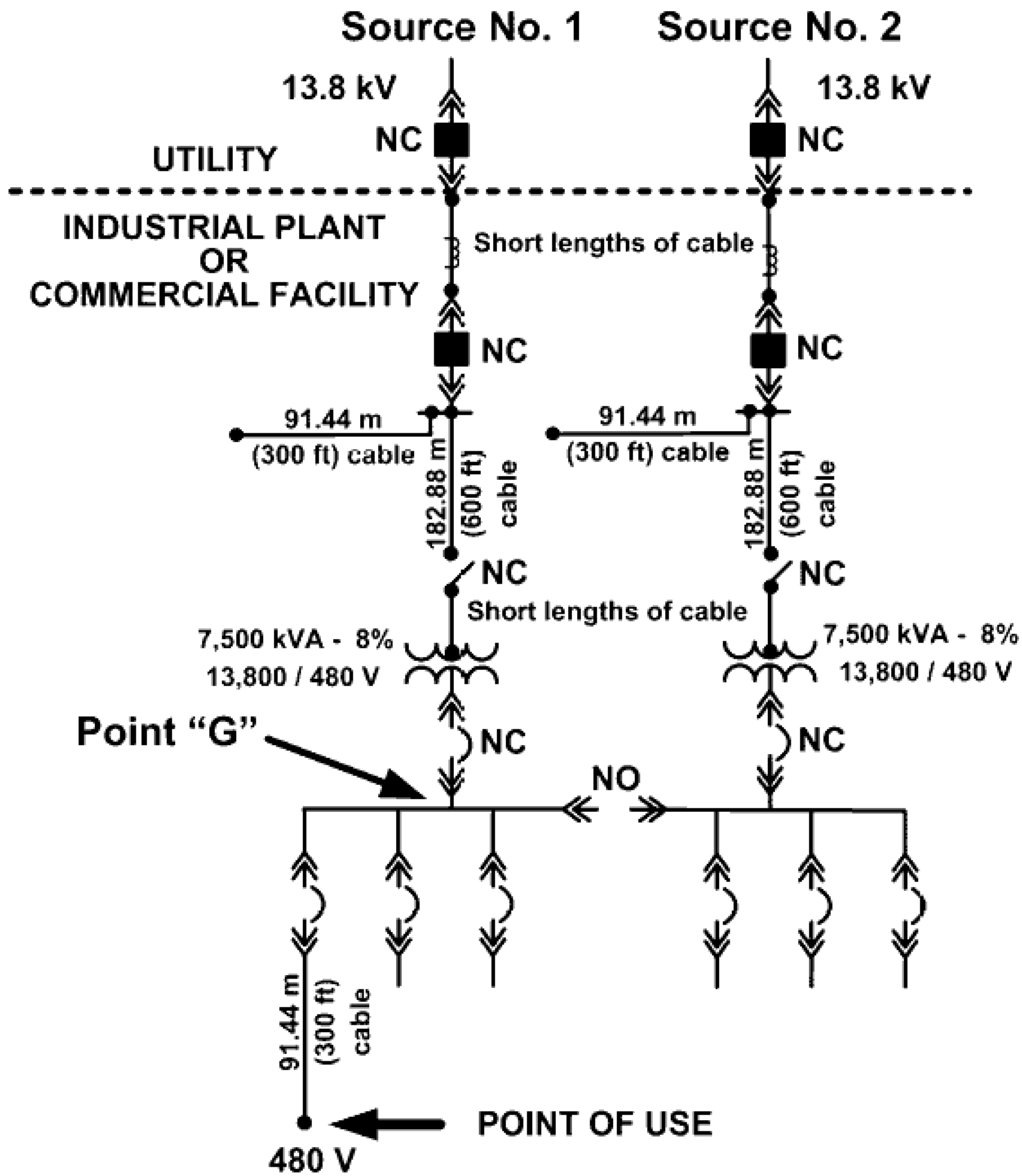

Figure 3.1 IEEE Gold Book Test System [31]

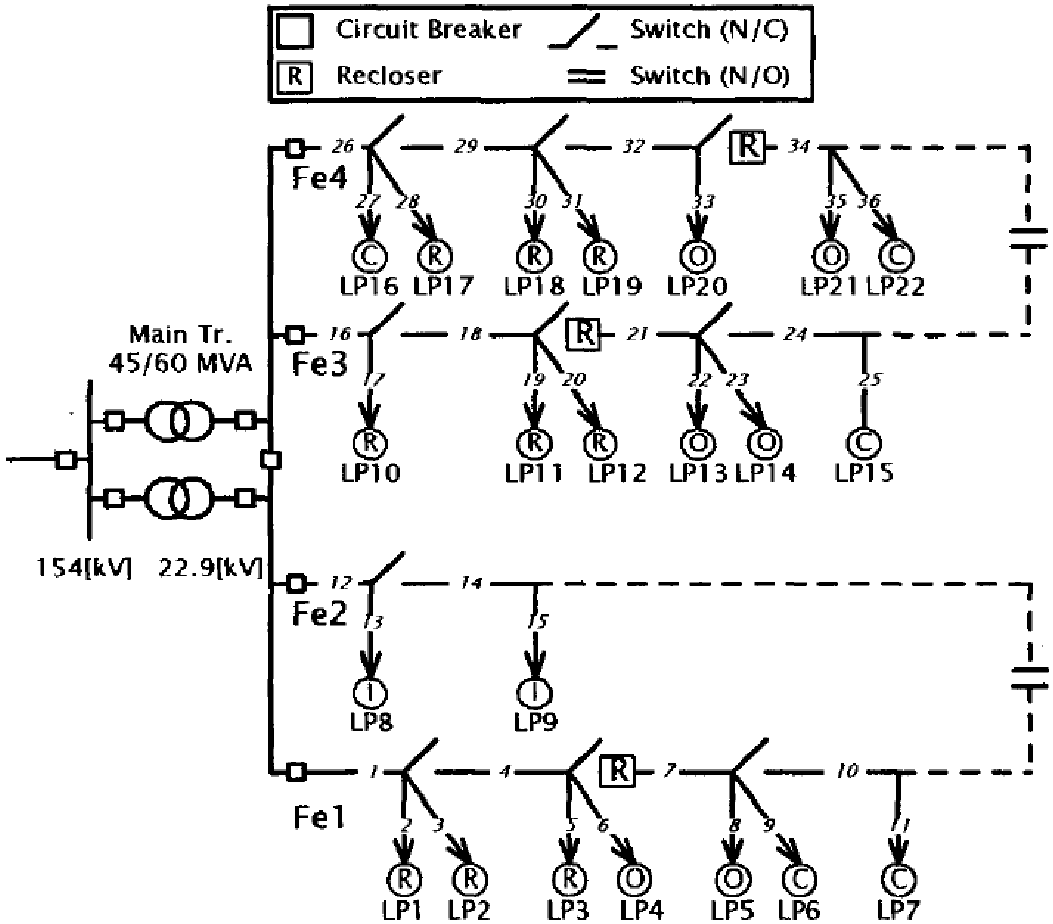

Figure 3.2 Modified Roy Billinton Test System (RBTS) [23]

The first part of this chapter will be the validation of the minimum cut set method adaptation developed for the purpose of this work. Unlike the classic minimum cut set approaches found in the literature, we provide a generic minimum cut set method that considers the impact of transfer switching actions. In the second part, case studies regarding to three different open-ring distribution networks along with three different transfer switch technologies are considered. Comparisons between them are summarized. Please refer to Appendices A and B for detailed description for minimum cut set method and how it is applied here in order to find possible sustained and momentary failure events in the open ring system.

As there is not a standard software package used for performing minimum cut set analyses, the author has developed a program code to adapt the method.

Program code for reliability assessment and further extended economic cost-worth evaluation has also been developed. Please refer to Appendix C for detailed information and code listings.

3.2 Validation of Reliability Assessment Method with IEEE-Gold Book Test System

In this part of the chapter, the test system presented in the IEEE Gold Book, Std. 493-2007, p. 54 [31], is used to validate the adaptation of the minimum cut set method which was implemented for the purpose of this research work. Figure 3.1 shows the one-line diagram of the test system. It is a secondary-selective power distribution system.

Circuit Description

The system shown in Figure 3.1 has two identical supply sources, source No.1 and source No.2, as shown in the figure. Both receive power at 13.8 kV from the electric utility and are connected to the 13.8 kV/480 V transformer through cables and 13.8 kV circuit breakers. Then through the 480 V main circuit breaker, the circuit is connected to the 480 V switchgear busbar. On the 480 V switchgear busbar, there is a normally open circuit breaker. Under normal conditions, the circuit breaker at the normally open point is in an open state, and each load point on the LV side is fed through the primary supply source. In the event that there is any failure along the first 13.8 kV utility supply, the fault is isolated and the transfer switch on the normally open point is put in a closed state. The alternative power supply source takes on the role of feeding the load points.

The average failure rate and average repair time of each component is listed in Table 3.1 below. It should be pointed out that since source No.1 and source No.2 are identical, only one group of data will be tabulated. All data are collected from [31].

Here it should be pointed out that in the IEEE Gold Book, the transfer switches at the normally open point are assumed to be 100% reliable. The utility power supply is not independent, and the data collected from the IEEE survey is tabulated in Table 3.2 below.

Table 3.1 Failure rate and repair time for components

Component	Failure rate, λ (freq./yr)	Repair time, r (h)
13.8 kV power source from electric utility	1.956000	1.32
Primary protection and control system	0.000600	5.00
13.8 kV metal-clad circuit breaker	0.001850	0.50
13.8 kV switchgear bus-insulted	0.004100	37.33
Cable(13.8 kV) 274.32 m (900 ft)	0.002124	15.70
Cable terminations at 13.8 kV	0.002960	0.75
Disconnect Switch	0.001740	1.00
Transformer	0.010800	132.43
480 V metal-clad circuit breaker	0.000210	6.00
480 V switchgear bus-bare	0.009490	7.29
480 V metal-clad circuit breaker for other 5 LPs (failed while opening)[a]	0.000019	3.98
Cable(480 V) 91.44 m (300 ft)	0.000021	8.00
Cable terminations at 480 V	0.000740	0.75

[a]It is assumed that failures when circuit breakers are required to be opened (failed while opening) and the backup protective devices required to operate contribute to 9% of the total failure for the circuit breaker [31].

Table 3.2 IEEE survey of reliability of electric utility power supplies

Number of circuits	Failure rate: λ (freq./yr)	Repair time: r (h)
Single circuit	1.956	1.32
Double circuit – loss of both circuits	0.312	0.52
Double circuit – Calculated value for loss of source 1 while source 2 is okay	1.644	Load transfer switchover time
Calculated two utility power source at 13.8 kV that are independent	0.00115	0.66

From Figure 3.1, we can observe that from the 13.8 kV power source point up to the 480 V switchgear bus-bare (point G), the circuit is purely radial. Any failure along the feeder requires isolation and the alternative power source will cooperate with the NO transfer switches to replace the function of source No.1. Therefore, from the location point of the 13.8 kV utility source until point G, all components are in series, and the failure rate of losing one supply is the summation of failure rates of all components up to point G. Also, for each load point, account should be taken of the failed-while-opening issue for 480 V circuit breakers connecting other load points.

The equivalent circuit for one load point is presented below.

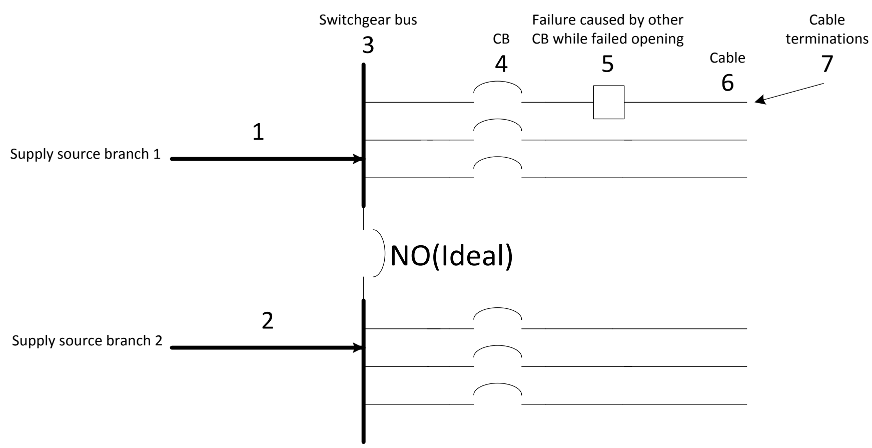

Figure 3.3 Equivalent circuit of the secondary selective system

The corresponding component reliability data is listed in table below. Based on the method, the minimum path p (see Appendix B for a formal definition) for load point 1 is,

$$p = \begin{pmatrix} 1 & 3 & 4 & 5 & 6 & 7 \\ 2 & 3 & 4 & 5 & 6 & 7 \end{pmatrix}$$

where each row of matrix p represents a successful path for power delivered to load point 1. All components appears in the row should be in operational mode.

Table 3.3 Failure rate and repair time for corresponding components in Figure 3.3 (Assuming supply source branch 1 and 2 are completely independent)

Component	Failure rate: λ (freq./yr)	Repair time: r (h)
Supply source branch (1)	1.980380	2.1247
Supply source branch (2)	1.980380	2.1247
480 V switchgear bus-bare (3)	0.009490	7.2900
480 V metal-clad circuit breaker (4)	0.000210	6.0000
480 V metal-clad circuit breaker for other 2 LPs (failed while opening) (5)	0.000019	3.9800
Cable(480 V) 91.44 m (300 ft) (6)	0.000021	8.0000
Cable terminations at 480 V (7)	0.000740	0.7500

Based on the minimum cut set method, we can find the failure rate for sustained interruptions. The corresponding minimum cut sets for one load point of this type of circuit can be obtained below.

Table 3.4 Minimum cut sets for one LP (Assuming NO transfer switch ideal.)

	First order cut set	**Second order cut set**
Minimum cut sets for one LP	3 4 5 6 7	1+2

(It should be pointed out, in the case that NO transfer switch is not 100% reliable, assuming it is component 8, then the minimum path p for load point 1 will be

$$p = \begin{pmatrix} 1 & 3 & 4 & 5 & 6 & 7 & 0 \\ 2 & 3 & 8 & 4 & 5 & 6 & 7 \end{pmatrix}$$

And there will be one more second order cut set [1+7] added to the overall computation.)

When load transfer is possible, the components and the switchover time involving short-duration interruption for load point 1 are listed below.

Table 3.5 Short duration interruption data for one LP (Assuming NO transfer switch ideal.)

Component	Interruption duration: r (h)
1	Switchover time

The following two tables will summarize the failure rate and the annual outage time at the 480 V point of use for two cases, source 1 and source 2 dependent and source 1 and 2 completely independent, respectively.

