University of Alberta

Modeling and Evaluating Electrical Power System: Risk and Reliability

By

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Abstract

Two popular analytical methodologies for evaluating the risk and reliability of electrical power systems, the Spreadsheet and Cut-Set models, were investigated and modified. When a failure related to parallel configuration is involved, the two models greatly underestimate the mean time to repair and the failure rate, respectively, generating a large discrepancy in the reliability indices generated by the two models. For the purpose of improving the evaluation of parallel configurations, these two models were modified by altering the evaluating procedure and using self-deduced formula equations. These modified models were validated by applying them to the IEEE Gold Book Standard Network. The revised Spreadsheet Model was then applied to optimize a conceptual designation for a power distribution station. As one of the most significant contributions of this thesis, issues were addressed regarding the failure modes (short/open) of circuit breakers and their influence on network reliability.

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List of Symbols and Abbreviations

MTTF	Mean time to failure
MTTR	Mean time to repair
FDT	Forced down time for a component or system due to a failure
i	Subscript i identifies the index for a specific component
λ	Failure rate, usually expressed as failures per year
d	Symbol for mean time to failure
r	Symbol for mean time to repair
μ	Repair rate, numerically equal to $1/r$
R_i	Probability for component i to be operational
Q_i	Probability for component i to fail
R_S	Probability for a defined system to be operational
Q_S	Probability for a defined system to fail
λ_S	Failure rate of a defined system
P_i	Probability of occurrence for a specific state "i".
A_i	Availability of component "i"
f_{down}	Frequency for a system being down
λ_{eq}	Partial failure rate for a parallel connected system that accounts for the case without considering common cause factor
A_{eq}	Partial availability for a parallel connected system that accounts for the case without considering common cause factor
λ_C	The failure rate from an operational state to a failed state due to common cause factor
r_C, μ_C	The *MTTR* and the repair rate from the failed state due to common cause factor to an operational state
C	Coefficient for the common cause factor
$\lambda_O(\lambda_S)$	Failure rate for failing open (or short)

Chapter 1

Introduction

This chapter presents the practical significance of reliability research and gives a brief introduction to reliability research methodologies. Problems existing in the currently available reliability methodologies and the goals of this thesis are addressed.

1.1 Practical Significance of Reliability Research

Power system reliability investigation has its significant meanings in two aspects. First of all it is the basis upon which the maintenance strategy should be planned for a modern power system. Second, in nowadays competitive energy market, power supply reliability is an important factor that affects customers' choice.

In the early years of power distribution network, system reliability assessment was not the first consideration towards maintenance. In Moubray's book "*Reliability-centered Maintenance*" [1] identifies three generations since 1930's in the development of the role of reliability in maintenance, as shown in Fig. 1-1. (i) Before World War II, because industry was not very highly mechanized yet, the downtime didn't matter much, furthermore most equipment was simple and often over-designed, reliability was not even considered and a "fix when broken" maintenance approach was enough. (ii) The increased mechanization during World War II made industry more machines-

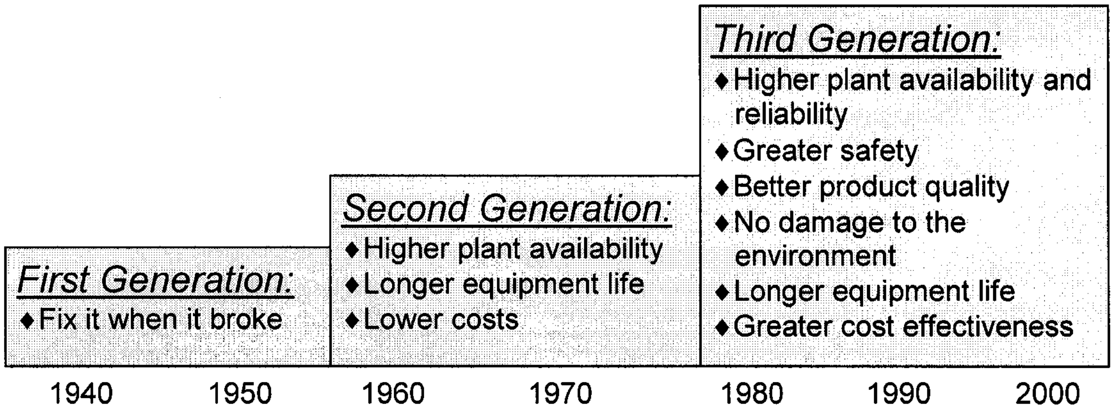


Fig. 1-1 Growing expectations in maintenance [Moubray1997]

dependent and the downtime of machines came into sharper focus. Preventive maintenance (such as equipment overhauls at fixed intervals) was usually scheduled. (iii) Since the mid seventies, the process of change in industry has gathered even greater momentum. New expectations, new research and new techniques were required and "downtime has always affected the productive capability of physical assets by reducing output, increasing operating cost and interfering with customer service [1]". Therefore, the reliability of physical assets is much more important than ever in maintenance programs to achieve higher expectations. Reliability-centered maintenance has been rapidly developing in recent years and is becoming a cornerstone of equipment maintenance. A manager of a modern power system must have enough knowledge of the system reliability so that he/she may make proper schema to maintain it.

On the other hand, the energy market is highly deregulated compared with the situation twenty years ago, and is characterized by intense competition due to the large debts, budget constraints, safety, environment and economic issues [2]. This requires a good balance between cost and reliability when designing and/or upgrading a power system, *i.e.* new designs require to be optimized. Although a high reliability design usually causes high cost, an optimized design does help to improve the system reliability while keeping the cost reasonably low. In order to obtain an optimized design, a quick and easy-going tool is necessary to assess the design by considering realistic factors.

1.2 Reliability Research Methodologies

Reliability indices of an electrical power system can be calculated using a variety of methodologies that fall into two main categories: analytical and simulation as shown in Fig. 1-2. In the days before high computer speed was dramatically improved, the vast majority of reliability research methodologies had been analytically based while simulation had taken a minor role in specialized applications [3]. This is because most power systems are complicated and simulations generally involve a large amount of computation; consequently require extremely long computing time so that it is non-practical.

Zone Branch methodology developed by Dr. Don Koval [4] is one of the early examples in analytical category. It is to divide a given circuit into different zones branches and then study the power flow path for each zone branch based upon a reliability analysis. In 1995, Propst [5] proposed a Spreadsheet-based Model based upon

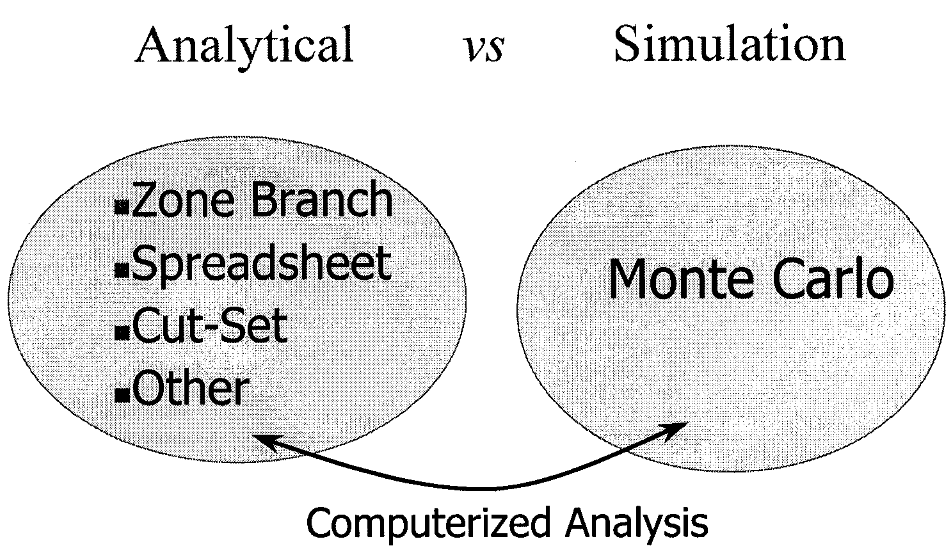


Fig. 1-2 Two categories of reliability research methodologies

accepted straightforward methods described in the IEEE Gold Book [6]. In this model a circuit is divided into number of zones. Reliability parameters of each zone may be evaluated using the components' reliability indices covered by the zone. Different zones are connected either in series or in parallel that can be defined by a configuration table, as called "Zone Table" in the model [5]. The reliability parameter (failure rate and mean time to repair, *etc*) for each point is then determined by evaluating the upstream zones to this point accordingly. Recently J. Propst [7] developed this model further and made it more effective for easy and quick assessment of large industrial electrical systems. Similarly a Cut-Set model was applied by Coyle *et al* [8] that divides a circuit into some basic units called Minimal Cut Sets. A diagram that reveals the logical relationship amongst the cut-sets is then built and the reliability parameters of any point may be evaluated by using a logic diagram. Other analytical methodologies include Go-Branch [9] that applies a Boolean Algebra concept to circuit, and more [10].

With the dramatically improved performance of computers today, simulation has been playing a more and more important role in reliability evaluations. One of the popularly used simulation methodologies is the Monte-Carlo method. A sequential Monte Carlo method involving the application of multi-computer platforms was described by Borges *et al* [11]. Other literatures on simulations methodology may refer to Billinton's book [12] and many other papers [13-17].