Case I. Supply source 1 and supply source 2 dependent

From Table 3.2, the IEEE survey of the reliability of electric utility power supplies, we know that for cases when both sources are lost, the statistical data show that the annual failure rate is 0.312. Meanwhile, when load transfer is possible, the reliability of losing both source 1 and source 2 is 1.644.

Table 3.6 Failure rate and repair time for corresponding components in Figure 3.3 (Assuming supply source branch 1 and 2 are dependent and NO switch ideal)

Component	Failure rate: λ (freq./yr)	Repair time: r (h)
Supply source branch (1)[a]	1.668384	NA
Supply source branch (2)[a]	1.668384	NA
480 V switchgear bus-bare (3)	0.009490	7.29
480 V metal-clad circuit breaker (4)	0.000210	6.00
480 V metal-clad circuit breaker for other 2 LPs (failed while opening) (5)	0.000019	3.98
Cable(480 V) 91.44 m (300ft) (6)	0.000021	8.00
Cable terminations at 480 V (7)	0.000740	0.75

[a]Sources 1 and 2 are dependent.

Table 3.7 Summary of reliability data for LP 1, assuming a 9 min manual switchover time to source 2.

	Failure rate, λ (freq./yr)	Repair time, r (h)	Annual outage time, U (h/yr)
Sum of first order cut set	0.010499	6.792679	0.071316
Sum of second order cut set	0.312000	0.52000	0.162240
Interruption while load transferring	1.668384	0.15000	0.250258
Total at 480 V	1.990883	0.243015	0.483814

Table 3.8 Summary of reliability data for LP 1, assuming a 5 s automatic switchover time to source 2.

	Failure rate, $\boldsymbol{\lambda}$ (freq./yr)	Repair time, $\boldsymbol{r}$ (h)	Annual outage time, $\boldsymbol{U}$ (h/yr)
Sum of first order cut set	0.010499	6.792679	0.071316
Sum of second order cut set	0.312000	0.520000	0.162240
Interruption while load transferring	1.668384	0.001389	0.002317
Total at 480 V	1.990883	0.118477	0.235873

Summary

For the manual switchover case, we can observe that the results for λ and U are exactly the same as the results presented in Table 3-13 in the IEEE Gold Book [31]. However, for the case of automatic switchover, the results are different. In [31], it is assumed that if the interruption duration for load transferring is less than 5 s, then the failure of the utility source can be ignored. However, in Table 3.8, the failure rate of source 1 is still taken into account. That is the reason we get λ equal to 1.990883 instead of 0.322499, and U equal to 0.235873 instead of 0.233556 in Table 3-13 of [31]. It should be pointed out that the difference between annual outage times for these two considerations is 0.7%.

Case II. Supply source 1 and supply source 2 completely independent

From Table 3.2, the IEEE survey of reliability of electric utility power supplies for independent sources, the failure rate is 1.956 and the annual outage time is 2.582 hours.

Table 3.9 Failure rate and repair time for corresponding components in Figure 3.3 (Assuming supply source branch 1 and 2 are indep. and NO switch ideal)

Component	Failure rate, λ (freq./yr)	Repair time, r (h)
Supply source branch (1)[a]	1.980384	2.1247
Supply source branch (2)[a]	1.980384	2.1247
480 V switchgear bus-bare (3)	0.009490	7.2900
480 V metal-clad circuit breaker (4)	0.000210	6.0000
480 V metal-clad circuit breaker for other 2 LPs (failed while opening) (5)	0.000019	3.9800
Cable(480 V) 91.44 m (300 ft) (6)	0.000021	8.0000
Cable terminations at 480 V (7)	0.000740	0.7500

[a]Source 1 and 2 are independent.

Table 3.10 Summary of reliability data for LP 1, assuming a 9 min manual switchover time to source 2.

	Failure rate, λ (freq./yr)	Repair time, r (h)	Annual outage time, U (h/yr)
Sum of first order cut set	0.010499	6.792679	0.071316
Sum of second order cut set	0.001902	1.062350	0.002021
Interruption while load transferring	1.980384	0.150000	0.297057
Total at 480 V	1.992785	0.185868	0.370395

Table 3.11 Summary of reliability data for LP 1, assuming a 5 s automatic switchover time to source 2.

	Failure rate, λ (freq./yr)	Repair time, r (h)	Annual outage time, U (h/yr)
Sum of first order cut set	0.010499	6.792679	0.071316
Sum of second order cut set	0.001902	1.062350	0.002021
Interruption while load transferring	1.980384	0.001389	0.002751
Total at 480 V	1.992785	0.038182	0.076088

Table 3.12 below will compare the dependency ratio in both dependent and independent cases.

Table 3.12 Failure rate and annual outage time dependency ratio in scale between dependent and independent cases

	Failure rate ratio	Annual outage ratio
Manual switchover	0.9990	1.3062
Automatic switchover	0.9990	3.1000

After considering the comparison results shown in Table 3.12, we can see that there will be only a slight difference in failure rate for both dependent and independent case. However, there is a difference in the annual outage term if the dependency of the sources is taken into account. The scale of the dependency ratio is 1.3062 for the manual case and 3.1000 for automatic case.

Summary

Through comparison and analysis the results above, it can be shown that the minimum cut set method (described in Appendix B) is applicable to simple system reliability evaluations. This is quite appealing, since it simplifies the computation for a parallel system while providing a reasonable expected value for failure frequency at load points. Moreover, it is easily programmable, thus reducing the work load of manual computation.

3.3 Case Study – Assessing Impact of Transfer Switch Technology

In this part of research, case studies of two types of open ring distribution network will be discussed, as shown in Figure 3.1 and Figure 3.2. The difference between these two topologies is the installation position of the NO transfer switches. For Figure 3.1, the NO transfer switches are installed on the switchgear bus, which functions as a secondary selective system between two supply sources. For Figure 3.2, the NO transfer switches are installed at the end of feeder lines connecting two radial distribution networks (with one supply source). A modified ring network in Figure.3.2 with two supply sources will then be studied. The data below are obtained under the assumption that every component is independent, and the results are calculated using the same method described in section 3.2. Only results will be presented here. Please refer to Appendices B and C for detail information.

In each case of studies, three sets of data will be presented in order to consider manual switchover time (9 min), automatic switchover time (5 s), and switchover time (5 ms) when static transfer switches are applied to the NOP.

3.3.1 Case Studies for IEEE-Gold Book Test System

From Section 3.2, the data of manual switchover and automatic switchover have already been computed.

Case I. Manual switchover – 9 min switchover time

Table 3.13 Summary of reliability data for LP 1, assuming a 9 min manual switchover time to source 2.

	Failure rate, λ (freq./yr)	Repair time, r (h)	Annual outage time, U (h/yr)
Sum of first order cut set	0.010499	6.792679	0.071316
Sum of second order cut set	0.001902	1.062350	0.002021
Interruption while load transferring	1.980384	0.150000	0.297057
Total at 480 V	1.992785	0.185868	0.370395

Case II. Automatic switchover – 5 s switchover time

Table 3.14 Summary of reliability data for LP 1, assuming a 5s automatic switchover time to source 2.

	Failure rate, λ (freq./yr)	Repair time, r (h)	Annual outage time, U (h/yr)
Sum of first order cut set	0.010499	6.792679	0.071316
Sum of second order cut set	0.001902	1.062350	0.002021
Interruption while load transferring	1.980384	0.001389	0.002751
Total at 480 V	1.992785	0.038182	0.076088

Case III. Static transfer switch – 5 ms switchover time

It should be pointed out that although there are different definitions for a failure based on complete loss of power duration, the bottom line is that power losses of less than 1 cycle should be neglected. Since the nominal switching time for STS is greater than 4ms but within half cycle, the interruption caused by transition should be neglected. The tables below include both cases for comparison purpose, neglecting the interruption effect for less than one cycle and taking account of the effect. The 5 ms switchover time is chosen for simplicity.

Table 3.15 Summary of reliability data for LP 1, assuming a 5 ms switchover time to source 2 (interruption less than 1 cycle considered).

	Failure rate, $\boldsymbol{\lambda}$ (freq./yr)	Repair time, $\boldsymbol{r}$ (h)	Annual outage time, $\boldsymbol{U}$ (h/yr)
Sum of First order cut set	0.010499	6.792679	0.071316
Sum of Second order cut set	0.001902	1.062350	0.002021
Interruption while load transferring	1.980384	$1.389 \cdot 10^{-6}$ [a]	$2.751 \cdot 10^{-6}$
Total at 480 V	1.992785	0.036803	0.073340

[a]Switchover time

Table 3.16 Summary of reliability data for LP 1, assuming a 5 ms switchover time to source 2 (interruption less than 1 cycle not considered).

	Failure rate, $\boldsymbol{\lambda}$ (freq./yr)	Repair time, $\boldsymbol{r}$ (h)	Annual outage time, $\boldsymbol{U}$ (h/yr)
Sum of first order cut set	0.010499	6.792679	0.071316
Sum of second order cut set	0.001902	1.062350	0.002021
Interruption while load transferring	0	$1.389 \cdot 10^{-6}$ [a]	0
Total at 480 V	0.012401	5.913797	0.073337

[a]Switchover time

By observing the two sets of data, we can see that the interruption frequency is significantly affected. The interruption frequency in the second case is actually 160.7 times lower than in the first case, but the difference in annual outage time is on the order of 10^{-6}, which can be neglected.

Summary of customer-oriented indices for the three cases

For analysis purposes, assuming that customers at the 480 V point of use are purely residential, for a 7500 kVA transformer capacity (with a 0.8 power factor) the power delivered should be 6 MW. Assuming an average instantaneous power consumption of 2 kW at any given time for one residential customer [32], there is then a total of 3000 customers at the 480 V point of use. Therefore, for one load point, there are 500 customers.

Table 3.17 Summary of customer-oriented indices for three cases

	Manual Switchover – 9 min	Automatic Switchover – 5 s	STSs Application – 5 ms Switchover
$\boldsymbol{CI}$	996.39	996.39	6.2007
$\boldsymbol{CMI^a}$	185.20	38.044	36.669
$\boldsymbol{SAIFI}$	1.9928	1.9928	0.0124
$\boldsymbol{SAIDI}$	0.3704	0.0761	0.0733
$\boldsymbol{CAIFI}$	1.9928	1.9928	0.0124
$\boldsymbol{CAIDI}$	0.1859	0.0382	5.9136
$\boldsymbol{ASAI}$	0.9999577	0.9999913	0.99999162815
$\boldsymbol{ASUI}$	0.0000423	0.0000087	0.00000837185

[a]CMI here is presented in the unit of hours

The table below will summarize the difference between ATS and STS cases versus manual cases in customer-oriented indices.

Table 3.18 Difference in customer-oriented indices

	ATS vs Manual	STS vs Manual
$\boldsymbol{\Delta CI}$	0	990.19
$\boldsymbol{\Delta CMI^a}$	147.16	148.531
$\boldsymbol{\Delta SAIFI}$	0	1.9804
$\boldsymbol{\Delta SAIDI}$	0.2943	0.3374
$\boldsymbol{\Delta CAIFI}$	0	1.9804
$\boldsymbol{\Delta CAIDI}$	0.1477	5.7277
$\boldsymbol{\Delta ASAI}$	$3.36 \cdot 10^{-5}$	$9.16 \cdot 10^{-5}$

[a]CMI here is presented in the unit of hours

For purely residential customer categories, with the assumptions made above, we observe that customers benefit significantly from fast load transfer times, especially in indices involving outage durations. For the CMI index, it is at least a reduction of 147 hours annually for one load point. Even though the $CAIDI$ is 5.9136 hours for STS case, which is 31.81 times higher than the manual switchover case, we should notice that the CI is only 6.2007, which is 160.69 times less than the manual case. Relatively, it can be seen as a tradeoff. Meanwhile, we can observe that with a faster transfer switch, the average system availability index is slightly improved.

3.3.2 Modified RBST Open Ring Distribution Network with One Supply Source

The system configuration used in this part of case study will be a simplified version of Figure 3.2 from [23].It is a modified RBTS system with a NO transfer switches connecting two radial feeders at the end of the feeder lines.

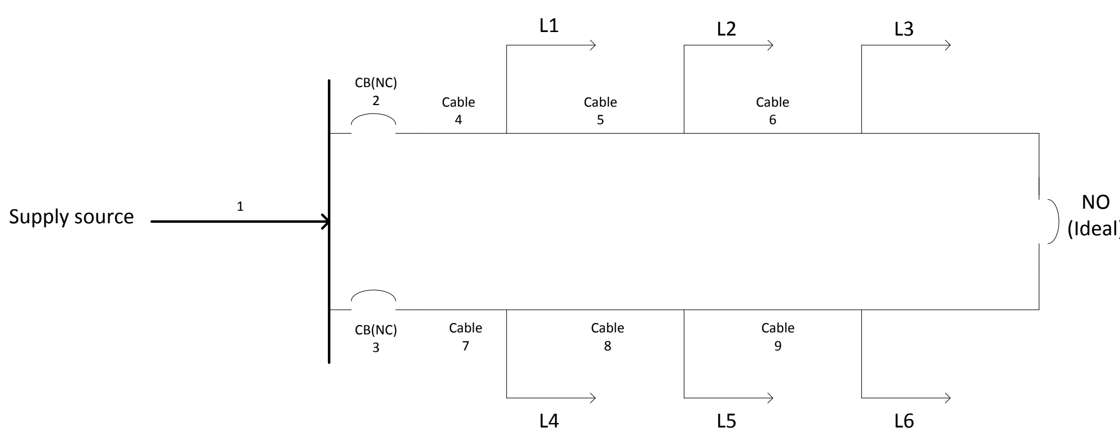

Figure 3.4 Modified open ring distribution system of Figure 3.2

For simplification, the configuration of the supply source branch will be the same as in Figure 3.1. The potential failure components for each load point branch are displayed below, assuming that all load points are identical. From Figure 3.1, we know that the load points are 300 ft away from the bus. For comparison purposes, we assume the total length of the cables from the bus to the load points are the same, which equals to 300 ft.

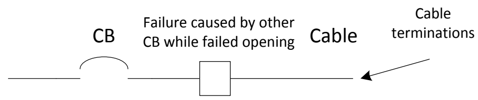

Figure 3.5 Expanded load point potential failure components

Assume that all components are independent and that 100% reliable fast-blow fuses are installed at the T-point of each load point section along the main feeder.

The average failure rate and average repair time for each component will be tabulated in the following table. Since we are dealing with six identical load points, only one group of data will be documented below.