The extensive applications of computers today results in interaction of analytical and simulation methodologies. High proficiency and accuracy may be achieved in analytical methodologies by programming with different algorithms, either complicated or simple [5,6,18,19]. As early as in 1971, a program using BASIC computer language was developed to evaluate reliability of systems composed of series equipment (or subsystems) [18]. Complicated models were developed following the rapidly increased computing ability of computers. Recently fuzzy set theory was employed in reliability assessment for evaluating coefficient of different terms of reliability expression [19].

The Spreadsheet Model [7] that is discussed in detail in this thesis is an excellent example of computerized analytical methodologies.

1.3 Complicacy and Accuracy

Many methodologies are complicated. For example, the Cut-Set Model involves at least five steps of (i) dividing the network into cut-sets; (ii) calculating the reliability indices for each cut-set as event indices; (iii) constructing a unique logic diagram for each load point that attracts interest; (iv) building the configurations of all the cut-sets from the logic diagram into a worksheet; (v) applying equations to obtain the results for reliability indices of any specific load points. Each step is complicated and time consuming.

The inaccuracy usually is resulted from two aspects. First of all, a circuit protective device may fail either as short or as open, and this can result in different actions of the circuit. This issue has not been well addressed yet in the current available methodologies. Another issue that may result in inaccuracy is the dependency among different equipment or components, especially when apparently redundant parallel configuration is involved. Theoretical reliability redundancy equations frequently lead to reliability levels that are significantly outside the realm of reality, for example one failure in a thousand years. For example, the following IEEE surveyed reliability indices for single and dual electric utility power supplies are shown in Table 1-1 [6]. The actual double-circuit utility power supply has a failure rate more than 270 times larger than the theoretical prediction from theoretical expectation, a significant error in assessing the reliability of any industrial power system substation configuration. This is because the two supplies may be dependent and fail simultaneously due to a common cause, known as common cause failure mode. As pointed out in the IEEE Gold Book the electric utility supply is the largest contributor to both the failure rate and forced hours downtime per year for many substation configurations. The use of actual or surveyed data as opposed to data derived from theoretical equations is required for

Table 1-1. Comparison of actual and calculated reliability of a double-circuit utility power supply (Failure defined as loss of both power sources)

No. of circuits (all voltages)	Failures per year (λ)	MTTR per failure (r)	Annual hours of Downtime (λr)
Failure of Single Circuit	1.956	1.32	2.582
IEEE Surveyed Failure of Both Circuits	**0.312**	**0.52**	**0.1622**
Theoretical calculations with independency assumption	**0.001153**	**0.66**	**0.000760994**

accurate reliability analysis of utility power supplies to industrial substation configurations, a difficult task in this era of utility deregulation. However, many methodologies simply make an independency assumption and ignore the common cause failure mode that results in significant error. The Spreadsheet Model takes this factor into consideration when dealing with failure rate for parallel configuration, but it fails to take reasonable considerations when evaluating the Availability and MTTR of each failure. Therefore, the final annual down time is not accurate, as discussed in detail in Chapter 3 of this thesis.

The goal of the thesis is to achieve a convenient methodology with enough accuracy. Two analytical models, the Spreadsheet Model and the Minimum Cut-Set Model, will be analyzed and discussed as to their flexibility and limitations, and some improvements are then made to each model. The models are to be validated by applying them to actual network. As an excellent combination of analytical methodology with programmed process, the revised Spreadsheet Model is proved to be a convenient and accurate methodology.

Chapter 2

Theoretical Background

The frequently used terms and equations in reliability research and applications are summarized in this chapter. The related equations introduced in this chapter include:

- Relationships among different reliability indices
- Reliability indices for components connected in series
- Reliability indices for components connected in parallel

2.1 Terminology

The term "reliability" usually reminds us of a number with the value between 0.0 to 1.0, and for most of the cases it is larger than 0.9. It is not always easy to get a clear sense for the difference between two reliability parameters expressed by two numbers such as 0.9995 and 0.9996, while it may result in a large difference in actual system performance. Therefore, some performance indices are described in this chapter that are frequently used to describe system reliability so that the customers may get a clearer sense and understand the difference in a more tangible way. Besides the valuable statistical data related to system reliability, financial risk is also an important issue in industrial management. The frequently used terms related to system reliability and financial risk are briefly reviewed here and described in more detail in the IEEE Gold Book [6].

Annual Risk - The calculated financial losses of production due to an electrical system failure divided by the frequency of the failure.

Availability - A ratio that describes the percentage of time a component or system can perform their required function.

Component - A piece of electrical or mechanical equipment, a line or circuit, or a section of a line or circuit, or a group of items that is viewed as an entity for the purpose of reliability evaluation. "Component" and "equipment" will not be distinguished throughout the thesis.

Failure - The termination of the ability of an item to perform a required function.

Failure rate - The mean number of failures of a component per unit exposure time.

Forced downtime - The averaged total time per year a system is unavailable in between failures and expressed in hours per year.

Lambda (λ) - The inverse of the mean exposure time between consecutive failures. Lambda is typically expressed in either failures per year or failures per million hours.

MTTF – Stands for mean time to (between) failure. The mean exposure time to consecutive failures of a component or system. The mean time between failures is usually expressed in either years per failure or millions of hours per failure. For some applications, measurement of mean time to repair (MTTR) rather than mean time to failure may provide more statistically correct information.

MTTR – Stands for mean time to repair. While the Forced Downtime gives the total amount of time within one year when the system is unavailable, MTTR refers to the mean time to repair a failed component. For a system, it is the total amount of time during which it is unavailable in between failures and is expressed in hours.

System - A group of components connected or associated in a fixed configuration to perform a specified function of distributing power.

Reliability - An indication of the ability of a component or system to perform its intended function during a specified time.

Point - Any place or location within the electrical system. The name or designation for a point is always the same as the name of the zone that the point is located within.

RAM Table - A lookup table in the model that displays the Lambda and MTTR for electrical components. Because the program randomly refers to this table for reliability indices of any component, this area has the function similar to a randomly accessed memory (RAM) in computer architecture. This is why it is called RAM Table.

Zone - A segment of a power distribution system in which a fault at any location within the segment or zone would have the common impact of causing the first upstream protective device to isolate the system.

Restore Time - In the model, the time to restore is the sum of the mean time to repair (MTTR) for the failure plus the computed time to re-stream or restart the connected process unit or load.

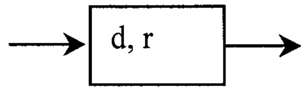
2.2 Single Component Analysis – Non Repairable

Some fundamentals related to reliability research are discussed below. The discussion is based on the knowledge obtained from two courses provided by the Electrical Engineering Department at the University of Alberta, "*Engineering Reliability*" (EE514) and "*Design of Reliable Industrial and Commercial Power Systems*" (EE528) instructed by Dr. D. Koval [20, 21]. The equations described in sections 2.2 to 2.4 are based on two assumptions:

(a) The components are independent;

(b) The component life has an exponential distribution.

Reliability parameters that describe the characteristics of a single component:



$d = MTTF$ (in hours)

$r = MTTR$ (in hours)

MTTF stands for mean time to failure. The reciprocal of MTTF, called "failure rate", usually represented by a Greek symbol λ, is a measurement of failures per unit exposure time. Therefore, it is directly related to component reliability. MTTR stands for mean time to repair, being an important parameter to evaluate the forced down time (in hours) for a system during a unit time. The reciprocal of MTTR called "repair rate", represented by a Greek symbol μ, is affected by multiple factors such as service quality, parts availability, *etc*.

Regarding the units, failure rate is frequently given as failures per million hours of operating time. When MTTF is given in hours, failure rate may be expressed as:

$$\lambda = 10^6 / MTTF \text{ (failures per million hours)} \qquad (2\text{-}1)$$

Throughout this thesis, failure rate (λ) is always given as failures per year and MTTF is in years:

$$\lambda = 1 / MTTF \text{ (failures per year)} \qquad (2\text{-}2)$$

thus, the component reliability (R) for one year is given by:

$$R = e^{-\lambda \cdot t} = e^{-\lambda} \text{ (when } t = 1 \text{ year)} \qquad (2\text{-}3)$$

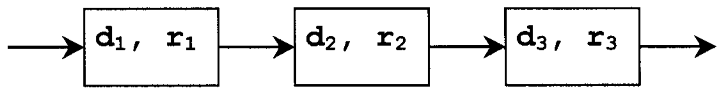
For a single component, the availability (A) is given as the total operating time (MTTF) over the total time (MTTF + MTTR). Following the convention, MTTF is given in years and MTTR is in hours, the availability may be expressed as:

$$A = \frac{8760 \cdot MTTF}{8760 \cdot MTTF + MTTR} = \frac{8760 \cdot \mu}{\lambda + 8760 \cdot \mu} \qquad (2\text{-}4)$$

where 8760 is the number of hours for one year.

2.3 Analysis for Components in Series – Non Repairable

For the system shown below with three different components in series,



$d_i = MTTF_i$ (in years)

$r_i = MTTR_i$ (in hours)

The characteristics of each individual component "*i*" can be calculated using:

$$\lambda_i = \frac{1}{d_i} \tag{2-5}$$

$$A_i = \frac{d_i}{d_i + r_i} \tag{2-6}$$

$$R_i = e^{-\lambda_i} \text{ (for one year)} \tag{2-7}$$

The combined reliability for a series system:

$$R_S = R_1 \cdot R_2 \cdot R_3 \tag{2-8}$$

Therefore, the combined failure rate for a serial system is:

$$\lambda_S = \lambda_1 + \lambda_2 + \lambda_3 \tag{2-9}$$

Reliability of the system for one year:

$$R_S = e^{-\lambda_S} \tag{2-10}$$

System availability:

$$A_S = A_1 \cdot A_2 \cdot A_3 \tag{2-11}$$

Probability of failure during one year:

$$P_S = (1 - R_S) \cdot 100\% \tag{2-12}$$

MTTF is the reciprocal of failure rate according to its definition :

$$MTTF = \frac{1}{\lambda_S} \tag{2-13}$$

MTTR in hours:

$$MTTR = 8760 \cdot (\frac{MTTF}{A_S} - MTTF) \quad (2\text{-}14)$$

Forced downtime:

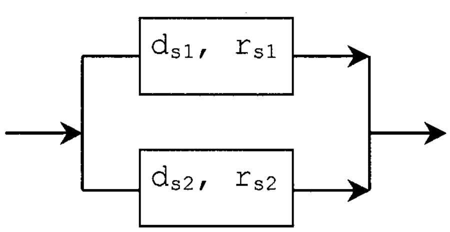
$$FDT = (1 - A_S) \cdot 8760 \quad (2\text{-}15)$$

For the three indices of failure rate, availability and mean time to repair, one of them can always be expressed by using the two others. Therefore, if two of them are known, the third one is also known.

2.4 Redundant Components Analysis

By "redundant" we mean if one component fails, the other component can perform its function. One example is a system that operates satisfactorily if either one or both of the two parallel components functions. Reliability can be dramatically increased by installing a parallel system without requiring to increase the reliability of any individual components, where the components are redundant. Sometimes we refer to a system as "redundant system" that is made up of redundant components.

2.4.1 Redundant Active Systems - Non-repairable



The reliability for such a system for one year can be calculated using:

$$\begin{aligned} R_S &= 1 - Q_{S1} \cdot Q_{S2} \\ &= 1 - (1 - R_{S1})(1 - R_{S2}) \\ &= R_{S1} + R_{s2} - R_{S1} \cdot R_{S2} \end{aligned} \quad (2\text{-}16)$$

the combined failure rate is:

$$\lambda_S = \ln(1/R_S) \quad (2\text{-}17)$$

the system availability is:

$$A_S = 1-(1-A_{S1})\cdot(1-A_{S2}) \\ = A_{S1}+A_{S2}-A_{S1}\cdot A_{S2} \qquad (2\text{-}18)$$

and the probability of failure during one year is:

$$P_S = (1-R_S)\cdot 100\% \qquad (2\text{-}19)$$

2.4.2 Redundant Active Systems - Repairable

In many practices, when a component fails, it may be either repaired or replaced with a new one. When this is true, the reliability of the systems described above is also dependent upon the time required to repair the component in failure or replace it with a new part. In this case the combined reliability of the redundant system may be figured out by using the Frequency Balance Approach [20]. Figure 2.1 shows the state space diagram of the system. The four circled bold numbers indicate the four possible states for a two-component parallel system. In state 1, both of the two components function well (in a "up" state). In state 4, neither of the two components functions well (in a "down" state). In state 2 and 3, one component is up and the other is down. When the two components are redundant, only one of them is necessarily required to make the system operate. Therefore, among the four states, states 1, 2 and 3 are operational states, and only state 4 is a failed state. Accordingly, the four states may be grouped into two categories of states. One represents the operational state with the probability of R_s; another represents the failed state with the probability of Q_s = 1- R_s as shown in the bottom of Fig. 2-1. The underlying principle of the Frequency Balance Approach is:

The frequency of departure from a given state is equal to the frequency of entry to the given state.

If the probabilities of states 1, 2, 3 and 4 are defined as P_1, P_2, P_3 and P_4, a set of linear equations can be formed according to the above-mentioned principle. The linear equation set is not described here because a more practical model discussed in section 3.2 covers more details. The reliability of the redundant system may be represented by the probabilities of different states P_1, P_2, P_3 and P_4.

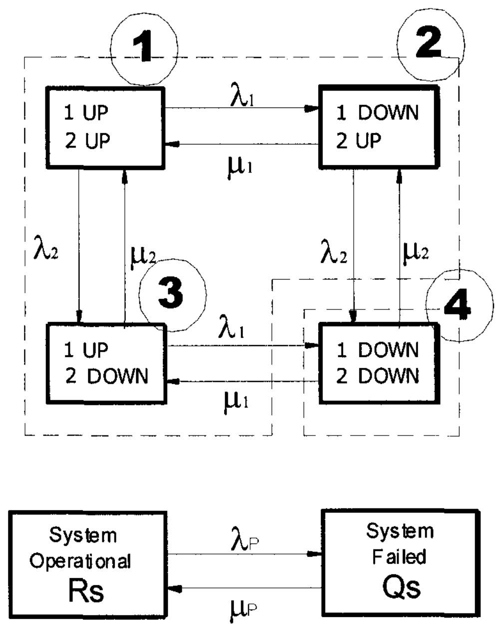


Figure 2.1 State space diagram of a redundant system composed of two unequal components

$$R_S = P_1 + P_2 + P_3 = \frac{(\mu_1\mu_2 + \lambda_1\mu_2 + \lambda_2\mu_1)}{(\lambda_1 + \mu_1)\cdot(\lambda_2 + \mu_2)} \tag{2-20}$$

$$Q_S = P_4 = \frac{\lambda_1\ \lambda_2}{(\lambda_1 + \mu_1)\cdot(\lambda_2 + \mu_2)} \tag{2-21}$$

The frequency of the system being down can be expressed as:

$$f_{\text{down}} = Q_S \cdot (\mu_1 + \mu_2) \tag{2-22}$$

The average duration in the down state for the parallel system (r_P) is then:

$$MTTR = r_P = Q_S / f_{\text{down}} = \frac{1}{(\mu_1 + \mu_2)} = \frac{r_1 r_2}{r_1 + r_2} \tag{2-23}$$

$$\mu_P = \frac{1}{r_P} = \frac{r_1 + r_2}{r_1 r_2} \tag{2-24}$$

Applying the frequency balance principle to the bottom part of Fig. 2 -1:

$$R_S \lambda_P = Q_S \mu_P \tag{2-25}$$

Therefore:

$$\lambda_P = \frac{(\lambda_1 \lambda_2) \cdot (r_1 + r_2)}{1 + \lambda_1 r_1 + \lambda_2 r_2} \approx (\lambda_1 \lambda_2) \cdot (r_1 + r_2) \tag{2-26}$$

$$A_P = \frac{8760 \cdot \mu_P}{\lambda_P + 8760 \cdot \mu_P} \tag{2-27}$$

The equations discussed above are based on the two assumptions of component independency and componential distribution for component life. However, in a practical parallel system composed of two or more components, it is still possible for the system to fail due to a common mode factor (component dependency). This possibility results in a greatly higher failure rate in practice than the mathematical prediction by the above equations, sometimes the surveyed actual failure rate could be hundreds times of the theoretical prediction as shown in Chapter 1 by an example. Modified treatments for 2nd and 3rd orders parallel configurations are discussed in Chapter 3 and 4, respectively.

Chapter 3

Spreadsheet Methodology-Modifications and Applications

This chapter uncovers the inner mechanism including equations and evaluating process used by the Spreadsheet Model, reveals the problems existing in the model when dealing with parallel configurations, and derives a new set of equations by using Frequency Balance Approach. The model is then modified by using different evaluating procedure and equations so that the common cause factor may be considered completely. Some special considerations and technical treatments on circuit breakers are discussed and applied to the revised version of the Spreadsheet Model. The revised model is applied to optimize a power distribution substation design. The modifications of the model and considerations on circuit breakers are two important contributions of the thesis.

3.1 Uncovering the Spreadsheet Model

3.1.1 Introduction to the Spreadsheet Model

The model proposed by Propst [5, 7] is a spreadsheet-based software that represents an actual circuit in terms of zones. Sometimes it is also called zone branch model named after the zone concept applied in the model. In order to distinguish this model with the

Zone Branch Model developed by Dr. Koval [4], we use "Spreadsheet Model" to refer to Propst's model throughout the thesis. Besides the ability to evaluate the reliability of any point inside a known circuit, another function of the model is to produce a financial risk report provided the related financial data input is available in the entries. Due to the lack of financial information resource, only the reliability assessment will be conducted in this thesis.