Table 3.19 Failure rate and repair time for corresponding components in Figure. 3.4 (assuming NO switch ideal)

Component	Failure rate, λ (freq./yr)	Repair time, r (h)
Supply source branch (1)	1.980380	2.1247
480V metal-clad circuit breaker (2)	0.000210	6.0000
480V metal-clad circuit breaker (3)	0.000210	6.0000
Cable(480 V) 30.48 m (100 ft) (4)-(9)	0.000007	8.0000

Table 3.20 Failure rate and repair time for corresponding components in Figure. 3.5

Component	Failure rate, λ (freq./yr)	Repair time, r (h)
480 V metal-clad circuit breaker	0.000210	6.000000
480 V metal-clad circuit breaker for other 2 LPs (failed while opening)	0.000038	3.980000
Cable terminations at 480 V	0.000740	0.750000
Cable(480 V) 30.48 m (100 ft)	0.000007	8.000000
L1 (10)	**0.001002**	**2.074092**
L2 (10)	**0.000995**	**2.032402**
L3 (10)	**0.000988**	**1.990121**

Due to the symmetry of the configuration, only L1 to L3 will be studied.

For load point 1, the minimum path p_{L1} is,

$$p_{L1} = \begin{pmatrix} 1 & 2 & 4 & 10 & 0 & 0 & 0 & 0 \\ 1 & 3 & 5 & 6 & 7 & 8 & 9 & 10 \end{pmatrix}$$

For load point 2, the minimum path p_{L2} is,

$$p_{L2} = \begin{pmatrix} 1 & 2 & 4 & 5 & 10 & 0 & 0 \\ 1 & 3 & 6 & 7 & 8 & 9 & 10 \end{pmatrix}$$

For load point 3, the minimum path $p_{L3}$is,

$$p_{L3} = \begin{pmatrix} 1 & 2 & 4 & 5 & 6 & 10 \\ 1 & 3 & 7 & 8 & 9 & 10 \end{pmatrix}$$

The corresponding minimum cut sets for sustained interruptions of each load point are summarized below.

Table 3.21 Minimum cut sets for LP L1-L3 (assuming NO ideal.)

	L1	L2	L3
First order	1,10	1,10	1,10
Second order	(2,3),(2,5),(2,6),(2,7), (2,8),(2,9),(3,4),(4,5), (4,6),(4,7),(4,8),(4,9)	(2,3),(2,6),(2,7),(2,8),(2,9), (3,4),(3,5),(4,5),(4,6),(4,7), (4,8),(4,9),(5,6),(5,7),(5,8), (5,9)	(2,3),(2,7),(2,8),(2,9),(3,4), (3,5),(3,6),(4,7),(4,8),(4,9), (5,7),(5,8),(5,9),(6,7),(6,8), (6,9)

When load transfer is possible, i.e. components 1 and 10 are in operational mode, components and switchover time involving short duration interruption for load point L1-L3 are listed below.

Table 3.22 Short duration interruption data for LP 1-3

	Component	Interruption duration, r (h)
L1	(2,4)	Switchover time
L2	(2,4,5]	Switchover time
L3	(2,4,5,6)	Switchover time

Case I. Manual switchover – 9 min switchover time

Table 3.23 Summary of reliability data for LP 1, assuming a 9 min manual switchover for reconfiguration.

	Failure rate, λ (freq./yr)	Repair time, r (h)	Annual outage time, U (h/yr)
Sum of first order cut set	1.981382	2.124674	4.209792
Sum of second order cut set	$7.50 \cdot 10^{-11}$	3.090000	$2.31 \cdot 10^{-10}$
Interruption while load transferring	0.000217	0.15[a]	0.000033
Total at 480 V	1.981599	2.124458	4.209825

[a]Switchover time

Table 3.24 Summary of reliability data for LP 2, assuming a 9 min manual switchover for reconfiguration.

	Failure rate, λ (freq./yr)	Repair time, r (h)	Annual outage time, U (h/yr)
Sum of First order cut set	1.981375	2.124654	4.209736
Sum of Second order cut set	$7.52 \cdot 10^{-11}$	3.089827	$2.32 \cdot 10^{-10}$
Interruption while load transferring	0.000224	0.15[a]	$3.36 \cdot 10^{-5}$
Total at 480 V	1.981599	2.12443	4.209769

[a]Switchover time

Table 3.25 Summary of reliability data for LP 3, assuming a 9 min manual switchover for reconfiguration.

	Failure rate, λ (freq./yr)	Repair time, r (h)	Annual outage time, U (h/yr)
Sum of First order cut set	1.981368	2.124633	4.209680
Sum of Second order cut set	$7.53 \cdot 10^{-11}$	3.090909	$2.33 \cdot 10^{-1}$
Interruption while load transferring	0.000231	0.15[a]	$3.47 \cdot 10^{-5}$
Total at 480 V	1.981599	2.124403	4.209714

[a]Switchover time

Case II. Automatic switchover – 5 s switchover time

Table 3.26 Summary of reliability data for LP 1, assuming a 5 s automatic switchover for reconfiguration.

	Failure rate, λ (freq./yr)	Repair time, r (h)	Annual outage time, U (h/yr)
Sum of first order cut set	1.981382	2.124674	4.209792
Sum of second order cut set	$7.50 \cdot 10^{-11}$	3.090000	$2.31 \cdot 10^{-10}$
Interruption while load transferring	0.000217	0.001389[a]	$3.01 \cdot 10^{-7}$
Total at 480 V	1.981599	2.124442	4.209792

[a]Switchover time

Table 3.27 Summary of reliability data for LP 2, assuming a 5 s automatic switchover for reconfiguration.

	Failure rate, λ (freq./yr)	Repair time, r (h)	Annual outage time, U (h/yr)
Sum of first order cut set	1.981375	2.124654	4.209736
Sum of second order cut set	$7.52 \cdot 10^{-11}$	3.089827	$2.32 \cdot 10^{-10}$
Interruption while load transferring	0.000224	0.001389[a]	$3.11 \cdot 10^{-7}$
Total at 480 V	1.981599	2.124413	4.209736

[a]Switchover time

Table 3.28 Summary of reliability data for LP 3, assuming a 5 s automatic switchover for reconfiguration.

	Failure rate, λ (freq./yr)	Repair time, r (h)	Annual outage time, U (h/yr)
Sum of first order cut set	1.981368	2.124633	4.209680
Sum of second order cut set	$7.53 \cdot 10^{-11}$	3.090909	$2.33 \cdot 10^{-10}$
Interruption while load transferring	0.000231	0.001389[a]	$3.21 \cdot 10^{-7}$
Total at 480 V	1.981599	2.124403	4.209714

[a]Switchover time

Case III. Static transfer switch – 5 ms switchover time

Table 3.29 Summary of reliability data for LP 1, assuming a 5 ms switchover time to source 2

	Failure rate, λ (freq./yr)	Repair time, r (h)	Annual outage time, U (h/yr)
Sum of first order cut set	1.981382	2.124674	4.209792
Sum of second order cut set	$7.50\cdot10^{-11}$	3.090000	$2.31\cdot10^{-10}$
Interruption while load transferring	0	$1.389\cdot10^{-6}$[a]	0
Total at 480 V	1.981382	2.124675	4.209792

[a]Switchover time

Table 3.30 Summary of reliability data for LP 2, assuming a 5ms switchover time to source 2

	Failure rate, λ (freq./yr)	Repair time, r (h)	Annual outage time, U (h/yr)
Sum of first order cut set	1.981375	2.124654	4.209736
Sum of second order cut set	$7.52\cdot10^{-11}$	3.089827	$2.32\cdot10^{-10}$
Interruption while load transferring	0	$1.389\cdot10^{-6}$[a]	0
Total at 480 V	1.981375	2.124653	4.209736

[a]Switchover time

Table 3.31 Summary of reliability data for LP 3, assuming a 5ms switchover time to source 2

	Failure rate, λ (freq./yr)	Repair time, r (h)	Annual outage time, U (h/yr)
Sum of first order cut set	1.981368	2.124633	4.209680
Sum of second order cut set	$7.53\cdot10^{-11}$	3.090909	$2.33\cdot10^{-10}$
Interruption while load transferring	0	$1.389\cdot10^{-6}$[a]	0
Total at 480 V	1.981368	2.124633	4.209680

[a]Switchover time

Summary

The problem with having only one supply source is that when any component fails in the supply branch, the whole system fails as a result. Also, since the supply branch contains the power source and its transformer, both dominant terms contributing to failure frequency and repair time, the overall system performance turns out to be poor compared to that of the system with 2 identical power supply sources (Figure 3.1). The annual outage and the failure frequency for each load point merely improve with different types of switches due to the fact that the benefit of fast load transfer is hidden by the dominant failure rate of the supply branch.

3.3.3 Modified RBST Open Ring Distribution Network with Two Supply Sources

In section 3.3.2 the modified RBST open ring distribution network with a single supply source was discussed. Due to the dominant feature of the single supply source, the failure frequency and annual outage time for each load point don't improve as the load transfer rate becomes faster. In this section, the modified RBST open ring distribution network with two independent supply sources, shown in Figure 3.6, will be discussed using the same methodology described before.

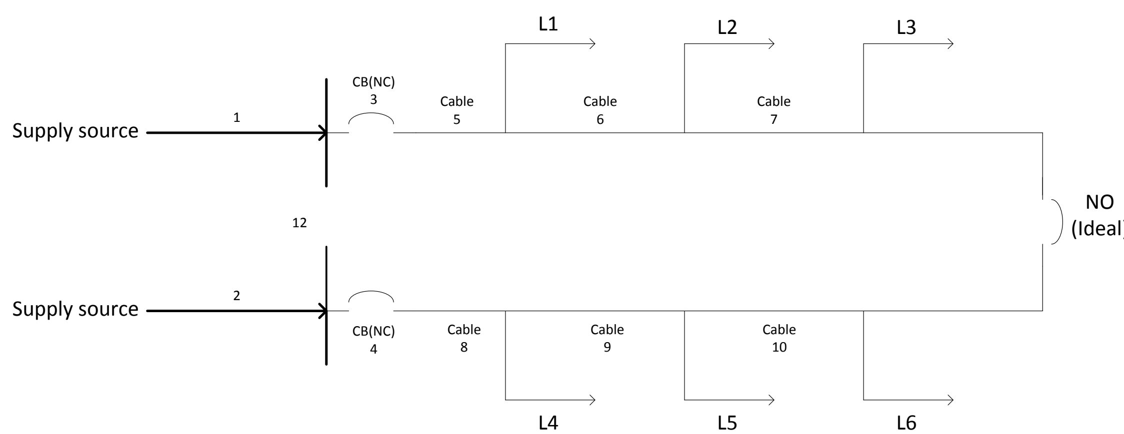

Figure 3.6 Modified RBST ring network with two supply sources

Assume that supply sources 1 and 2 are identical and independent. All the components and all the reliability data for the load points are identical to the ones used in section 3.3.1 and 3.3.2.

The following tables summarize the failure frequency and annual outage results for load points L1-L3 in three cases.

Table 3.32 Summary of reliability data for LP 1

	Manual Switchover	ATS	STS
Failure rate, λ (freq./yr)	1.992992	1.992992	0.012395
Annual outage time, U (h/yr)	0.370413	0.076034	0.073283

Table 3.33 Summary of reliability data for LP 2

	Manual Switchover	ATS	STS
Failure rate, λ (freq./yr)	1.992992	1.992992	0.012388
Annual outage time, U (h/yr)	0.370358	0.075978	0.073227

Table 3.34 Summary of reliability data for LP 3

	Manual Switchover	ATS	STS
Failure rate, λ (freq./yr)	1.992992	1.992992	0.012381
Annual outage time, U (h/yr)	0.370304	0.075922	0.073174

Summary

Upon comparing Table 3.23-3.31 with Table 3.32-3.34, we can see that even though the failure frequency for each load point is slightly higher due to the additional supply source, the annual outage time for each load point is significantly reduced. For load point 3 with manual switchover case alone (the worst case scenario), the annual outage time is 11.37 times shorter.

The following tables, Table 3.35 and Table 3.36, summarize the comparison results for different placements of NO transfer switches with regard to load point 1 in Figure 3.1 and load point 3 in Figure 3.6 (worst case scenario), both with two independent supply sources.

Table 3.35 Failure frequency result comparison for Figure 3.1 and Figure 3.6

	IEEE Gold Book Test Ring Configuration	Modified Ring with Two Supply Sources	Difference in Percentage (%)
Manual	1.992785	1.992992	0.010387
ATS	1.992785	1.992992	0.010387
STS	0.012401	0.012381	0.161277

Table 3.36 Annual outage result comparison for Figure 3.1 and Figure 3.6

	IEEE Gold Book Test Ring Configuration	Modified Ring with Two Supply Sources	Difference in Percentage (%)
Manual	0.370395	0.370304	0.024568
ATS	0.076088	0.075922	0.218168
STS	0.073337	0.073174	0.222262

From Tables 3.35 and 3.36, it is evident that even though the failure frequency for the IEEE Gold Book Test case is slightly smaller than the frequency for the modified ring case, it turns out that the latter case provides better annual outage duration per load point. This is due to the fact that the NOP is located at the MV bus for the IEEE topology. The NO transfer switches reduce the interruption duration caused by failures along the supply branch only; however, any line failure detected along the feeder will trigger the 480 V metal-clad CB. This load point can only be re-fed when the restoration of the line is complete. However, for the modified RBST open ring distribution network, the NOP is located at the end of the feeders. Each load point can be fed from two lines. If any upstream line failure is detected, customers can be re-fed through the load by transferring from the adjacent feeder. Therefore, this will further reduce the duration of the interruption suffered by customers. Relatively speaking, failure frequency for each load point in modified RBST topology is slightly higher, since power needs to go through a higher number of components for load transfer.

Meanwhile, we should keep in mind that in the IEEE Gold Book Test case, there is only one MV bus along with a 1800-ft cable section, while in the modified RBST case, there are two MV buses but only 1200 ft of cables. We can conclude here that for application of a fast transfer switch, the placement of a NO switches should be at the end of the feeder if the main concern is to further reduce customer interruptions.

3.4 Summary

This chapter describes a reliability evaluation methodology for a simple distribution network. This method is validated using an IEEE Gold Book [31], open-ring bus configuration example.

Detailed reliability analyses are presented for three different types of open ring distribution configurations related to different placements of the NO switches and different types of transfer switches. The resulting load point and customer-oriented indices are also presented. The relative impact of different configurations, different placements of NO transfer switches, and different types of transfer switches on the load point indices can be clearly seen from the analysis results. It is apparent that fast transfer switches do influence the annual outage time, compared to the manual switch case for configurations having alternative supply sources. The placement of the NO transfer switches should be decided based upon whether the main concern is to further reduce the duration of customer interruptions or to reduce the failure frequency. It should also be pointed out that the dependency of components does affect the results considerably. When data is presented, one should always consider the dependency of components.