In an electrical power network, the failure rates at points that are between protective devices such as circuit breakers, re-closures, or fuses are the same. Accordingly the electrical network can be divided into zones based upon the circuit protective device location. A zone is defined as a segment of a power distribution system in which a fault at any location within the segment (*i.e.* zone) would have the common impact of causing the first upstream protective device to isolate the system [5]. The relationships among the different zones are configured within the spreadsheet model in an area that is called Zone Table. In this table, a zone can be configured as in series with the zone immediately above it (in the direction of its upstream), or as parallel with a neighboring zone that has the same level with it in the power stream. The reliability parameters (failure rate, mean time to repair, availability, *etc.*) of each point within the corresponding zone may then be evaluated using reliability equations either for parallel or serial configurations. In order to show the structure of the Spreadsheet Model, different areas in the spreadsheet layout corresponding to different functions and their relationships in the model are mapped below as in Fig. 3-1. The content of the twelve areas are defined as following:

1. RAM Table Master in an individual worksheet (separated from the Model worksheet). It contains the reliability indices for each electrical components utilized in the system. The name of "RAM" is a borrowed computer term in order to describe the function of this table: the program may access to this table randomly for reliability information of the related components used in the network.
2. RAM Table for Zones 1-35.

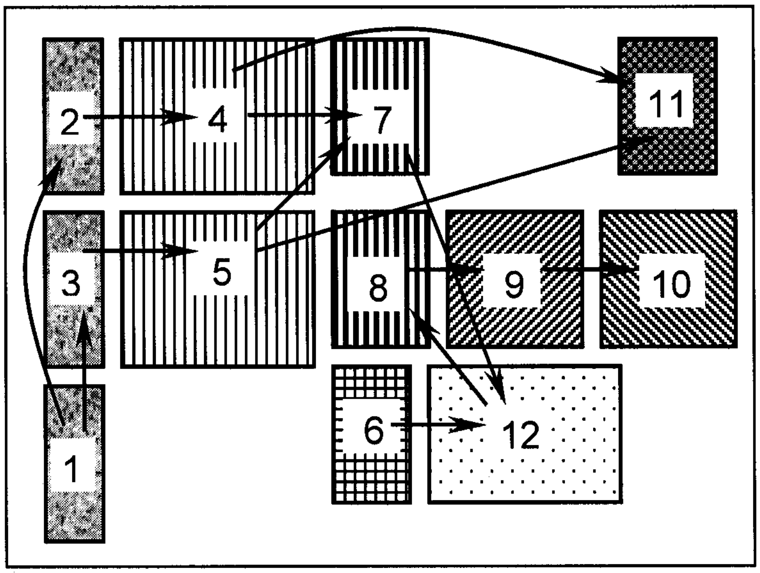


Figure 3-1. Layout of the worksheet space for the Spreadsheet Model

3. RAM Table for Zones 36-70.
4. Quantity Input for Zones 1-35, defining the contents of each zone from zone 1 to zone 35.
5. Quantity Input for Zones 36-70, defining the contents of each zone from zone 36 to zone 70.
6. Zone Table for configuration, defining the relationships amongst different zones.
7. Zone Calculate Table for Zone results, defining the reliability parameters for each zone separately.
8. Point Calculate Table for Point results, defining the reliability parameters accumulated to each point.
9. Unit Impact Table for Financial Results.
10. Consequence Table for Model Results.
11. Model Component Summary.
12. Miscellaneous Point & Configuration Calculations, intermediate data storage. Equations used in the intermediate process are also defined here.

3.1.2 Data Entries in the Model

In order to represent an actual circuit with the spreadsheet, data may be entered with the following data entries:

◈ Enter and edit RAM table ("RAM table" worksheet)

Define and review the RAM table to make sure it has all of the required components with their reliability parameters in the system to be modeled.

◈ Divide system into zones and enter zone entries

Divide the system into individual zones connected either in series or in parallel according to the definition for *zone*. Attention should be paid to Closed Tie Breaker or Open Breaker in the system (refer to section 3.3). The quantity and type of components in each zone are entered into the zone area (area 4 and 5 in the model layout). This area is located in the "Model" worksheet but linked to the RAM table worksheet. The component characteristics in the RAM table are the resource based on which calculation will be made. Reliability characteristics corresponding to each zone are available in area "7" as shown in Fig. 3.1.

◈ Enter system configuration (Zone Table)

The connection and relationship amongst different zones can be defined in Zone Table area according to the actual system. Points are consequently defined according to the connection and configuration. Reliability characteristics corresponding to each point are available in area "8" and this will give a basis for accumulating reliability behavior for the whole system.

◈ Check ZoneCalc and PointTable

Check these two areas and make sure all of the individual number corresponding to certain zone and/or point is reasonable. "#DIV/0!" or infinite value means input error either when entering zone information or when defining Zone Table. Going back to debug is often a necessity.

◈ Other data input

This model provides also with the opportunity to evaluate a system to get helpful information for management in language of dollars. Lacking the data for actual cost when a failure occurs with different extent, this part is not done yet in the current work.

3.1.3 Capabilities of the Model

The Spreadsheet Model is a complex PC based spreadsheet. The following objectives can be achieved by using the Spreadsheet Model:

◈ **Ability to represent an actual system**

Electrical systems are created using groups of electrical components connected in either series or parallel separated by various protective devices such as fuses and circuit breakers. The model makes use of this fact by dividing a system into different zones. For each zone, the model provides a means for entering the quantity and type of electrical components [7]. Therefore, it is convenient to represent the actual circuit by defining the components and their connections in the model.

◈ **Define/redefine characteristics of components**

All of the components used in the system may be entered into a RAM table with their descriptions, failure rates and mean time to repair (MTTR) parameters. The RAM table may be modified whenever necessary and the modification can be immediately reflected in the "Model" worksheet.

◈ **Enter/change system configuration**

The configuration of a system may be entered and edited in a ZoneTable where connection and relationship among different zones are defined. This provides with the opportunity to re-configure a system to get an optimized network connection.

◈ **Optimize a system**

The modification for the characteristics of the components and their configuration in the system can also be directly reflected in the program output; therefore it is easy to optimize a system by adjusting the components reliability parameters or adjusting the configuration of the components. For instance, when necessary, the key components to system reliability may be recognized as the sensitive parts, and then it could be replaced by a part with higher reliability to improve the system reliability in the most effective way.

3.1.4 Dealing with Parallel Components

◈ **Failure Rate**

Mathematically, a parallel system with *redundant* components greatly improves the reliability when assuming that the two components are independent. This mathematical consideration often leads to unreasonably small failure rate compared with the actual case. In reality, probability still exists for a redundant system to fail from a common mode. Examples of common mode failure include common electrical connections, common alarm wiring or the environment. When monitoring the failure rate of a system with components that are interdependent, often a much greater number may be observed compared to that evaluated from equation 2-26, that is $\lambda_p = (\lambda_1 \lambda_2)(r_1 + r_2)$. Although the parallel configuration still remarkably improves the reliability, it cannot achieve the improvement so much as mathematically predicted by equation 2-26 (refer to the example shown in Chapter 1). Therefore a common cause factor has to be considered when dealing with parallel components. In the original Spreadsheet Model, the common cause factor was considered when evaluating the parallel failure rate in the following way[§]:

$$\lambda_p = \lambda_1 + \lambda_2 - \lambda_1 \cdot A_1 - \lambda_2 \cdot A_2 + \max(\lambda_1, \lambda_2) \cdot CCF \qquad (3\text{-}1)$$

[§] The equations described here were obtained by tracking the original spreadsheet.

where *CCF* (stands for common cause factor) is a number between 0.1 to 0.95. A larger *CCF* means a higher probability that the parallel system fails in common mode, and therefore leads to a higher failure rate evaluation.

◈ Availability and Mean Time To Repair

From the equations described in Section 2, if one knows any of the three variables of λ, availability or MTTR, the third can then be deduced. The Spreadsheet Model selects to determine availability prior to MTTR using the following equation:

$$A_p = 1-(1-A_1)\cdot(1-A_2)\cdot\frac{MTTF_{eq}}{max(MTTR_1, MTTR_2)+MTTF_{eq}}$$
$$> A_{eq} \approx 1-(1-A_1)\cdot(1-A_2) \quad \text{(Over-Estimated)} \tag{3-2}$$

where $MTTF_{eq} = 1 / \lambda_{eq}$. The subscripts "*eq*" represents the reliability index evaluated from the 2nd parallel configuration without considering common cause factor. The ">" sign is because the fraction part in equation (3-2) is smaller than 1.0. With considering common cause factor, the availability shall be smaller than A_{eq}, while the estimation used in the original Spreadsheet Model is larger than A_{eq}. Therefore, the result for Availability in the original model has been overestimated.

According to the relationships among the three reliability indices of failure rate (λ), availability (*A*) and mean rime to repair (*R*), the mean time to repair may be determined by using equation (3-3), which is the way how mean time to repair is obtained in the original model.

$$R_p = 8760\cdot\left(\frac{1}{A_p\cdot\lambda_p}-\frac{1}{\lambda_p}\right) \quad \text{(Under-Estimated)} \tag{3-3}$$

The coefficient 8760 is used when the unit for λ is failures per year. Because A_p has been overestimated as discussed according to equation (3-2), It is obvious that the mean time to repair in equation (3-3) is underestimated. Accordingly, the annual forced down time is also underestimated as shown in equation (3-4):

$$FDT = 8760 \cdot \lambda_p \cdot R_p \text{ (Under-Estimated)} \tag{3-4a}$$

or

$$FDT = 8760 \cdot \lambda_p \cdot (1 - A_p) \quad \text{(Under-Estimated)} \tag{3-4b}$$

Therefore, the original Spreadsheet Model overestimate the system reliability by underestimating its mean time to repair and annual forced down time (or by overestimating its availability). In the next section, effort is taken to remodel the equations and alter the evaluating process to achieve more reasonable results. The revised model is to be tested by applying it to actual designs.

3.2 Modifying the Spreadsheet Model

3.2.1 Reliability for a Parallel System with Common Cause Failure

As discussed above, it is necessary to remodel the parallel redundant system to obtain proper reliability evaluation. The Frequency Balance Approach introduced in Section 2 is applied to evaluate the reliability of a redundant system with consideration of the Common Cause Factor. A Common Cause Failure refers to an event originated by a single external cause with two or more failure effects that are not consequence of each other. The state space diagram for the parallel component configuration is shown in Fig.3-2. The failed state due to the Common Cause Factor is represented by the state "5". The transferring rate for each path among the different states in the State Space Diagram as shown in Fig. 3-2 are obtained based upon the following assumptions:

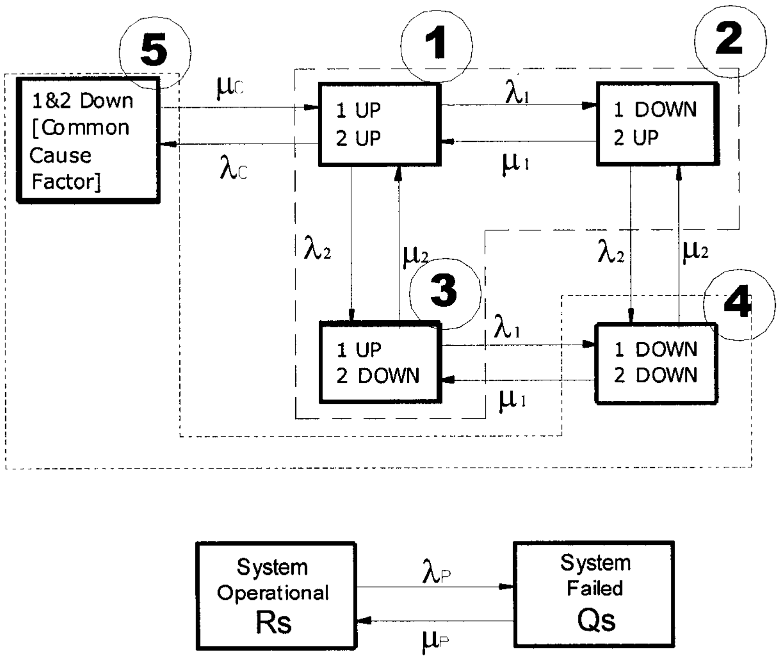


Figure 3-2. State space diagram of a redundant system with common cause factor considered

- The components failing due to Common Cause Factor are repaired simultaneously and returned to service as soon as the repair is finished;
- The component failing individually due to other reasons is repaired one at a time and returned to service as soon as the repair is finished.

According to the first assumption, state "5" can only transfer to state "1". The failing rate from state "1" to state "5" is the common cause failure rate λ_C. The repairing rate from state "5" back to state "1" is μ_C. Because the repair is done simultaneously, the repair rate is restricted by the slowest one, that is:

$$\mu_C = 1/\max(r_1, r_2) \qquad (3\text{-}5)$$

The transferring rates among the other states are based upon a one-component repair, therefore, for example, the transferring rates from state "4" to state "2" and "3" are μ_1 and μ_2, respectively.

The system-failed state comprises state "5" and state "4" as shown by the shadow area in Fig. 3-2. Other states are operational states. The regrouped operational state with a probability of R_s and the failed state with a probability of Q_s are shown in the bottom of Fig.3-2.

According to the Frequency Balance Approach, we have the following equations:

$$P_1(\lambda_1 + \lambda_2 + \lambda_C) = P_2\mu_1 + P_3\mu_2 + P_5\mu_C \qquad (3\text{-}6)$$

$$P_2(\lambda_2 + \mu_1) = P_1\lambda_1 + P_4\mu_2 \qquad (3\text{-}7)$$

$$P_3(\lambda_1 + \mu_2) = P_1\lambda_2 + P_4\mu_1 \qquad (3\text{-}8)$$

$$P_4(\mu_1 + \mu_2) = P_2\lambda_2 + P_3\lambda_1 \qquad (3\text{-}9)$$

$$P_5\mu_C = P_1\lambda_C \qquad (3\text{-}10)$$

From (3-10), we have

$$\frac{P_5}{P_1} = \frac{\lambda_C}{\mu_C} \tag{3-11}$$

By using (3-7) $\cdot\mu_1$ – (3-8) $\cdot\mu_2$, we may get:

$$P_2(\lambda_2 + \mu_1)\cdot\mu_1 - P_3(\lambda_1 + \mu_2)\cdot\mu_2 = P_1(\lambda_1\mu_1 - \lambda_2\mu_2) \tag{3-12}$$

Eliminating P_3 by combining (3-6) and (3-12), we get:

$$\frac{P_2}{P_1} = \frac{\lambda_1}{\mu_1} \tag{3-13}$$

Substituting (3-13) into (3-12), we have:

$$\frac{P_3}{P_1} = \frac{\lambda_2}{\mu_2} \tag{3-14}$$

Substituting (3-14) into (3-8), we have:

$$\frac{P_4}{P_1} = \frac{\lambda_1\lambda_2}{\mu_1\mu_2} \tag{3-15}$$

Because

$$P_1 + P_2 + P_3 + P_4 + P_5 = 1.0$$

$$i.e.\quad P_1(1 + \frac{P_2}{P_1} + \frac{P_3}{P_1} + \frac{P_4}{P_1} + \frac{P_5}{P_1}) = 1.0 \tag{3-16}$$

we may have the probability for each state solved as following:

$$\begin{cases} P_1 = \dfrac{\mu_1\mu_2\mu_C}{\lambda_C\mu_1\mu_2 + \mu_C(\mu_1\mu_2 + \lambda_1\mu_2 + \lambda_2\mu_1 + \lambda_1\lambda_2)} \\ \quad = \dfrac{\mu_1\mu_2\mu_C}{\lambda_C\mu_1\mu_2 + \mu_C(\lambda_1 + \mu_1)(\lambda_2 + \mu_2)} \\ P_2 = \dfrac{\lambda_1}{\mu_1} P_1 = \dfrac{\lambda_1\mu_2\mu_C}{\lambda_C\mu_1\mu_2 + \mu_C(\lambda_1 + \mu_1)(\lambda_2 + \mu_2)} \\ P_3 = \dfrac{\lambda_2}{\mu_2} P_1 = \dfrac{\lambda_2\mu_1\mu_C}{\lambda_C\mu_1\mu_2 + \mu_C(\lambda_1 + \mu_1)(\lambda_2 + \mu_2)} \\ P_4 = \dfrac{\lambda_1\lambda_2}{\mu_1\mu_2} P_1 = \dfrac{\lambda_1\lambda_2\mu_C}{\lambda_C\mu_1\mu_2 + \mu_C(\lambda_1 + \mu_1)(\lambda_2 + \mu_2)} \\ P_5 = \dfrac{\lambda_C}{\mu_C} P_1 = \dfrac{\lambda_C\mu_2\mu_C}{\lambda_C\mu_1\mu_2 + \mu_C(\lambda_1 + \mu_1)(\lambda_2 + \mu_2)} \end{cases} \tag{3-17}$$

Therefore the system reliability is:

$$R_S = P_1 + P_2 + P_3 = \frac{\mu_1\mu_2\mu_C + \lambda_1\mu_2\mu_C + \lambda_2\mu_1\mu_C}{\lambda_C\mu_1\mu_2 + \mu_C(\lambda_1 + \mu_1)(\lambda_2 + \mu_2)} \tag{3-18}$$

$$Q_S = P_4 + P_5 = \frac{\lambda_1\lambda_2\mu_C + \lambda_C\mu_1\mu_2}{\lambda_C\mu_1\mu_2 + \mu_C(\lambda_1 + \mu_1)(\lambda_2 + \mu_2)} \tag{3-19}$$

The frequency of the system being down can be expressed as:

$$f_{down} = P_4(\mu_1 + \mu_2) + P_5\mu_C \tag{3-20}$$

Mean time to repair (MTTR) for the parallel system is then:

$$R_P = \frac{Q_S}{f_{down}} = \frac{P_4 + P_5}{P_4(\mu_1 + \mu_2) + P_5 \mu_C} = \frac{1 + X}{(\mu_1 + \mu_2) + X \cdot \mu_C} \qquad (3\text{-}21)$$

where $X = \frac{P_5}{P_4} = \frac{\lambda_C \mu_1 \mu_2}{\lambda_1 \lambda_2 \mu_C}$ (an intermediate variable), $\lambda_C = CCF \cdot \max(\lambda_1, \lambda_2)$ with CCF representing the common cause factor.