4. Evaluation of Economic Benefit Worth

4.1 Introduction

In this part of the research, economical evaluation will be performed for both the customer and the utility side. The first part will be an analysis of interruption cost for various customer types and caused by different switchover times. The second part will be an economical analysis of the utility side, focused mainly on economic benefit worth and cost recovery due to lost sales. Based on the present value method, the feasibility of the program, whether it is economically viable, and whether it achieves a sustainable level of customer complaints for a win-win situation, will all be discussed using results from the customer and utility sides. The capital investment for the equipment will also be analyzed.

4.2 Customer Interruption Cost

For the customer side, the costs to customers associated with different levels of load point reliability are one of the significant factors that should always be explicitly considered during system planning and during the designing process. One of the economic evaluation methods based on customer perception of the level of system reliability is the customer interruption cost (CIC) [2], [3]. This is regarded as the worth of the service that customers are willing to pay for, and this measure can provide the estimated dollar value of various level of reliability. The interruption cost is determined based on customer types and is presented as a function of interruption duration.

The data related to the customer interruption costs for sustained and momentary interruptions and customer types are shown in Table 4.37 below. The sustained customer interruption costs are calculated from the data compiled from customer surveys and from the corresponding sector damage function

(SCDF) of Canada [3]. The data for momentary interruption durations are data presented in [23].

Table 4.37 Customer interruption cost $/kW for various customer types and interruption durations

Customer Interruption Cost ($/kW)								
Customer Type	**Momentary Interruption**		**Sustained Interruption**					
	0.5 s	**15 s**	**1 min**	**20 min**	**1 h**	**2 h**	**4 h**	**8 h**
Residential	0.00068	0.0520	0.021	0.093	0.482	1.64	4.914	15.69
Commercial	0.02932	0.2198	0.881	2.969	8.552	14.44	31.32	83.01
Office	0.15912	1.1923	4.778	9.878	21.06	38.39	68.83	119.2
Industrial	0.05412	0.4055	1.625	3.868	9.085	13.31	25.16	55.81

The figure below is the graphical representation of Table 4.37. 2nd order polynomial interpolations for sustained interruptions were made for four types of customer types based on the precise data points so that intermediate values for specific interruption duration can be estimated.

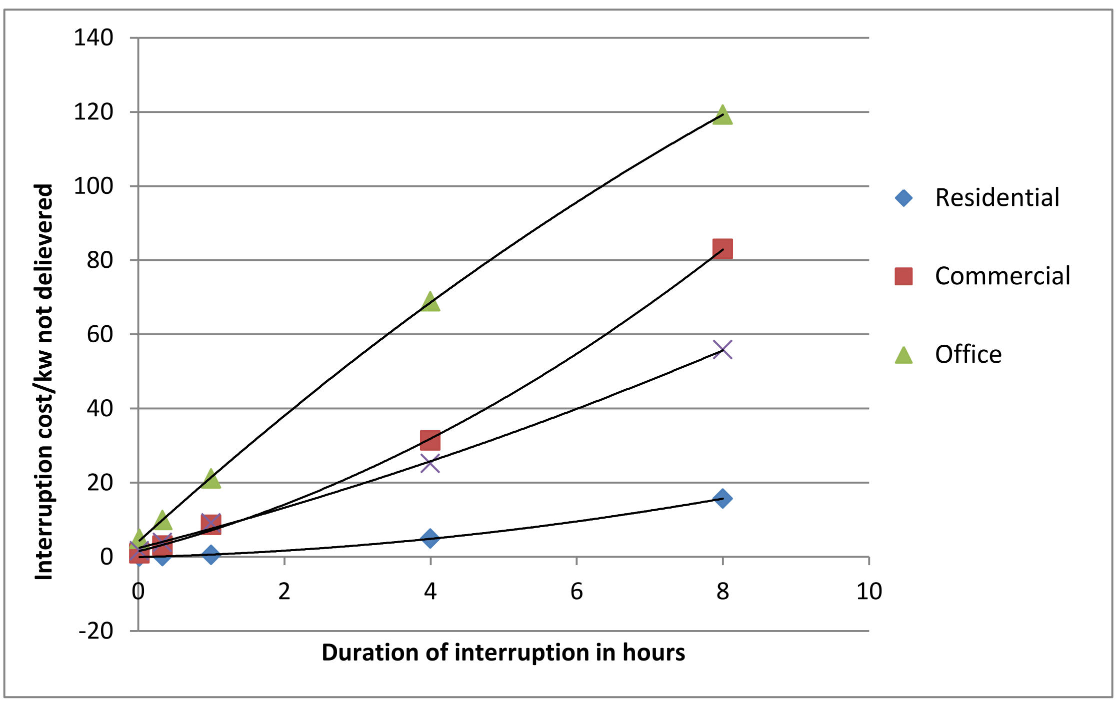

Figure 4.1 2nd order polynomial interpolation of sustained interruption for customer types

Table 4.38 2nd order polynomial interpolation equations for customer types

	2nd Order Polynomial Interpolation Equation
Residential	$y = 0.1845x^2 + 0.4969x - 0.0791$
Commercial	$y = 0.6441x^2 + 5.0229x + 1.487$
Office	$y = -0.4345x^2 + 17.872x + 4.08$
Industrial	$y = 0.2028x^2 + 5.0436x + 2.3538$

For momentary interruptions, it is hard to quantify the loss to customers for interruptions less than 1 min. With only two sets of data, it is hard to create an interpolation for the trend lines. Hence, in this chapter, the assumption for momentary interruption cost will be that for any interruption duration less than 1 min but longer than or equal to 15 s, the customer cost will be the counted as the cost for 15 s; for interruption durations less than 15 s but longer than or equal to 0.5 s, the customer cost will be the cost for 0.5 s; the interruption cost can be neglected otherwise.

Provided with the SCDF, the customer interruption cost (CIC) can be obtained based on the following equation [2].

$$CIC = \lambda_E \cdot L \cdot CIPKW$$

where λ_E is the failure rate of the failure event E, L is the average load connected at the load point associated with the failure event i, and $CIPKW$ is the cost of interruption per kW for a set of duration, which is provided in Table 4.37. The total cost of interruptions for a load point can be obtained through summation of all costs of failure events associated with this load point. Then, the total cost of the interruptions for all the customers in the system can be evaluated.

In order to perform the case study for different ring configurations and various customer types, we should first make assumptions about the average load level for customer types and the number of customers per load point. The data related to the customer average level per customer type and the number of customers per load point are both summarized in the table below. It should be pointed out that some data are slightly modified to meet the capacity assumptions made in Chapter 3. Original data are collected from [23] and [33].

Table 4.39 Customer load level

Customer Type	Average Load Level Per Customer (kW)	Number of Customers
Residential	2	500
Commercial	37.83	26
Office	500	2
Industrial	1000	1

The following section presents CIC case studies for different ring configurations. For each configuration, four cases will be performed, which are CIC when load transfer is not possible and CIC under three different types of switches. The first test case is for comparison purposes.

4.2.1 IEEE Gold Book Ring Configuration

Due to the symmetry of this type of system, all load points are identical. Results for only one load point will be documented.

Case I. Purely radial network – load transfer not available

Table 4.40 CIC - no load transfer

Customer Type	Annual Interruption Cost ($)
Residential	3713.11
Commercial	30543.15
Office	80489.67
Industrial	28185.20

Case II. Manual Switch over – 9 min

Table 4.41 CIC - Manual

Customer Type	Annual Interruption Cost ($)
Residential	129.92
Commercial	5185.04
Office	14506.50
Industrial	6672.49

Case III. Automatic Switchover with mechanical switch – 5 s

Table 4.42 CIC - ATS

Customer Type	Annual Interruption Cost ($)
Residential	132.08
Commercial	777.49
Office	1452.02
Industrial	610.98

Case IV. Automatic switchover with STS – 5 ms

Table 4.43 CIC - STS

Customer Type	Annual Interruption Cost ($)
Residential	130.74
Commercial	719.43
Office	1136.91
Industrial	503.80

4.2.2 Modified RBST Ring with Two Supply Sources

Because we want to observe the average customer lost per load point per feeder, we take the average value between three load points.

Case I. Purely radial network – load transfer not available

Table 4.44 CIC - no load transfer

Customer Type	Annual Interruption Cost ($)
Residential	3714.20
Commercial	30049.83
Office	80511.90
Industrial	28192.58

Case II. Manual Switch over – 9 min

Table 4.45 CIC - Manual

Customer Type	Annual Interruption Cost ($)
Residential	128.84
Commercial	5096.46
Office	14509.16
Industrial	6671.67

Case III. Automatic Switchover with mechanical switch – 5 s

Table 4.46 CIC - ATS

Customer Type	Annual Interruption Cost ($)
Residential	130.96
Commercial	760.49
Office	1452.56
Industrial	609.23

Case IV. Automatic switchover with STS – 5 ms

Table 4.47 CIC - STS

Customer Type	Annual Interruption Cost ($)
Residential	129.61
Commercial	703.37
Office	1137.40
Industrial	502.04

4.2.3 Summary

It can be clearly observed that the CIC for one load point is significantly reduced with a faster transfer switch and further reduced when the placement of NO transfer switches is at the end of two feeders. Ultimately, due to the symmetry of the system, the CIC of the example system is six times the documented data per load point. Therefore, in the real world, as the network grows bigger, the reduction in CIC brought by fast transfer switches will be more significant.

4.3 Lost-Utility Sales Revenue

For utility concerns, improving the reliability of the network is not the only primary purpose. The cost-benefit tradeoff of the investment and the possibility of cost recovery should always be taken into account.

In a case where the electricity price is fixed, and where a manual switch has been replaced with an automatic mechanical transfer switch or an advanced ultra-fast static transfer switch, one significant improvement in the system performance involves the interruption duration decrement. Utilities can evaluate the worth of the project in terms of the differences in customer minutes lost and find out the extra profit that the project will bring, i.e. lost energy sales. Provided with average load demand per customer per load point, the number of customers at the load point, and the electricity charge per kilowatt-hour, one can find differences in electricity bills using the following proposed formula.

$$\Delta Revenue = \Delta U \cdot L_{ave} \cdot Pr \cdot N_{LP} = \Delta CMI \cdot L_{ave} \cdot Pr = \Delta E \cdot Pr$$

where N_{LP} is the number of customers at the load point and Pr is the price of electricity in \$/kWh.

Table 4.48 CMI summary for IEEE Gold Book case

	Manual	ATS	STS
Residential	185.1975	38.0440	36.6685
Commercial	9.6303	1.9783	1.9068
Office	0.7408	0.1522	0.1467
Industrial	0.3704	0.0761	0.0733

Table 4.49 CMI summary for modified ring with two supply sources

	Manual	ATS	STS
Residential	185.1792	37.9890	36.6135
Commercial	9.2590	1.8995	1.8307
Office	0.7407	0.1520	0.1465
Industrial	0.3704	0.0760	0.0732

From Table 3.36, 4.39, 4.48, and 4.49, we can calculate the ΔE delivered through interruption reduction.

Table 4.50 ΔE for IEEE Gold Book Test System, modified ring with two sources based on Manual Switchover

	Manual vs ATS	Manual vs STS
IEEE Gold Book Test System	294.307	297.058
Modified ring with two sources	294.382	297.130

By only comparing the results in Tables 4.48 and 4.49, we can see that there are no significant differences in CMI between ATS and STS in both typologies. Since we assume that the average load level ($L_{avg} \cdot N_L$) per load point is 1 MW for each customer type per load point, ΔE in the Table 4.50 above are roughly the same. Even though STS reduces the transfer time from 5 s to 5 ms (1000 times faster), it is still significantly small on an annual hour unit basis. Therefore, the benefit of STS in terms of ΔE can't be clearly observed here. Meanwhile, in section 4.2, we already proved that CIC can be further reduced if faster transfer switches are applied. We now need to combine results from section 4.2 and 4.3 to make conclusions about what types of switches are economical viable for which types of customers for both typologies. Meanwhile, we should always keep in mind that the other benefit brought about by the application of STS is the enormous improvement in the rate of failure frequency in the uninterrupted power supply, which can't be explicitly observed.

4.4 Net Present Value

The traditional way to evaluate different projects and decide between alternative implementations is mainly based on whether the project will be profitable and maximize investments. Net present value (NPV) is the basic investment selection tool. Net present value is the sum of the present value of the cash inflows from a project minus the total cost of the investment.

If a project has a positive NPV, then the investment is expected to be recovered from the period of production. In other words, the project is economical acceptable.

If a project has a negative NPV, then it is implied that wealth will be lost for the investor, and the project may not be accepted.

If the project has an NPV of zero, then the project neither adds nor subtracts wealth for the investor. There should be no difference for the investor whether the project will be implemented or not. Other evaluation methods or other factors not involved in the calculation should be considered for further comparison.

If two or more projects have positive NPVs, then the one yielding the highest NPV should be considered. If two or more projects have negative NPVs (due to restrictions such as lack of data), then the one yield the biggest NPV should be considered.

Table 4.51 Present value conversion formulas [2]

Known value	Convert to	Symbol	Formula
Present value P	Future value F	$(F/P,i,n)$	$(1+i)^n$
Future value F	Present value P	$(P/F,i,n)$	$1/(1+i)^n$
Present value P	Annuity A	$(A/P,i,n)$	$\frac{i(1+i)^n}{(1+i)^n-1}$
Annuity A	Present value P	$(P/A,i,n)$	$\frac{(1+i)^n-1}{i(1+i)^n}$
Annuity at t=0, A geometrically grows with g	Present value P	$(P/A,i,g,n)$	$\frac{1-\left(\frac{1+g}{1+i}\right)^n}{i-g}$

The NPV gives an absolute evaluation of the economic value of the project. Also it takes into account the time value of the cash flow over the lifetime of the project. The disadvantage of this method is that it is normally very difficult to decide a discounted interest rate, due to the fact that it is difficult to determine the exact risk or uncertainty of the future cash flow [2].

The following is the continuous analysis for the case of a modified RBST ring with two sources. Due to the performance similarity for both typologies, the corresponding test for the IEEE Gold book case won't be presented here.

The assumption here is that the capital investment cost for the automatic mechanical transfer switch and the static transfer switch has the relationship shown in the table below.

Table 4.52 Equipment prices [33]

	Manual mechanical transfer switch	Automatic mechanical transfer switch	Static transfer switch
Price ($)	$0.2x$	$0.4x$ —$0.7x$ ($0.55x$ on average)	$1.0x$[b]

[b]x represents the price for a static transfer switch

It should be pointed out that the cost for manpower is hard to quantify due to a lack of data. Therefore, for the manual switchover case, we take an approximate equipment cost of 0.2 times of STS's. For simplification, during NPV computation, only CIC and equipment cost are considered. Lost sales for each case will be presented as well. The staff salaries, tax payment, reinvestment, maintenance, etc. are not considered.

Modified ring with two sources

Assume that the discounted interest rate i is 10%, and the lifetime n for the transfer switch is 20 years. Annual load growth g is assumed to be 1%. From Table 4.15, we can get

$$(P/CIC, 0.1, 0.01, 20) = 9.0959$$

Recall, from section 4.2, that we saw

Table 4.53 Annual CIC per load point ($)

	No transfer available	Manual switchover	Automatic switchover	STS
Residential	3714.20	128.84	130.96	129.61
Commercial	30049.84	5096.46	760.49	703.37
Office	80511.90	14509.17	1452.56	1137.40
Industrial	28192.58	6671.67	609.23	502.04

Table 4.54 Cumulative present value of CIC over 20 years per load point ($)

	No transfer available	Manual switchover	Automatic switchover	STS
Residential	33784.03	1171.95	1191.19	1178.94
Commercial	273330.30	46356.90	6917.30	6397.77
Office	732328.20	131974	13212.31	10345.70
Industrial	256436.90	60684.82	5541.47	4566.48

By combining results from section 4.2 and Chapter 3, we can obtain the following tables.

Table 4.55 Probability for system in operation mode for Modified ring with 2 sources

	No transfer available	Manual	ATS	STS
P_{up}	0.189384	0.729765	0.929435	0.931815

Table 4.56 NPV equations

	No transfer available	Manual switchover	Automatic switchover	STS
Residential	-202704.2	$-0.2x - 7031.706$	$-fx - 7147.134$[c]	$-x - 7073.634$
Commercial	-1639982	$-0.2x - 278141.4$	$-fx - 41503.82$[c]	$-x - 38386.6$
Office	-4393969	$-0.2x - 791844$	$-fx - 79273.86$[c]	$-x - 62074.2$
Industrial	-1538621	$-0.2x - 364108.9$	$-fx - 33248.83$[c]	$-x - 27398.87$
P_{up}	0.189384	0.729765	0.929435	0.931815

[c] $f \in [0.4,0.7]$[30]

The following analysis is based on the assumption that $f \in [0.4,0.7]$, i.e., $fx < x$.

From table above, we can see that it is obvious that the worst case scenario for all customer types is when no load transfer is available, which gives a system P_{up} of 0.18.

For the residential type of users, inspection of the equations shows that manual switchover is preferable to the ATS case. However, application of ATS will improve the reliability of the system by 19.967%. For comparison between STS and ATS, there is no situation where the STS case can yield a smaller negative NPV. Therefore, for this specific topology, we can conclude that for residential customers, ATS brings economic benefits to both customers and utilities.

For commercial users, ATS is preferable to manual switchover is under the following condition.

$$-0.2x - 278141.4 < -fx - 41{,}503.82$$

$$x < \frac{236{,}637.58}{f - 0.2}, f \in [0.4,0.7]$$

Therefore, when $x < 473{,}275.16$, ATS is preferable to manual switchover. For the comparison between ATS and STS, we have,

$$-x - 38386.6 > -fx - 41503.82$$

which can be simplified into

$$x < \frac{3117.228}{1-f}, f \in [0.4,0.7]$$

Therefore, the only case when STS is preferable over ATS and the manual setup is when the equipment cost for STS is less than $5195.38. Otherwise, ATS is preferable overall for commercial customers.

Applying the same technique for the office group of customers, we can conclude that ATS is preferable over manual switchover when $x < 1{,}425{,}140.28$. When the equipment cost of STS is less than $28,666.20, STS is preferable over all other alternatives. Otherwise, one should choose ATS.

Similarly, for industrial customers, ATS is highly preferable to manual switchover when $x < 661{,}719.948$. The condition when the application of STS is preferable overall is when the equipment cost for STS is less than $9749.94; otherwise, ATS is preferred.

4.5 Combined Benefit Assessment for Customer and Utility

The table below summarizes the impact of the different transfer switches in terms of sales lost.

Table 4.57 Summary of cumulative present value of loss-sale over 20 years per load point

	P_{up} improvement	ΔEquipment cost	Lost sale			
			Residential	**Commercial**	**Office**	**Industrial**
No_xfer vs Manual	0.62475	$0.2x$	1892.02	2939.93	3223.55	3223.55
No_xfer vs ATS	0.82442	fx	2034.47	3151.99	3466.26	3466.26
No_xfer vs STS	0.82680	x	2035.80	3151.99	3468.52	3468.52
Manual vs ATS	0.19967	$(f-0.2)x$	142.45	212.06	242.70	242.70
Manual vs STS	0.20205	$0.8x$	143.78	214.04	244.97	244.97
ATS vs STS	0.02380	$(1-f)x$	1.33	1.98	2.27	2.30

There should be no doubt that for the first three cases, ATS is preferred for high lost sale returns and for better reliability improvement compared to manual switch cases. Meanwhile, ATS requires relatively low investments cost compared to STS.

When choosing between manual and ATS (case 4), or manual and STS (case 5), the first case is preferable due to the fact that STS does not bring back lost sales or bring the reliability improvement high enough to compensate for the difference in equipment cost. However, for the last three cases, we can clearly see that when choosing between manual, ATS or STS, none of them can perform cost-recovery if the only loss-sale is considered as profit. And the normally price for a STS is assumed to be above $5000.

The situation we need to discuss here is when one should choose STS instead of ATS. Assume that the aggregate customer interruption cost for the combination of customers served in the system is $14/kWh [2] and that the average electricity price is approximately $0.1/kWh [33]. We want to evaluate how much the interruption cost per kWh increases can offset the capital investment of replacing a faster transfer switch. We also want to determine whether customers are willing to pay more to compensate for their loss. The method is illustrated below. The energy loss avoided, A, is

$$A = \frac{\Delta CIC_{avoided}}{\$14/\mathrm{kWh}}$$

Where $\Delta CIC_{avoided}$ is summarized in Table 4.22 below.

Table 4.58 Change in customer side - $\Delta CIC_{avoided}$ per load point

	Residential	Commercial	Office	Industrial
ATS vs STS	12.25036	519.5378	2866.609	974.9922

And the total benefit (TB) is,

$$TB = \Delta CIC_{avoided} + 0.1A$$

When

$$NPV(TB) \geq \Delta eq_{cost}$$

utilities can earn a profit by the replacement of STS.

We should point out here that the lost sales revenue is not significant enough to justify the replacement cost. It is the drop of CIC that mainly drives the situation here.

On the other hand, if

$$\frac{\Delta eq_{cost}}{\Delta CIC_{avoided}} \$14/\mathrm{kWh} = \$C/\mathrm{kWh}$$

where C here is the marginal investment cost per kWh saved for customers.

If C < \$14/kWh, the investment cost can be recovered from the replacement; if C = \$14/kWh, it is the break-even point; if C > \$14/kWh, it is not worthwhile to replace the transfer switch from ATS to STS unless the customers' interruption cost has increased to C amount and the customers are willing to pay extra to compensate for their loss.

Table 4.59 Summary of equipment cost ($) vs corresponding interruption cost charge based on CIC ($)

STS Cost	Residential	Commercial	Office	Industrial
5000	428.5589	10.1051	1.8314	5.3847
10,000	857.1177	20.2102	3.6629	10.7693
15,000	1285.6765	30.3154	5.4943	16.1540
20,000	1714.2353	40.4205	7.3257	21.5386
25,000	2142.7942	50.5257	9.1572	26.9233
30,000	2571.3530	60.6308	10.9886	32.3080
35,000	2999.9118	70.7360	12.8200	37.6926
40,000	3428.4707	80.8410	14.6515	43.0773
45,000	3857.0295	90.9462	16.4829	48.4619
50,000	4285.5883	101.0514	18.3143	53.8464

By observing the table above, we can see that residential customers should always choose ATS instead of STS. When the price for STS is $5000 or lower, it is suitable for all remaining customers. STS is preferable for office customers until its price hits the price line of $40,000, and it is best for industrial customers if the price is below $15,000. In all other cases, ATS is highly preferable unless the interruption cost has increased to the corresponding amount and the customers are willing to pay the corresponding increment to offset the equipment cost.

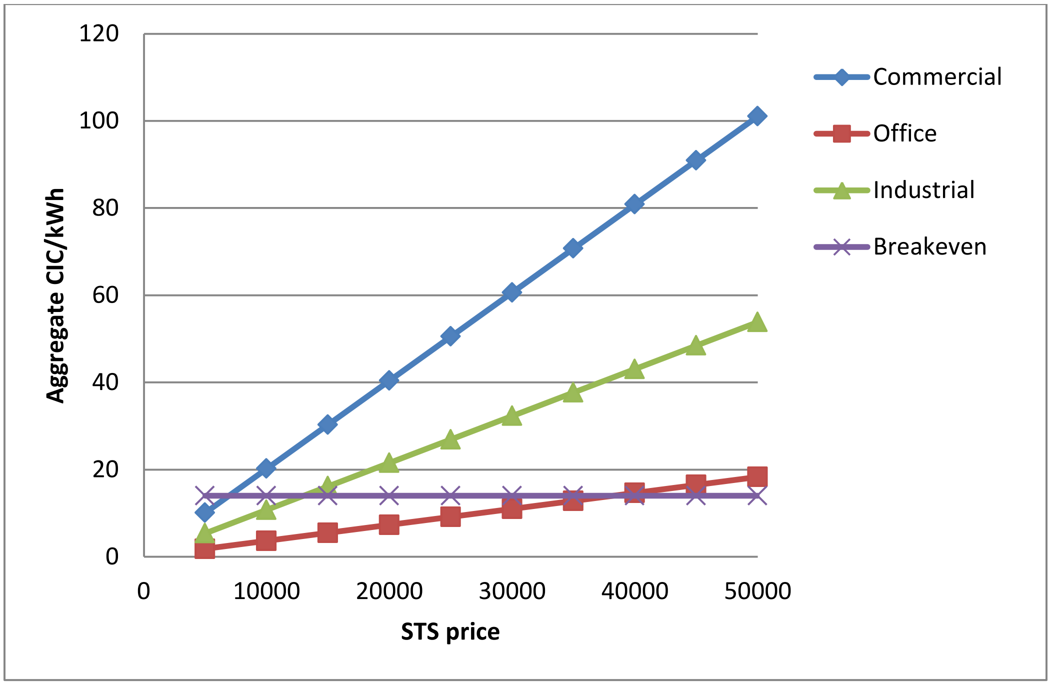

Figure 4.2 Incremental cost of investment versus cost per kWh saved for customers during interruption

Excluding residential customers, the break-even points are clearly shown above. For customer types that have relatively low interruption costs, i.e. commercial and industrial groups, customers gain more per kWh saved for every $5000 invested. Thus, cheaper equipment is required in order to earn a profit while meeting commitments to customers as well. For customer types with relatively high interruption cost, i.e. office customers, for every $5000 invested, we get roughly $1.83/kWh saved for customers based on interruption cost, and therefore the break-even point is relatively high at $40,000.

4.6 Summary

From results above, we can observe that the differences brought into effect by replacing STS with ATS are quite small for most customer types. The benefit is not high enough to offset the equipment cost of the STS unless the customer interruption cost is originally high, or unless the customer interruption cost increased to certain amount and customers proved willing to pay more to compensate. We can see that as a transfer switch, ATS already performs well when interruptions are allowed and will not lead to disastrous results. For economic considerations, ATS is preferred. For customer types that cannot tolerate interruptions and have losses that are hard to quantify, i.e. hospitals and banks, an STS with a backup generator is the much-preferred choice.

5. Conclusion and Future Work

5.1 Conclusion

In this research, we have presented the effect of load transfer on reliability improvement. Further improvements brought by different transfer switch technologies, i.e., manual switchover, ATS and STS, have been investigated. Studies of the placement and the switching time of the NO transfer switches have also been presented. These analyses have been based mainly on two typologies, i.e. the IEEE Gold Book Test case [31] and the Modified RBTS open ring system with two supply sources [23]. In this research, the minimum cut set method is mainly applied to assist the reliability evaluation. Detailed description and derivation of this method is also presented.

Along with the reliability data obtained in Chapter 3, economic analysis for both customers and utility providers has been performed. Due to the lack of data, unfortunately only a portion of the evaluations can be considered authoritative reference material. For customer concerns, customer interruption costs based on various switch types and customer per-unit loss has been documented. For utility concerns, relative sale losses due to the benefit of changing to a faster switch and the comparison of different capital investments to changing equipment have been studied. In the end, the combined economic worth of changing to STS from ATS for both customer and utility sides has been considered. We have also examined the incremental cost of investment (the price of STS) compared with the cost per kWh saved for customers during interruptions.

Conclusions from the research have been summarized below:

- Systems reliability assessment involving switching and reconfiguration events is easily applicable using the minimum cut set method.

- The application of STS significantly improves the failure frequency index, and reduces annual outage time. However, the benefit of using ultra fast STS cannot be clearly observed in annual outage reduction compared to ATS. This is due to the fact that first order cut sets dominate this index, i.e. supply branches involving transformers and supply sources.
- Placing the transfer switch at the end of two adjacent feeders (Modified RBTS open ring with two supply sources) reduced the annual outage time suffered by load points. On the other hand, placing the NO transfer switch at the bus (IEEE Gold Book Test) lowered the failure frequency.
- We also found that the dependency of components does impact the overall system reliability performance.
- CIC was significantly reduced when load transfer was available, and further reduction can be achieved by application of the faster transfer switch
- CIC was reduced when a NO transfer switch is installed at the end of the feeders.
- Under the condition of fixed electricity price, ATS in most cases was good enough when lost sale revenue is the only factor involved in the profit assessment.
- The following has been studied as well: The break-even point of using STS instead of ATS, and the incremental cost of investment (per $5000 invested) compared with cost per kWh saved for customers during interruptions. In addition, we investigated the ability of investment to compensate for the losses for customer types with initially high per unit interruption costs.

5.2 Future Work

In this research, the reliability of two simple distribution configurations with different placements of the NO transfer switch has been studied. Besides discussing the reliability impact of different locations of the NO transfer switch, further study can be conducted by combining these two typologies and evaluating the system reliability change compared to the originals. Meanwhile, conditions of active failure and passive failure for the NO transfer switches can be taken into consideration. Restrictions on load transfer can also be taken into account if load flow data are available.