Applying the Frequency Balance Approach to the bottom part of Fig. 3-2, *i.e.* $R_S \lambda_P = Q_S \mu_P$, the failure rate of the redundant system can be obtained as:

$$\lambda_P = \frac{Q_S}{R_S} \mu_P = \frac{(\lambda_1 \lambda_2 \mu_C + \lambda_C \mu_1 \mu_2)}{\mu_1 \mu_2 \mu_C + \lambda_1 \mu_2 \mu_C + \lambda_2 \mu_1 \mu_C} \cdot \mu_p$$

$$= \frac{(\lambda_1 \cdot \lambda_2) \cdot (r_1 \cdot r_2) + \lambda_C \cdot (\frac{1}{r_1} \cdot \frac{1}{r_2}) \cdot r_C}{\frac{1}{r_1 r_2} + \frac{\lambda_1}{r_2} + \frac{\lambda_2}{r_1}} \cdot \mu_p \qquad (3\text{-}22)$$

$$= \frac{(\lambda_1 \cdot \lambda_2) \cdot (r_1 \cdot r_2) + \lambda_C r_C}{(1 + \lambda_1 r_1 + \lambda_2 r_2) \cdot R_p}$$

The common cause failure mode was discussed in Ramakumar [22] and it is considered an extra term added to the equivalent failure rate for a parallel configuration with completely independent components:

$$\lambda_p \cong \lambda_1 \lambda_2 (r_1 + r_2) + \lambda_C = \lambda_{eq} + \lambda_C \qquad (3\text{-}23)$$

where $\lambda_{eq} \cong \lambda_1 \lambda_2 (r_1 + r_2)$ is the parallel failure rate when neglecting the Common Cause Factor. This is a rough approximation by observing the format of the failure rate equation with speculation. However, the closed form equations of (3-21) and (3-22) are directly developed from the State Space Diagram with Frequency Balance Approach. The equations derived in this thesis are applied to revise Spreadsheet Model to achieve a higher accuracy. When modeling a real system, one has to determine the coefficient

"*CCF*" according to the operational experience which is the most difficult task in determining the reliability indices.

3.2.2 Updating Equations and Evaluating Procedure

Based up on the discussion above, the reliability evaluation equations and calculation order in the Spreadsheet Model are modified accordingly. In the modified spreadsheet, whenever parallel configuration is involved, the mean time to repair (MTTR) is evaluated by using equation (3-21) prior to the failure rate evaluation using equation (3-22).

The availability is the last one among the three most important reliability indices (Failure Rate, MTTR and Availability) to be evaluated by using the revised failure rate and MTTR:

$$A_p = \frac{8760}{8760 + r \cdot \lambda} \qquad (3\text{-}24)$$

After revising the equations and evaluating order of different reliability indices, it can be guaranteed that the common cause is considered for every reliability index evaluating process, while the original model overestimates the availability and consequently underestimates the mean time to repair and annual forced downtime.

3.2.3 Dealing with Circuit Breakers

A circuit breaker usually has the function to isolate a faulted component from the system, and therefore may act as the critical location to separate the whole system into zones. However, it still keeps an open question that how the circuit breaker itself should be accurately included in the upstream or downstream zone. Actually a protective breaker may fail either as open or as short mode, and different failing modes may result in different actions of its neighboring protective devices. For instance, if a circuit breaker fails short, the fault can be detected by its first order upstream protective device and results in a tripped action there, whereas when it fails open, the fault can only affect the operations of the downstream devices. Therefore, the circuit breaker shall be included in neither its upstream zone nor its downstream zone. And yet the failing mechanism of a breaker needs to be identified and accordingly attributed to different zones when dividing a system to apply the Spreadsheet Model. The failure rates as short/open usually vary with different voltage applied to the breaker. This is also why we have to deal with the circuit breakers by considering these two failure modes separately. This aspect is discussed for different breaker configurations with regards to actual failing process and mathematical meaning. The following symbol schema is used to attribute the failing process to open and short mode.

$\lambda = \lambda_O(\text{open}) + \lambda_S(\text{short})$ – failure rate for protective breaker

$\lambda_O(\text{open})$ – failure rate for failing open

$\lambda_S(\text{short})$ – failure rate for failing short.

A. Breakers Connected in Series:

Two breakers connected in series are shown in Fig. 3-3 (a). It is obvious that if breaker B2 fails short it would trip out breaker B1 immediately above it, while if it fails open, it would block the power flow in the downstream direction. If we know the percentage of the two failure modes for a specific breaker, we may accordingly include the circuit breaker partly in the upstream neighboring zone and partly in the downstream neighboring zone. Consequently the zone branches can be divided as shown in Fig. 3-3(b). For breakers connected in series it may be concluded for each breaker that the short-circuit failure rate (λ_S) will only affect the zone to its upstream, and the open-circuit failure rate (λ_O) will affect the zones to its downstream.

B. Breakers Connected in Parallel:

If two breakers (B1 and B2) are connected in parallel as shown in Fig. 3-4(a), the protective mechanism is much different from that in series. Taking breaker B1 as an example, when it fails open with B2 functioning well, it won't result in any tripping for

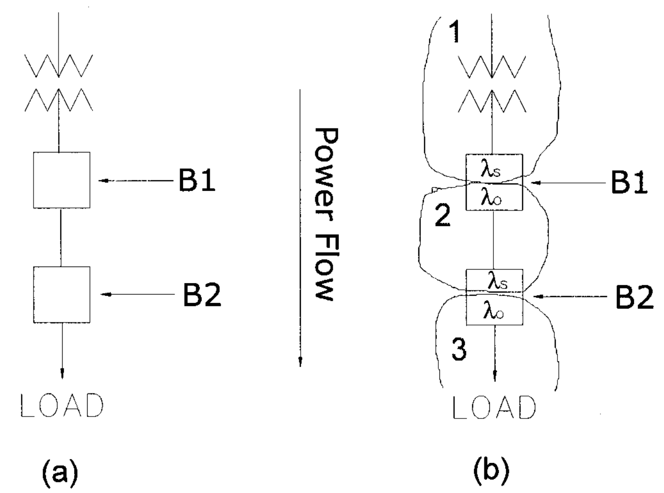


Figure 3-3. Two breakers connected in series: (a) Circuit; (b) Zones and attribution of the two failure modes (open and short)

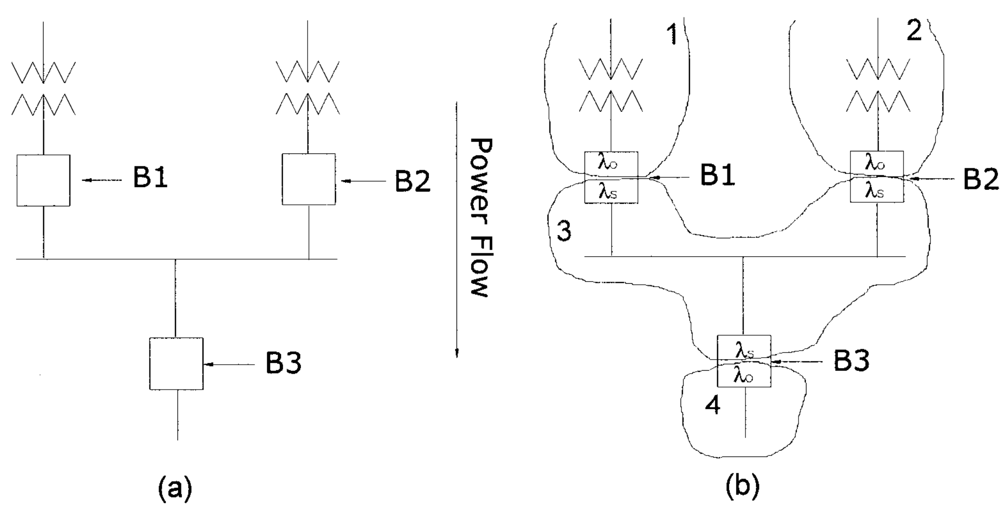


Figure 3-4. Two breakers connected in parallel: (a) Circuit; (b) Zones and attribution of the two failure modes (open and short)

B2 or B3, *i.e.* the power continues to flow through B3. Only when breakers B1 and B2 fail open simultaneously, the power flow to B3 will be cut. However, if B1 fails short, both breakers B2 and B3 would be tripped out. The process described here implies the following facts:

- When B1 or B2 fails open, the breaker configuration has a parallel effect, *i.e.* as long as one of them is operational, the breaker set (B1 and B2) can be treated as operational.
- When B1 or B2 fails in short, the breaker configuration has an equivalent effect as in series, *i.e.* either of them fails, the breaker set (B1 and B2) should be treated as a failure.

In order to reflect this actual process, we divide the zones and attribute the failure rates corresponding to different failure modes (λ_O(open) and λ_S(short)) as shown in Fig. 3-4(b). From this zone dividing strategy, when one of the breakers B1 and B2 fails open, it would only affect zone 1 or zone 2 (note that zone 1 and zone 2 are in parallel). However, if either B1 or B2 fails short, it would result in a failure of zone 3 and consequently the power flow would be cut.

Regarding the breaker B3, it is connected in series with the parallel output of B1 and B2. Therefore its two failure modes corresponding to λ_O and λ_S are dealt with in the same way as described in section A.