For our cost-reliability worthiness analysis, the main problem we encountered is the lack of data. Therefore, only a partial economic evaluation can be provided as a reference. In future work, when more sets of data are available, more realistic economic models can be built for both the customers and the utility providers. Relationships between the level of reliability and the cost then can be obtained. We define R as the reliability level of the system. $CIC(R)$ presents customer interruption cost as a function of reliability level. $Eq(R)$ presents the capital investment cost of advanced equipment required in order to reach the corresponding reliability level. The objective function, total cost of the utility as a function of reliability level, $TC(R)$ can be formed as

$$TC(R) \;=\; CIC(R) + Eq(R).$$

Under the condition of fixed per unit interruption cost, the optimum investment, or win-win situation for both the customer and utility sides can be easily obtained by taking the first derivative of the previous equation and finding the value when the equation goes to zero.

Appendices

For the benefit of readers, we include this appendix, summarized from Billinton & Allan [3], [34]. Appendix A provides basic information and described traditional analytical methods used in distribution system reliability evaluation. Appendix B provides guidance for readers who want a better view of how to apply the minimum cut set method. Appendix C contains the program code that the author has developed to adapt the method and code used for this thesis.

Appendix A: Classic Distribution Reliability Evaluation Methodologies

A.1 Introduction

The methodology of reliability evaluation for power distribution systems can be divided into two parts, analytical and probabilistic. The analytical method evaluates the average value and the expected value of the system, while the probabilistic method evaluates the probability distribution of the system reliability. In this research, the analytic method is mainly used to assess the system reliability for designed configurations. This chapter describes three traditional analytical reliability evaluation methodologies, i.e., Failure mode and effect analysis and (FMEA) method, minimum cut-set method, and Markov process method.

A.2 Classic Analytical Reliability Evaluation Methodology

The analytic method uses the quantitative techniques to evaluate the historical performance of the system and to predict the impact of changing conditions on system performance, based on the topology and the information for system components. FMEA, minimal cut set, and discrete Markov Model Method are three representative methods.

A.2.1 Failure Mode and Effect Analysis

FMEA is one of the first proposed systematic assessment techniques in reliability evaluations [34]. It is a worksheet-based representation of the complex relationship between the system/components, the failure likelihood modes, and the corresponding severity ranking. The FMEA worksheet is established by first searching the status of each component of the system and then listing all possible system states. All those system states will then be examined and analyzed to form a list of failure likelihood modes. Their effects on the system level and the system reliability indices will then be determined. Finally, a severity number ranking the consequences of the failures is given to the failure mode, based on the suggested severity ranking criteria according to the effect of the failure. A good FMEA sheet can provide a great view of potential failure modes and helps to prevent the occurrence of such failures. However, the procedure of establishing an FMEA worksheet is complicated and the number of states of the system can be enormous as the system becomes more complex. Nevertheless, FMEA is one of the most effective reliability evaluation methods for a distribution network. It provides the basis for the other evaluation methods, i.e. the minimal cut set method, which will be presented in the next section.

A.2.2 Minimum Cut Set Method

Most distribution systems either do not have simple radial distribution structures or have a combination of series and parallel networks [3], [34]. When the network becomes more complicated, the minimal cut set method can act as a powerful tool for reliability assessment. The main feature of the minimal cut set method is its ability to simplify an arbitrarily complex system into the equivalent of a series-parallel structure for the system. Its reliability then can be easily obtained from the resulting topology of the block diagram. Meanwhile, the cut set method directly presents all paths and the combination of the components that leads to the failure modes. Upon obtaining the minimum cut sets of the system, distinct types of system failures can be easily identified. Another main advantage of the minimum cut set method is that it can be easily programmed for fast and general reliability evaluation for a system. The minimum cut set method is mainly used in this research for the system performance evaluation of a normally open-ring distribution network. Detailed definitions and the derivation of a computation algorithm will be presented in Appendix B.

A.2.3 Markov Processes

In order to understand the effects of component failures on overall system performance, component failure processes should be studied. The Markov process describes the component outage processes in terms of a discrete and finite number of states that are continuous in time. Component outage processes involve component failures, repair, and switching activities.

The basic Markov model of a repairable component with two states, i.e. up and down states, can be modeled as shown below [34].

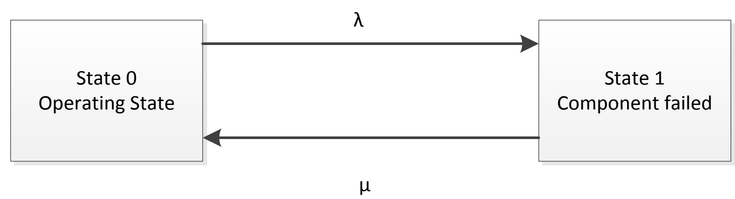

Figure A.1 State space diagram for a component has two states [34]

where state 0 represents the operating state and state 1 is when the component is in a failed state. The transition between state 0 and state 1 is determined by the failure rate λ and the repair rate μ, where μ is obtained by the reciprocal of r. From then the steady state probability for the component to remain in ab operating state and a failed state, respectively, can be obtained by the following equations [34].

$$P_0 = \frac{\mu}{\mu + \lambda}$$

$$P_1 = \frac{\lambda}{\mu + \lambda}$$

The Markov model above is used for repairable components that only involve two states. For situations when switches are installed and switching actions occur for restoration or isolation purposes, a Markov model for the component that contains three transition states is needed, as shown below. This model includes active and passive failures of components, which are defined in [3].

Passive failure: A component failure that doesn't trigger the operation of protection devices and does not have an impact on the remaining healthy network. Restoration of the service occurs after the replacement or repair of the failed component.

Active failure: Opposite to a passive failure, an active failure of a component causes the operation of the primary protection zone around the failed component and therefore causes the negation of the remaining healthy network.

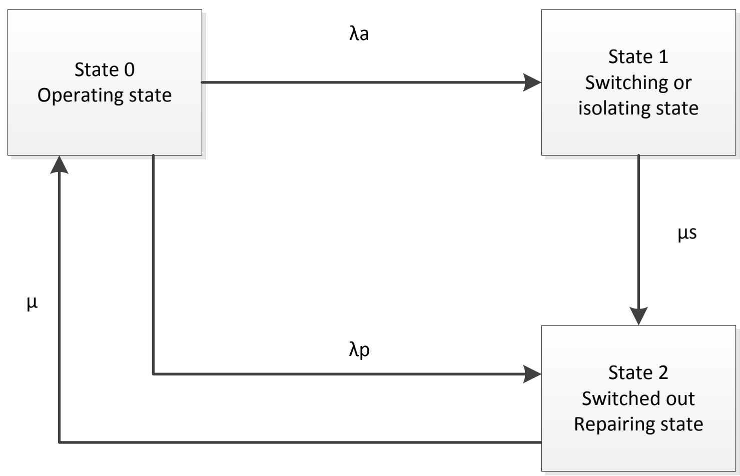

Figure A.2 State space diagram for active and passive failures [34]

where λ_a in Figure A.2 is the active failure rate of a component and λ_p is the passive failure rate. The transition rate from state 0 and 1 is λ_a. When component has actively failed and triggered the operation of a protective device, the rate of transition from state 0 to state 2 is λ_P. The transition rate from state 1 to state 2 is μ_s, which is the reciprocal of the switching time required of the switches for isolation or restoration purposes.

The Markov process becomes more complicated when the number of components connected in a system increases. For systems only containing n components that only have operating and failed states, the state space diagram will involve 2^n states, which could be enormous when n becomes large.

Appendix B: Minimum Cut Set Method

The first part of Appendix B will present the theory of the minimum cut set method and discuss how it will be applied in order to find possible sustained failure events in the open ring system. The second part of this chapter will be a discussion of assessment of the momentary interruption events caused by load transfer. In each part of Appendix B, a simple open-ring network will be used as an example to present how to apply the method for reliability calculation. All the materials and derivations are based on materials presented in books [3] and [34].

B.1 Reliability Evaluation for Ring Structured Distribution Network based on Minimum Cut Set Method (Sustained Interruption)

B.1.1 Basic Definition for Minimum Cut Set Method

For minimum cut set methods, the cut sets represents all possible paths and combinations of the components that directly lead to the system failures.

A path can be defined as a set of system components which constitutes the minimum distance between the input and output node. The paths guarantees the system's successful operation if all components are operational. All the components in a minimum path are in series, and all minimum paths are in parallel. This indicates that as long as any of the paths are in operation, the operation of the system is ensured.

A cut set is the opposite of a path. It is a set of system components which, when they fail, causes failure of the system. Therefore, the cut sets directly relate to the failure modes for a system.

The minimal cut set is the minimum subset of any given set of components, which when any component fails directly leads to system failure. On the other hand, if any components in the minimum cut set remain in operation mode, the system won't fail. Therefore, all components in a minimum cut set are in parallel and all minimum cut sets are in series. The number of minimum cut sets gives a representation of the number of ways that the system may fail.

B.1.2 Deducing the Minimum Cut Sets

Algorithm of finding the minimum cut sets

1. Provide information for all possible successful paths.
2. Form an incidence matrix based on the success events (number of paths x number of components). 1 indicates that the minimum path will pass through this component, 0 otherwise.
3. Check each column of the matrix. If any column of the incidence matrix is non-zero, the component associated with that column forms the first order cut set.
4. Combine two columns of the incidence matrix. If all elements of the combined columns are non-zero, the elements associated with those columns form the second order cut set.
5. Eliminate any cut sets that involve previously-found first order cut sets and then form the minimum second order cut sets.
6. Continue to form the third order terms using the same method. Eliminate the terms involving the first and second order cut sets.
7. Return the results.

B.1.3 Example

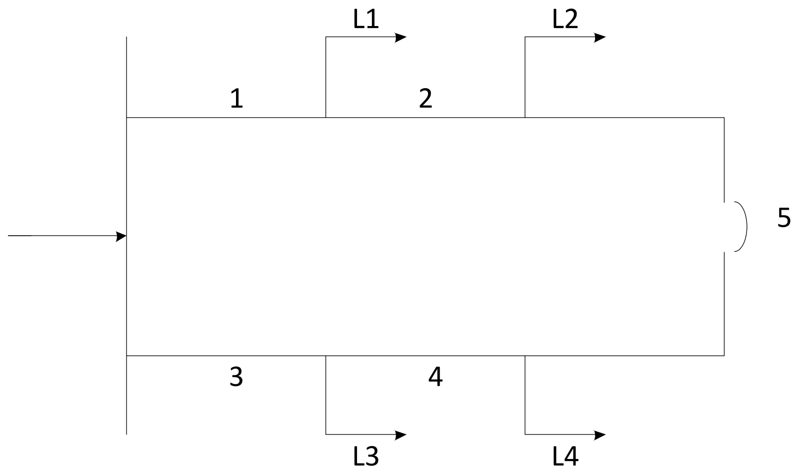

Figure B.3 Simplified open ring network

For the simple system shown above, we first assume that the fuses operate successfully and that the components that might fail are line segments 1 to 4 and component 5, which is a normally open breaker. We first evaluate the possible failure modes of sustained interruptions based on the minimum cut set method. Momentary interruptions caused during load transfer will be discussed later. Active failure events for the breaker are not considered here.

Considering the four load points shown above as the output points, the paths of each load point are shown in Table B.60.

Table B.60 Minimum paths for load points of Figure B.3

	Load Point 1: L1	Load Point 2: L2	Load Point 3: L3	Load Point 4: L4
Paths	1	1+2	3	3+4
	2+3+4+5	3+4+5	1+2+5+4	1+2+5

For illustration purposes, the minimum cut set for load point 1 will be shown below. From Table B.60, the paths p are

$$p = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 2 & 3 & 4 & 5 \end{pmatrix}$$

Given the minimum paths, we can form the incidence matrix A based on these operation modes. We have:

Table B.61 Minimum paths for load point 1

	Component				
	1	2	3	4	5
Path 1	1	0	0	0	0
Path 2	0	1	1	1	1

$$A = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 1 & 1 & 1 \end{pmatrix}$$

It is obvious that there is no first order event, and the second order events can be obtained by combing the first column of the matrix A with each of the remaining columns. The overall result for four load points will be summarized in Table B.62.

Table B.62Minimum cut sets for load points

	Load Point 1: L1	Load Point 2: L2	Load Point 3: L3	Load Point 4: L4
Minimum cut sets	1+2	1+3	3+1	1+3
	1+3	1+4	3+2	1+4
	1+4	1+5	3+4	2+3
	1+5	2+3	3+5	2+4
		2+4		3+5
		2+5		4+5

Here we should point out that the failure event of the normally open breaker in this case is when a load transfer is required but the breaker fails to close as requested. (This does not affect the remaining healthy network.)

Since the same components of a minimal cut set may appear in other cut sets, conditional probability should be involved in the theoretical calculations. However, in a large system involving hundreds of components, the amount of computation can be huge and time-consuming. Therefore, approximations are made for the cut set evaluation, as a tradeoff for precise evaluation. There are two main assumptions. We first assume that the system unreliability (Q_S) can be seen as the summation of the unreliability of each minimal cut set; i.e. each minimal cut set is independent. The second assumption is that we assume it is highly improbable for a higher order cut set to have taken place in the system (a situation where many components fail simultaneously). Therefore, higher order cut sets can be neglected.

For example, the reliability computation will be shown below for load point 1, and the intuitive reduced failure modes of load point 1 can be found in Figure B.4.

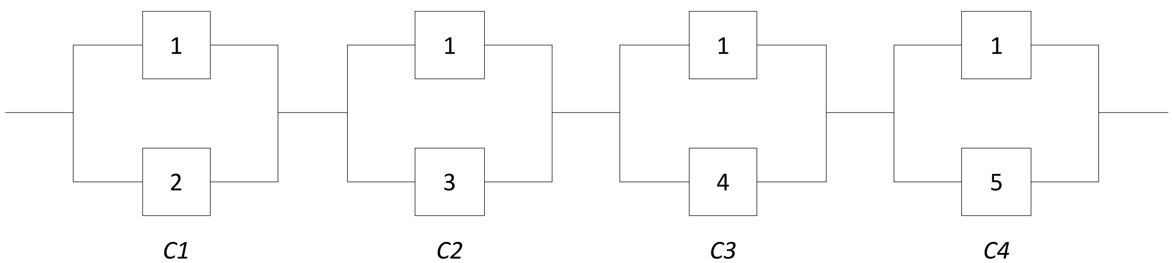

Figure B.4 Reliability diagram for Load Point 1 (L1)

From the reliability diagram of Figure B.4, the theoretical result is:

$$
\begin{aligned}
Q_s &= P(C_1 \cup C_2 \cup C_3 \cup C_4) \\
&= P(C_1) + P(C_2) + P(C_3) + P(C_4) - P(C_1 \cap C_2) - P(C_1 \cap C_3) - P(C_1 \cap C_4) - P(C_2 \cap C_3) \\
&\qquad - P(C_2 \cap C_4) - P(C_3 \cap C_4) + P(C_1 \cap C_2 \cap C_3) + P(C_1 \cap C_2 \cap C_4) \\
&\qquad + P(C_1 \cap C_3 \cap C_4) + P(C_2 \cap C_3 \cap C_4) - P(C_1 \cap C_2 \cap C_3 \cap C_4)
\end{aligned}
$$

Since we assume all components failure are independent, thus, $P(C_1 \cap C_2 \cap C_3 \cap C_4)$ for example just

$$P(C_1 \cap C_2 \cap C_3 \cap C_4) = Q_1 Q_2 Q_3 Q_4$$

If the unreliability of each component is of the order of 10^{-2}, then $P(C_1 \cap C_2 \cap C_3 \cap C_4)$ is in the order of 10^{-8} which is small enough to be negligible.