C. Closed Tie Breaker:

A circuit breaker may serve as a normally closed tie like B5 in Fig. 3-5(a). In order to avoid circular reference between two zones[£], it is suggested to redraw the circuit in the way as shown in Fig. 3-5(b). The actual operation of the breakers in Fig. 3-5 (a) may be described as following. When B5 fails open, it cuts the connection of B1-B4 and B2-B3. In other words, the rates to cut the connection between B1-B4 and between B2-B3

[£]When trying to perform reliability calculations on buses with closed tiebreakers, circular references may be experienced due to the characteristic of the system configuration unless specific efforts are taken to avoid this.

are both λ_O. When B5 fails short, it would trip out both B1 and B2, *i.e.* λ_S should be the rate to trip out B1 or B2 due to the short-circuit failure of breaker B5. In order to reflect this process, the zone branches are divided as shown in Fig. 3-5(b). Because of the replacement of B5 by B51 to B54, failure rate for each of B51 to B54 is halved. In

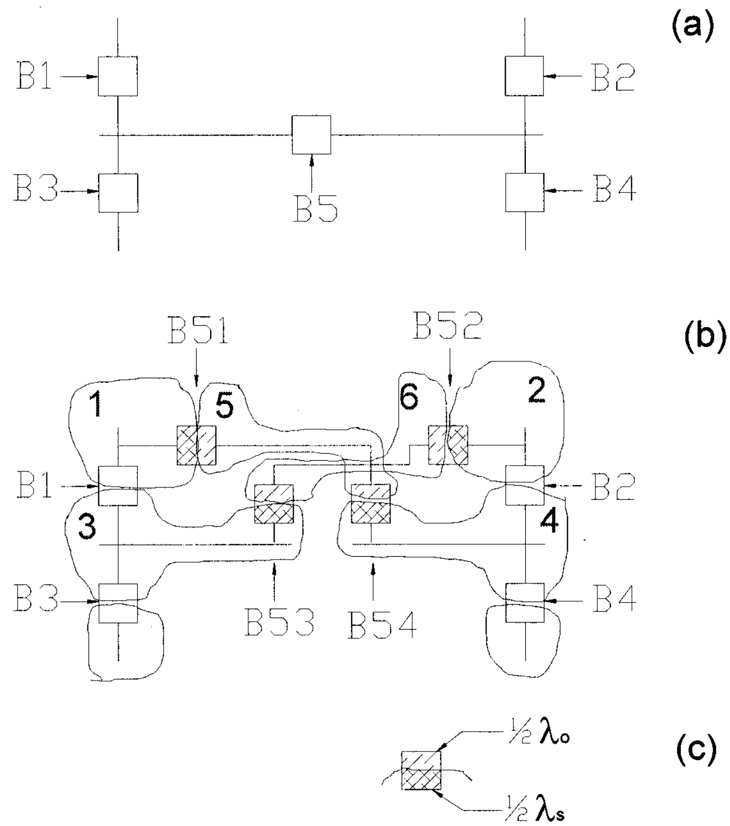


Figure 3-5. Failure rate for normally closed tie breaker: (a) Circuit; (b) Zones and attribution of the two failure modes (open and short); (c) Pattern legends

Fig.3-5 (b) and (c), the failure rate as open is indicated by the area filled with upward diagonal pattern in the breaker symbol, and the failure rate as short is indicated by outlined diamond pattern. By referring to Fig.3-5 (b), the action due to the failure of B5 described above can be well reflected by this zone dividing strategy:

- Zone 5 has a failure rate of λ_O (= ½ λ_O + ½ λ_O) to cut the connection between breakers B1 and B4. Zone 6 has the same failing rate of λ_O to cut the connection between breakers B2 and B3.
- The rate to trip out B1 and B2 due to the short- fail of the Closed Tie Breaker is λ_S (½ λ_S from zone 1 plus ½ λ_S from zone 3, or ½ λ_S from zone 2 plus ½ λ_S from zone 4)

D. Open Tie Breaker:

For the case of Open Tie Breaker, a failure as open does not really affect the operation of the circuit, but a failure as short will trip out the two breakers located immediately to its upstream direction. Therefore, the rate to trip out the two upstream breakers should both equal to λ_S (diagram omitted).

All the considerations discussed in section A-D have been applied into the revised Spreadsheet Model.

3.3 Applying the Model to a Power Distribution Substation Design

3.3.1 Description and Component Parameters of the System

In this section, the reliability of a power distribution station is evaluated and compared for eight different designs. These eight designs are a collection of basic designs that are commonly used in the power yard of a process plant. The system receives power at 13.8 kV from an electric utility. Then the power goes through a 13.8 kV circuit breaker inside the industrial plant, with 600 feet of cable in underground conduit. Through an enclosed disconnect switch, the power goes into the main 13.8kV/480V transformer. The output from the main transformer supplies power to six feeder breakers through a main breaker and a 50 feet bus (480V). A 300 feet distance is allowed from the bus to each feeder breaker. Each feeder breaker provides power to three users, each through a user transformer. The utility supply may be individual or dual, and the distribution system may also have different configurations. According to the different connection strategies, the eight basic designs considered here are defined as:

A. Simple radial
B. Dual Supply Radial – Single Bus
C. Dual Supply Radial with Tie Breaker
D. Dual Supply Loop with Tie Breaker
E. Dual Supply Primary Selective with Tie Breaker
F. Double Bus / Double Breaker Radial
G. Double Bus / Double Breaker Loop
H. Double Bus / Double Breaker Primary Selective

The schematics for these eight designs are shown in Fig. 3-6. The diagram for each design starts from the 13.8kV/480V main transformer with the supply unit omitted.

Reliability parameters of the components used in this system are collected and listed in Table 3-1. The reliability parameters for the supply unit is grouped by using the data for

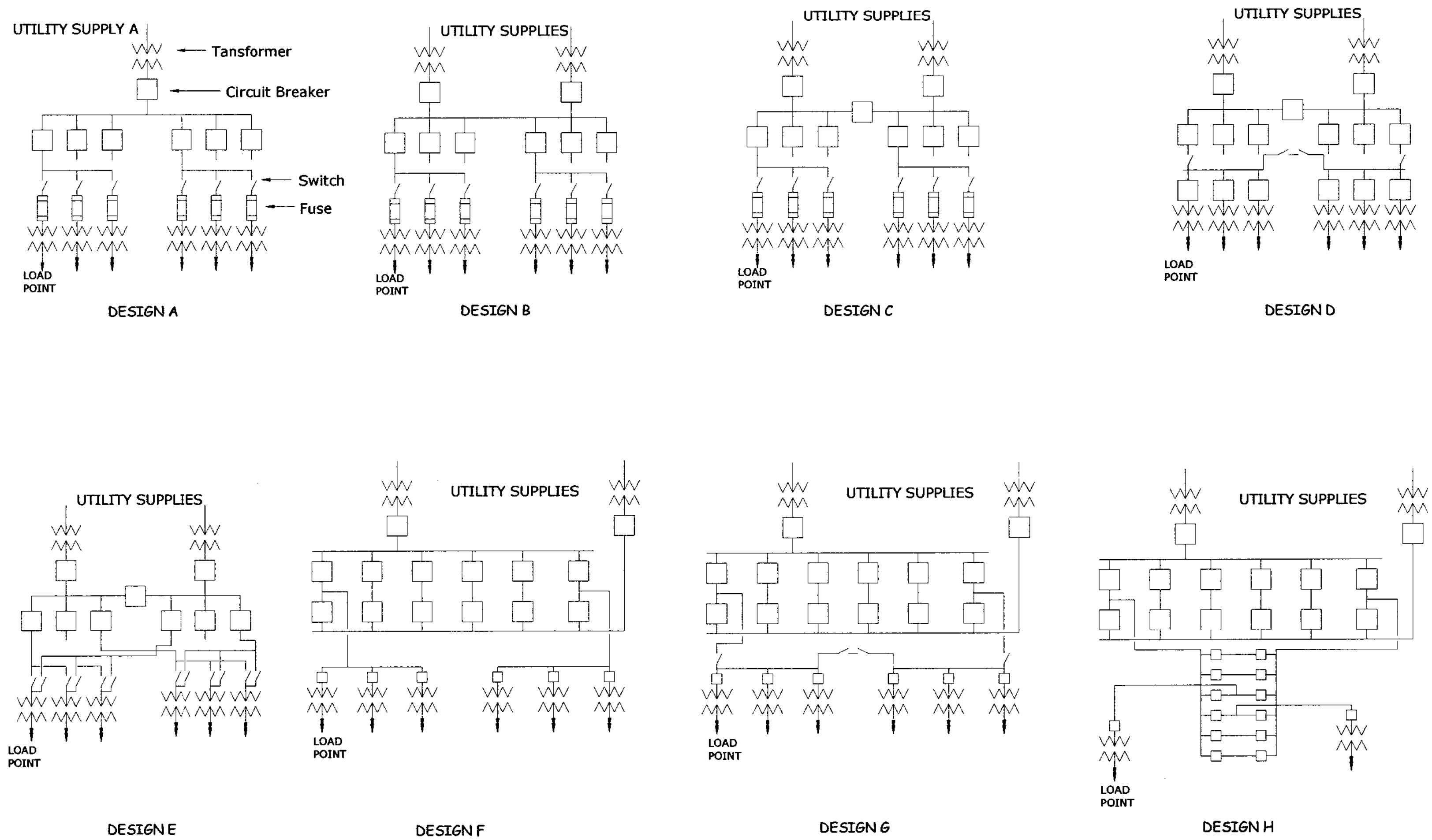


Figure 3-6. The eight typical designs for a distribution system with the supply unit omitted

the supply utility, the circuit breaker, ..ie underground cable and the enclosed disconnect switch as shown in bold italic font in the table.