Based on the first assumption, we can now obtain the unreliability of load point 1 as:

$$Q_s = P(C_1) + P(C_2) + P(C_3) + P(C_4)$$
$$= \sum_i C_i$$

This gives us:

$$Q_s = Q_1Q_2 + Q_1Q_3 + Q_1Q_4 + Q_1Q_5$$

B.1.4 General Mathematical Reliability Computation Algorithm for Load Point Based on Minimum Cut Sets

In each minimum cut set, all components need to be in the failure mode. Therefore, we consider the down state for each component.

For one component, the probability of the component being in the down state can be calculated by the following equation,

$$P_{down} = Q = \frac{\lambda}{\lambda + \mu}$$

For two components in parallel,

$$P_{success} = R_1 + R_2 - R_1R_2 = 1 - Q_1Q_2$$

($P_{success}$ *increases as the number of components in parallel increases*.)

Therefore,

$$P_{down} = Q_s = Q_1Q_2 = \frac{\lambda_1}{\lambda_1 + \mu_1}\frac{\lambda_2}{\lambda_2 + \mu_2} = \frac{\lambda_s}{\lambda_s + \mu_s}$$

Where the equivalent $\mu_s = \mu_1 + \mu_2$ and the equivalent r_s can be calculated by taking the reciprocal of u_s.

$$r_s = \frac{1}{\mu_s} = \frac{r_1 r_2}{r_1 + r_2}$$

Therefore, the equivalent λ_s then can be found.

$$\frac{\lambda_s}{\lambda_s + \mu_s} = \frac{\lambda_1}{\lambda_1 + \mu_1} \frac{\lambda_2}{\lambda_2 + \mu_2}$$

$$\lambda_s = \frac{\lambda_1 \lambda_2 \mu_s}{(\lambda_1 + \mu_1)(\lambda_2 + \mu_2) - \lambda_1 \lambda_2}$$
$$= \frac{\lambda_1 \lambda_2 (r_1 + r_2)}{\lambda_1 r_1 + \lambda_2 r_2 + 1 + \lambda_1 \lambda_2 r_1 r_2}$$

In practice, the result of $\lambda_1 r_1, \lambda_2 r_2, \lambda_1 r_1 \lambda_2 r_2$ are much less than unity. We can neglect the denominator term of the equivalent failure rate λ_s.

Then,

$$\lambda_s \approx \lambda_1 \lambda_2 (r_1 + r_2)$$

Eventually the equivalent annual outage time can be found by taking the product of λ_s and μ_s.

$$U_s = \lambda_1 \lambda_2 r_1 r_2$$

In contrast to the case for a series system, we can’t extend the equation for 2-components in parallel to a general n-component system, since the correlation of n-components needs to be considered for parallel systems.

A parallel system can fail only when all components in the network fail. In the case of three components in parallel, the failure of the system can occur if:

1. Component 1 fails, followed by failure of component 2 during the reparation of 1, followed by failure of component 3 during the overlapping reparation of 1 and 2, i.e. 123
2. Component 1 fails, followed by failure of component 3 during the reparation

of 1, followed by failure of component 2 during the overlapping reparation of 1 and 3, i.e. 132

3. Component 2 fails, followed by failure of component 1 during the reparation of 2, followed by failure of component 3 during the overlapping reparation of 1 and 2, i.e., 213
4. Component 2 fails, followed by failure of component 3 during the reparation of 2, followed by failure of component 1 during the overlapping reparation of 2 and 3, i.e., 231
5. Component 3 fails, followed by failure of component 1 during the reparation of 3, followed by failure of component 2 during the overlapping reparation of 1 and 3, i.e., 312
6. Component 3 fails, followed by failure of component 2 during the reparation of 3, followed by failure of component 1 during the overlapping reparation of 2 and 3, i.e., 321

Therefore, the equivalent λ_s is then:

$$\begin{aligned}\lambda_s &= \lambda_1(\lambda_2 r_1)\left(\lambda_3 \frac{r_1 r_2}{r_1 + r_2}\right) + \lambda_1(\lambda_3 r_1)\left(\lambda_2 \frac{r_1 r_3}{r_1 + r_3}\right) + \lambda_2(\lambda_1 r_2)\left(\lambda_3 \frac{r_1 r_2}{r_1 + r_2}\right)\\ &\quad +\lambda_2(\lambda_3 r_2)\left(\lambda_1 \frac{r_2 r_3}{r_3 + r_2}\right) + \lambda_3(\lambda_1 r_3)\left(\lambda_2 \frac{r_1 r_3}{r_1 + r_3}\right) + \lambda_3(\lambda_2 r_3)\left(\lambda_1 \frac{r_3 r_2}{r_3 + r_2}\right)\\ &\approx \lambda_1\lambda_2\lambda_3(r_1 r_2 + r_2 r_3 + r_1 r_3)\end{aligned}$$

$$\mu_s = \sum \mu_i$$

$$r_s = \frac{1}{\mu_s} = \frac{r_1 r_2 r_3}{r_1 r_2 + r_1 r_3 + r_2 r_3}$$

$$U_s = \lambda_s * r_s = \lambda_1\lambda_2\lambda_3 r_1 r_2 r_3$$

After determining these equivalent indices for a parallel system (minimum cut sets), we then can obtain the overall reliability indices of the whole network using a simple series reliability evaluation method, which has been explained.

B.1.3 Example Continued

Reconsider Example of B.1.3, and Figure B.3. The component failure data used are given in Table B.63. Those data are for illustration purposes.

The failure rate and the average repair time for the independent minimum cut sets associated with Load Point 1 are calculated in Table B.64 using equations derived in this section.

Table B.63 Component failure data for the example

	Failure rate, $\lambda\ (freq./yr)$	Restoration duration, $r\ (h)$
Line		
1	0.2	4
2	0.2	4
3	0.2	4
4	0.2	4
Component		
5	0.02	6

Table B.64 Independent minimum cut sets for Load Point 1

Event	Failure rate $\lambda\ (freq./yr)$, 10^{-4}	Restoration duration: $r\ (h)$
1+2	0.3653	2.000
1+3	0.3653	2.000
1+4	0.3653	2.000
1+5	0.0457	2.400
Total	1.1416	2.016

B.2 Reliability Evaluation for Ring Structured Distribution Network based on Minimum Cut Set Method (Momentary Interruption)

In case when load transfer is possible, i.e. the fault is isolated, and the other part of the system is healthy, the failure frequency of a load point is simply the summation of the failure rates of components connected from the supply source to the load point. And the duration of time that the system can be restored again becomes simply the switching time of the particular switch that is applied at the normally open point.

B.1.3 Example Continued

Reconsider Example B.1.3 and Figure B.3. The failure of feeding load point 1 through Line 1 requires a transfer of the load through switch 5:

$$\lambda = \lambda_1$$

$$r = switching\ time\ of\ component\ 5$$

$$U = \lambda_1 r$$

(Failure of (1,2),(1,3),(1,4),(1,5) have already been taken into account in the case of sustained interruption.)

The failure of feeding Load 2 is the case when Line 1 fails, or when both Line 1 and Line 2 fail. Thus, both components are in series, and the failure rate of load point 2 is the sum of the failure rates of Line 1 and Line 2. For momentary interruption, it requires a load transfer through switch 5. Therefore,

$$\lambda = \lambda_1 + \lambda_2\ (two\ compents\ in\ series)$$

$$r = switching\ time\ for\ component\ 5$$

$$U = \lambda_1 r + \lambda_2 r$$

The failure of feeding Load 3 is similar to the failure of feeding Load 1:

$$\lambda = \lambda_3$$

$$r = switching\ time\ of\ component\ 5$$

$$U = \lambda_3 r$$

Failure of feeding Load 4 through Line 3 and Line 4 and require a transfer of load through switch #5:

$$\lambda = \lambda_3 + \lambda_4 \ (two\ compents\ in\ series)$$

$$r = switching\ time\ for\ component\ 5$$

$$U = \lambda_3 r + \lambda_4 r$$

The overall primary indices (λ, r, U) for each load point are simply the summation of the long duration and short duration cases, respectively. From this point, system reliability can be obtained.

Appendix C: Code Listings

This appendix lists the main computer codes (MATLAB language) used in obtaining the results found in this thesis.

function parallel network_ring(lambda, r, N)

This function is the main function used in this thesis to compute reliability for the system. It takes three inputs, lambda, r and N. Input lambda is the failure frequency for each component in the system, r contains the information of the repair time for each component, and N represents number of customers at each load point in the computing system.

The function contains several parts. The function will first present a simple user interface requiring information such as component number for the transfer switch and its transferring time (manual, ATS, or STS), the possible paths for power delivery to the load point, and the alternative path when any components in the main path is down. The second part of the function will be the minimum cut sets computation. Provided with the information above, the function then will find the 1st , 2nd and 3rd minimum cut sets for each load point and then calculate the failure frequency, repair time and annual outage time for each load point for both sustained and momentary interruption case. Then the function can compute system reliability indices such as $SAIDI$ and $SAIFI$ at very last.

```
%Every component in a minimum cut set are in parallel with each other, and
%every minimum cut set are in series.

function parallel_network_ring(lambda,r,N)

num_comp = length(lambda);
load_num = length(N);

format long;
xfer_time = input(sprintf('Enter transferring time to an alternative source: '));

%Find the lambda,r,U for each load. then used it for later parameter
%computation
for m = 1:load_num
    name = sprintf('Load_%d',m);
    path = input(sprintf('Enter possible path for %s: ',name));
```

```
    breaker = input(sprintf('Enter breaker component number: '));
    path_xfer = input(sprintf('Failure of feeding %s through components and request load
transfer: ',name));

    [first_order,second_order,third_order] = cut_set_method(path,num_comp);

    alpha = linspace(0.1,1,10);
    fix_breaker = lambda(breaker);
    for cases =  1:10
        r_1st = 0;lambda_1st = 0;U_1st = 0;
        r_2nd = 0;lambda_2nd = 0;U_2nd = 0;
        r_3rd = 0;lambda_3rd = 0;U_3rd = 0;

        lambda_list = [];
        r_list = [];

        %varying value for breaker component
        lambda(breaker) = alpha(cases)*fix_breaker;

        %Find the indices for first order cut set
        i = 0;
        if isempty(first_order) == 0
            for i = 1: length(first_order(1,:))
                r_temp(i) = r(first_order(i));
                lambda_temp(i) = lambda(first_order(i));
                U_temp(i) = r_temp(i)*lambda_temp(i);
            end

            lambda_list = [lambda_temp];
            r_list = [r_temp];

            lambda_1st = sum(lambda_temp);
            U_1st = sum(U_temp);
            r_1st = sum(U_temp)/sum(lambda_temp);
        end

        j = i;

        %Find the indices for second order cut set
        %Initializing
        i = 0;
        r_temp = [];lambda_temp = [];U_temp = [];
        if isempty(second_order) == 0
            for i = 1:length(second_order(:,1))
                r_temp(i) =
r(second_order(i,1))*r(second_order(i,2))/(sum(r(second_order(i,:))));
                lambda_temp(i) =
lambda(second_order(i,1))*lambda(second_order(i,2))*(sum(r(second_order(i,:))))/8760;%87
60hours/year
                U_temp(i) = r_temp(i)*lambda_temp(i);

            end

            lambda_list = [lambda_list lambda_temp];
```

```
            r_list = [r_list r_temp];

            lambda_2nd = 0; U_2nd = 0;r_2nd = 0;

            lambda_2nd = sum(lambda_temp);
            U_2nd = sum(U_temp);
            r_2nd = U_2nd/lambda_2nd;

        end

        j = i;

        %Find the indices for third order cut set
        %Initializing
        i = 0;
        r_temp = [];lambda_temp = [];U_temp = [];
        if isempty(third_order) == 0
            for i = 1:length(third_order(:,1))
                temp =
r(third_order(i,1))*r(third_order(i,2))+r(third_order(i,1))*r(third_order(i,3))+r(third_
order(i,3))*r(third_order(i,2));
                r_temp(i) =
r(third_order(i,1))*r(third_order(i,2))*r(third_order(i,3))/temp;
                %note: divide 8760 twice to keep fr/yr unit
                lambda_temp(i) =
lambda(third_order(i,1))*lambda(third_order(i,2))*lambda(third_order(i,3))*temp/8760^2;
                U_temp(i) = r_temp(i)*lambda_temp(i);
            end

            lambda_list = [lambda_list lambda_temp];
            r_list = [r_list r_temp];

            lambda_3rd = sum(lambda_temp);
            U_3rd = sum(U_temp);
            r_3rd = sum(U_temp)/sum(lambda_temp);

            %display(lambda_3rd);
            %display(r_3rd);
            %display(U_3rd);
        end

        lambda_l(m) = lambda_1st+lambda_2nd+lambda_3rd;
        U_l(m) = U_1st+U_2nd+U_3rd;
        r_l(m) = U_l(m)./lambda_l(m);

        %For short duration interruption
        s_Lambda = sum(lambda(path_xfer));
        s_U = s_Lambda.*xfer_time;
        s_r = xfer_time;

        lambda_list = [lambda_list s_Lambda];
        r_list = [r_list s_r];

        %file = sprintf('Manual_Load_%d_%d.dat',m,cases); % generate filename
```

```
        %file = sprintf('ATS_Load_%d_%d.dat',m,cases); % generate filename
        %file = sprintf('STS_Load_%d_%d.dat',m,cases); % generate filename
        %disp(sprintf('Saving lambda and r list for Load_%d case %d
to %s',m,cases,file));
        %save('-ascii',file,'lambda_list','r_list'); % save data to file

        %Overall primary parameters for each load point
    end
end

% CI = sum(L_lambda.*N);
% CMI = sum(L_U.*N);
% NT = sum(N);
%
% %System average iterruption frequency index
% SAIFI = CI/NT;
%
% %System average iterruption duration index
% SAIDI = CMI/NT;
%
% %Customer average interruption duration index
% CAIDI = CMI/CI;
%
% %Customer average interruption frequency index
% CAIFI= CI/NT;                  %Customer affected should account once. In readial
network, it just simply
% %the sum of the total customers.
%
% %Average service availability index
% ASAI = 1-CMI/(NT*8760);         %Yearly based
%
% %Average service unavailability index
% ASUI = 1 - ASAI;
%
%
% %save('result_open_ring_STSs','L_lambda','L_U','L_r','CMI','SAIFI','SAIDI','CAIDI','CA
IFI','ASAI','ASUI');
% %save('result_open_ring_ATSs','L_lambda','L_U','L_r','CMI','SAIFI','SAIDI','CAIDI','CA
IFI','ASAI','ASUI');
% %save('result_open_ring_Mannual','L_lambda','L_U','L_r','CMI','SAIFI','SAIDI','CAIDI',
'CAIFI','ASAI','ASUI');

%end

end
```

function cost_calculation(lambda,r,L,type_user)

This function helps to calculate the CIC for each load point during different interruption durations. The function takes four inputs. Input lambda contains failure frequency data for each interruption events at a load point, r is the corresponding repair time. L represents the average load level at the load point, and type_user represents the customer types at the load point, i.e., 1 represents residential customer, 2 represents commercial, etc. The function uses SCDF summarized in Chapter 4 and CIC equation to help form a CIC matrix for the system under different customer types and different transfer switch technologies.

```
function [CIC] = cost_calculation(lambda,r,L,type_user)

if type_user == 1
    for i = 1:length(lambda)
        if r(i) >= 1/60
            CIPKW = 0.1845*r(i)^2 + 0.4969*r(i) - 0.0791;
        elseif r(i) >= 1.388e-4 && r(i) < 4.167e-3
            CIPKW = 0.00068;
        elseif r(i) >= 4.167e-3 && r(i) < 1/60
            CIPKW = 0.052;
        else
            CIPKW = 0;
        end
        CIC(i,1) = lambda(i)*L*CIPKW;
    end
end

if type_user == 2
    for i = 1:length(lambda)
        if r(i) >= 1/60
            CIPKW = 0.6441*r(i)^2 + 5.0229*r(i) + 1.487;
        elseif r(i) >= 1.388e-4 && r(i) < 4.167e-3
            CIPKW = 0.02932;
        elseif r(i) >= 4.167e-3 && r(i) < 1/60
            CIPKW = 0.2198;
        else
            CIPKW = 0;
        end
        CIC(i,1) = lambda(i)*L*CIPKW;
    end
end

if type_user == 3
    for i = 1:length(lambda)
        if r(i) >= 1/60
            CIPKW = -0.4345*r(i)^2 + 17.872*r(i) + 4.08;
        elseif r(i) >= 1.388e-4 && r(i) < 4.167e-3
            CIPKW = 0.15912;
        elseif r(i) >= 4.167e-3 && r(i) < 1/60
            CIPKW = 1.1923;
        else
            CIPKW = 0;
        end
```

```
        CIC(i,1) = lambda(i)*L*CIPKW;
    end
end

if type_user == 4
    for i = 1:length(lambda)
        if r(i) >= 1/60
            CIPKW = 0.2028*r(i)^2 + 5.0436*r(i) + 2.3538;
        elseif r(i) >= 1.388e-4 && r(i) < 4.167e-3
            CIPKW = 0.05412;
        elseif r(i) >= 4.167e-3 && r(i) < 1/60
            CIPKW = 0.4055;
        else
            CIPKW = 0;
        end
        CIC(i,1) = lambda(i)*L*CIPKW;
    end
end
end
```

function interruption_cost(type_TS, type_user)

This function helps to summarize total CIC under different cases. It takes only two variables, the type of transfer switches applied in the system and the type of users connected at the load point. It calls the previous function to sum up the total possible interruption cost at each load point.

```
function interruption_cost(type_TS,type_user)
format long;
cases = 1;
load_num = 3;
total_cost = zeros(load_num,cases);

L = [2 37.83 500 1000];
N = [500 26 2 1];

for m = 1:load_num
    CIC = [];
    for n = 1:cases
        %Initialize
        lambda_t = [];
        r_t = [];

        if type_TS == 1
            file =  sprintf('Manual_Load_%d_%d.dat',m,n);
        elseif type_TS == 2
            file =  sprintf('ATS_Load_%d_%d.dat',m,n);
        elseif type_TS == 3
            file =  sprintf('STS_Load_%d_%d.dat',m,n);
```

```
        elseif type_TS == 0 %no load transfer
            file = sprintf('No_load_transfer_%d.dat',m);
        end

        f = importdata(file);
        lambda_t = f(1,:);
        r_t = f(2,:);


        CIC(:,n) = cost_calculation(lambda_t,r_t,L(type_user),type_user);
        total_cost(m,n) = sum(CIC(:,n))*N(type_user);
    end

end

display(total_cost);
avg_CIC = mean(total_cost);
display(avg_CIC);
end
```

function economy_eval(STS_Pr,i,L_growth,n)

This function is used for economy evalution in Chapter 4. It takes five inputs. STS_Pr is the capital cost of the STS; i is the interest rate; L_growth is the load growth of the network; n is the lifetime of the transfer switch. This function uses net present value method, combing CIC and capital cost to help evaluate the economic viability of different transfer switch technologies.

```
function [NPV] = economy_eval(STS_Pr)

cic_matrix = load('Total_CIC_for_diff_user_diff_ts.dat');

% str1 = 'Switch type: 1 = Manual';
% str2 = '             2 = ATS';
% str3 = '             3 = STS';
type_TS = input('Enter switch type: ');

% str1 = 'User type: 1 = Residential';
% str2 = '           2 = Commercial';
% str3 = '           3 = Office';
% str4 = '           4 = Industrial';
% type_user = input('Enter user type: ');
%Investment cost for manual,ATS,STS switch
hw = [0 0.2 0.7 1]*STS_Pr;

%Cost NPV evaluation
for type_TS = 1:4
    for type_user = 1:4
```

```
        %Number of customer per load point for different user type
        if type_user == 1
            N = 500;
            L = 2;
        elseif type_user == 2
            N = 26;
            L = 37.83;
        elseif type_user == 3
            N = 2;
            L = 500;
        elseif type_user == 4
            N = 1;
            L = 1000;
        end

        CIC_y1 = cic_matrix(type_user,type_TS);

        GSPVF = (1-((1+L_growth)/(1+i))^n)/(i-L_growth);
        %Net present value
        NPV(type_user,type_TS) = -hw(type_TS) - CIC_y1*GSPVF;
    end
end

save('-ascii','Cost_NPV','NPV');
```

References

[1] *Global Energy Statistical Yearbook 2012* (n.d.) [Online]. Available: http://yearbook.enerdata.net/

[2] A. Chowdhury, and D. Koval, *Power distribution system reliability practical methods and applications*. Wiley, 2011.

[3] R. Billinton and R.N. Allan, *Reliability evaluation of power systems*, 2nd ed. New York: Plenum Press, 1992.

[4] G. Bertuzzi, U.S. Cinti, E. Cevenini, and A. Nalbone, “Static transfer switch (STS): Application solution. Correct use of the STS in systems providing maximum power reliability,” *Telecommunications Energy Conference, 2007. INTELEC 2007. 29th International*, pp. 587-594, Sept. 30, 2007- Oct. 4, 2007.

[5] J.W. Schwartzenberg and R.W. De Doncker, "15 kV medium voltage static transfer switch," *Industry Applications Conference, 1995. Thirtieth IAS Annual Meeting, IAS '95., Conference Record of the 1995 IEEE*, vol. 3, pp. 2515-2520, Oct. 8-12,1995.

[6] H. Mokhtari, S.B. Dewan, and M.R. Travani, "Performance evaluation of thyristor based static transfer switch," *Power Delivery, IEEE Transactions*, vol. 15, no. 3, pp. 960-966, Jul. 2000.

[7] R.E. Cosse and J. Bowen, "Is selectivity achieved in critical low-voltage UPS and standby generator power circuits?" *Petroleum and Chemical Industry Conference, 1999. Industry Applications Society 46th Annual*, pp. 139-150, 1999.

[8] R.A. Simmons and F.J. Salem, "High voltage automatic transfer switch. Going beyond normal distribution solutions," *Proceedings of the Ninth International Conference on Harmonics and Quality of Power*, vol. 3, pp. 882-886, 2000.

[9] H. Ashour, "Automatic transfer switch (ATS) using programmable logic controller (PLC)," *Mechatronics, 2004. ICM '04. Proceedings of the IEEE International Conference*, pp. 531- 535, June 3-5, 2004.

[10] I.K. Khan, J. Zheng, D.O. Koval, and V. Dinavahi, *"*Impact of manual versus automatic transfer switching on the reliability levels of an industrial plant," *Industry Applications, IEEE Transactions,* vol. 41, issue. 5, pp. 1329 - 1334, Sept.-Oct., 2005.

[11] R.E. Brown and J.H. Spare, "The Effects of System Design on Reliability and Risk," *Transmission and Distribution Conference and Exhibition, 2005/2006 IEEE PES*, pp. 1220-1225, May 21-24, 2006.

[12] M.M. Bhanoo, "Static transfer switch: advances in high speed solid-state transfer switches for critical power quality and reliability applications," *Textile, Fiber and Film Industry Technical Conference, 1998 IEEE Annual*, pp. 5/1-5/8, May 5-7, 1998.

[13] C. He, F. Li, and V.K. Sood, "Static transfer switch (STS) model in EMTPWorks RV," *Electrical and Computer Engineering, 2004. Canadian Conference*, vol. 1, pp. 111- 116, May 2-5, 2004.

[14] H. Mokhtari, "Performance evaluation of thyristor-based static transfer switch with respect to cross current," *Transmission and Distribution Conference and Exhibition 2002: Asia Pacific. IEEE/PES*, vol. 2, pp. 1326-1331, Oct. 6-10, 2002.

[15] H. Mokhtari, "High speed silicon controlled rectifier static transfer switch," Ph.D. dissertation, Univ. of Toronto, Dept. of Computer and Elect. Eng., Toronto, Canada, 1999.

[16] K. Chan, A. Kara, and G. Kieboom, "Power quality improvement with solid state transfer switches," *Harmonics and Quality of Power Proceedings, 1998. Proceedings. 8th International Conference*, vol. 1, pp. 210-215, Oct 14-18, 1998.

[17] M. Takami, T. Ise, and K. Tsuji, "Studies toward a faster, stabler and lower losses transfer switch," *Power Engineering Society Winter Meeting, 2000. IEEE*, vol. 4, pp. 2729-2734, 2000.

[18] E. Carroll, S. Klaka, and S. Linder. (1997, May). *Integrated Gate-Commutated Thyristors: A New Approach to High Power Electronics* [Online]. Available: http://www05.abb.com/global/scot/scot256.nsf/veritydisplay/f0c43c5bda88f53fc1256b9d0045425c/$file/mi97ec_copyright.pdf

[19] *Thyristor Theory and Design Considerations* (2006, Nov) [On-line]. Available: *www.onsemi.com/pub/Collateral/HBD855-D.PDF*

[20] M. Takeda, H. Yamamoto, T. Aritsuka, I. Kamiyama, and G.F. Reed, "Development of a novel hybrid switch device and application to a solid-state transfer switch," *Power Engineering Society 1999 Winter Meeting, IEEE*, vol. 2, pp.1151-1156, Jan. 31 –Feb. 4, 1999.

[21] H. Mokhtari, S.B. Dewan, and M.R. Iravani, "Analysis of a static transfer switch with respect to transfer time," *Power Delivery, IEEE Transactions*, vol. 17, no. 1, pp. 190-199, Jan 2002.

[22] A. Sannino, "Static transfer switch: analysis of switching conditions and actual transfer time," *Power Engineering Society Winter Meeting, 2001. IEEE*, vol. 1, pp.120-125, Jan. 28 – Feb.1, 2001.

[23] S.Y. Yun, J.C. Kim, J.F. Moon, C.H. Park, S.M. Park, and M.S. Lee, "Reliability evaluation of radial distribution system considering momentary interruptions," *Power Engineering Society General Meeting, 2003, IEEE*, vol. 1, no., pp. 485, July 13-17, 2003.

[24] R.E. Brown, S. Gupta, R.D. Christie, S.S. Venkata, and R. Fletcher, "Distribution system reliability assessment: momentary interruptions and storms," *Power Delivery, IEEE Transactions*, vol. 12, no. 4, pp. 1569-1575, Oct 1997.

[25] S. Bhattacharyya, J. Myrzik, and W.L. Kling, "Consequences of poor power quality - an overview," *Universities Power Engineering Conference, 2007. UPEC 2007. 42nd International*, pp. 651,656, Sept. 4-6, 2007.

[26] R.C. Degeneff, R. Barss, D. Carnovale, and S. Raedy, "Reducing the effect of sags and momentary interruptions: a total owning cost prospective," *Harmonics and Quality of Power, 2000. Proceedings. Ninth International Conference*, vol. 2, pp. 397-403, 2000.

[27] R. Billinton and P. Wang , "Distribution system reliability cost/worth analysis using analytical and sequential simulation techniques," *Power Systems, IEEE Transactions*, vol. 13, no. 4, pp. 1245-1250, Nov 1998.

[28] S. Yeddanapudi, Y. Li, J.D. McCalley, A.A. Chowdhury, and W.T. Jewell, "Risk-based allocation of distribution system maintenance resources", *IEEE trans. Power Syst.*, vol. 23, no. 2, pp. 287-295, May 2008.

[29] T.H. Ortmeyer, J.A. Reeves, D. Hou, and P. McGrath, "Evaluation of Sustained and Momentary Interruption Impacts in Reliability-Based Distribution System Design," *Power Delivery, IEEE Transactions*, vol. 25, no. 4, pp. 3133-3138, Oct. 2010.

[30] "IEEE Guide for Electric Power Distribution Reliability Indices," *IEEE Std. 1366-2012 (Revision of IEEE Std. 1366-2003)*, pp. 1-43, May 31, 2012

[31] "IEEE Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems - Redline," *IEEE Std. 493-2007 (Revision of IEEE Std. 493-1997) - Redline*, pp. 1-426, June 25, 2007.

[32] *Residential energy consumption survey* (2009) [Online]. Available: http://www.eia.gov/consumption/residential/data/2009/

[33] P. William and P.E. Risko. (n.d.). *A Comparison of Medium Voltage Static Transfer Switches and Medium Voltage Mechanical Transfer Switches* [Online]. Available: http://www.electricenergyonline.com/?page=show_article&article=43

[34] R. Billinton and R.N. Allan, *Reliability evaluation of engineering systems*, 2nd ed. New York: Plenum Press, 1992.