3.3.2 Modeling Efforts and Results

Because the circuit for each design is symmetric, the reliability viewed from each user end is the same as others within the same design. The reliability evaluation was therefore only necessary for one user in each design. The schematics for zone dividing

Table 3-1. Failure rate and MTTR for electrical equipment (IEEE std 493) used in this work

Equipment	Units	MTTR (Hrs)	Lambda (Fail/year)	FDT (hrs/year)
Supply utility	each	1.32	1.956000	2.581920
Metalclad 13.8kV Circuit Breaker	each	83.11	0.003600	0.299196
600 feet underground cable	each	26.51	0.003667	0.097212
Enclosed disconnect switch	each	3.61	0.006100	0.022021
1. ***SubTotal: Utility (group)***	***each***	***1.52***	***1.970000***	***2.994400***
2. Main Transformer, Liquid Filled	each	356.11	0.006200	2.207882
3. 480V Metalclad Circuit Breaker	each	4.00	0.002700	0.010800
3a. 480V Metalclad Circuit Breaker	each	4.00	0.001350	0.005400
4. Switchgear bus-bare	each	24.00	0.002400	0.057600
4a. Switchgear bus-bare (half)	each	24.00	0.001200	0.028800
5. Cable, above ground, 300ft	300ft	4.00	0.005670	0.022680
6. Switch (NC)	each	3.61	0.006100	0.022021
6a. Switch (NC) (short:open = 1:1)	each	3.61	0.003050	0.011011
7. Fuse (480V)	each	2.00	0.101540	0.203080
7a. Fuse (480V) fails open (5%)	each	2.00	0.005077	0.010154
7b. Fuse (480V) fails open (95%)	each	2.00	0.096463	0.192926
8. Unit Transformer	each	342.00	0.003000	1.026000
9. Crossover bus -20'	kCircuit Feet	4.00	0.018900	0.075600
9a. Crossover bus -20'	20ft	4.00	0.000378	0.001512

and configuration (zone table defined in the model) are omitted here. The evaluation was done using both the original model and the revised one.

A. Results Generated by the Original Model

The reliability parameters (failure rate, mean time to repair, forced downtime) from user's aspect in each design evaluated by using the original model are collected in Table 3-2. The determination of the common cause factor coefficient as involved in equations (3-21) and (3-22) are somewhat arbitrary. The exact value of this coefficient is dependent upon the experience accumulated during the operation of the system. In this evaluation, we choose C=0.1 and C=0.5 as two examples, and the results are listed in Table 3-2 (a) and 3-2(b), respectively. Comparing the two cases with C = 0.1 and C = 0.5, the failure rate is suppressed with smaller common cause factor (CCF) as expected. However, the forced down time evaluated from the original model makes no difference for different CCFs. This is because the availability evaluation in the original model does not consider the effect from the common cause factor and therefore the difference in this factor is not reflected in the forced downtime estimation. This problem has been solved in the revised model.

By observing the above date from the original model, design "A" has the lowest reliability, *i.e.* the highest failure rate and the longest forced downtime during one year. This is because there is only one supply resource to support the whole system in design "A", whereas two supplies are available in parallel in all other designs with the assumption that the two parallel supplies are redundant. Design "E" and "H" have the highest reliability *i.e.* the smallest failure rate because they have one more parallel level than the other dual supply system designs. This also implies that a redundant parallel connection always improve the reliability by suppressing the failure rate.

Table 3-2(a) Reliability indices from individual user's aspect evaluated using the original model with Common Cause Factor Coefficient C = 0.1

Design	Failure rate (failures/yr)	FDT (hrs/year)	MTTR (hrs/failure)
Design A	2.126863	6.223557	2.926168
Design B	0.351648	1.242175	3.532436
Design C	0.330606	1.242180	3.757278
Design D	0.232659	1.053675	4.528842
Design E	0.026476	1.54E-08	5.80E-07
Design F	0.215867	1.032613	4.783562
Design G	0.216782	1.097578	5.063053
Design H	0.028539	1.029929	36.088080

Table 3-2(b) Reliability indices from individual user's aspect evaluated using the original model with Common Cause Factor Coefficient C = 0.5

Design	Failure rate (failures/yr)	FDT (hrs/year)	MTTR (hrs/failure)
Design A	2.126863	6.223557	2.926168
Design B	1.142037	1.242175	1.087683
Design C	1.121046	1.242179	1.108054
Design D	1.023098	1.053674	1.029886
Design E	0.511942	1.54E-08	3.00E-08
Design F	1.010051	1.032612	1.022337
Design G	1.010966	1.296094	1.282035
Design H	0.511589	1.029929	2.013199

Regarding the forced down time, besides the unreasonable identity for different common cause factors, an extremely small value (close to zero) was obtained for design "E". This is also because the "*Availability*" is greatly overestimated in the original model by neglecting the effect from the common cause failure mode. This overestimation is greatly enlarged due to the extra parallel level near the user end. Furthermore, in the results obtained from the original model, the forced downtime for design "F" is smaller than design "G" although there is an open tie switch in design "G". However, installation of an open-tie breaker usually helps to decrease the FDT by suppressing the corresponding MTTR. This discrepancy is because the original model underestimates parallel MTTR due to the overestimation of availability and therefore screens the effect from installing an open tie switch.

B. Results Generated by the Revised Model:

The reliability parameters for each user in different designs obtained from the revised model are collected in Table 3-3 with the common cause factor coefficient of C = 0.1 in Table 3-3(a) and C = 0.5 in Table 3-3(b), respectively.

The result for failure rate has the same pattern and magnitude with that obtained from the original model because the common cause factor is considered in both of the two versions. The results for forced downtime and MTTR are obviously different, because in the revised model, the common cause factor was considered not only for the failure rate evaluation, but also for the MTTR evaluation, and the forced downtime was evaluated accordingly afterwards, whereas this factor was only considered for failure rate evaluation in the original model.

The difference in percentage of the results obtained from the original and the revised models is collected in Table 3-4. For design A, because there is no parallel connection involved from the supply utility to a specific user, the original model and the revised model generated almost the same results, *i.e.* the failure rate evaluation in series between the two versions is essentially close. The slight differences in FDT and MTTR for design A are resulted from the different calculation order in the two versions. As long as the parallel connection is involved, the MTTR and FDT evaluated by using the revised model are obviously different from the original model, while the failure rates obtained from the two models are very close, as can be seen in Table 3-4. Basically the differences for the case using C = 0.5 are larger than that when using C = 0.1 because of the larger influence of the larger common cause factor on the reliability evaluations. Two more special cases need to be pointed out with regard to Table 3-4:

- As the reason stated before, the FDT for design E is extremely small (in the order of 10^{-8} hours per year) according to the original model. The reasonable result generated by the revised model (in the order of a few hours) consequently produces a large relative difference.
- When an open tie breaker is used above the user end, the difference for the two versions of the model is much suppressed. This is because the MTTR related to the open tie breaker is basically the time required to close the tie as discussed in the introduction of the model. This fact can be identified from design D and G, where much smaller difference was obtained than other dual supply designs between the two versions.

Table 3-3 (a) Reliability indices from individual user's aspect evaluated using the revised model with Common Cause Factor Coefficient C = 0.1

Design	Failure rate (failures/yr)	FDT (hrs/year)	MTTR (hrs/failure)
Design A	2.126863	6.227152	2.927858
Design B	0.351650	1.944969	5.530986
Design C	0.330406	1.836304	5.557723
Design D	0.232458	1.101627	4.739032
Design E	0.026487	1.089900	41.148523
Design F	0.215868	1.562310	7.237338
Design G	0.216783	1.097708	5.063624
Design H	0.028566	1.096675	38.390902

Table 3-3 (b) Reliability indices from individual user's aspect evaluated using the revised model with Common Cause Factor Coefficient C = 0.5

Design	Failure rate (failures/yr)	FDT (hrs/year)	MTTR (hrs/failure)
Design A	2.126863	6.227152	2.927858
Design B	1.142038	3.851114	3.372140
Design C	1.120795	3.743733	3.340249
Design D	1.022847	1.299224	1.270204
Design E	0.512396	2.286514	4.462393
Design F	1.010052	3.502835	3.467975
Design G	1.010967	1.296254	1.282192
Design H	0.511826	1.247920	2.438174

Table 3-4 Comparison of results generated by the two versions of the Spreadsheet Model. The data were obtained by using (Revised – Original) / Original * 100%

	C = 0.1			*C* = 0.5		
Design	**Failure Rate**	**FDT**	**MTTR**	**Failure Rate**	**FDT**	**MTTR**
Design A	0.00%	0.06%	0.06%	0.00%	0.06%	0.06%
Design B	0.00%	56.58%	56.58%	0.00%	210.03%	210.03%
Design C	-0.06%	47.83%	47.92%	-0.02%	201.38%	201.45%
Design D	-0.06%	4.58%	4.64%	-0.02%	23.30%	23.33%
Design E	0.04%	7.10E+07	7.09E+07	0.09%	1.49E+08	1.49E+08
Design F	0.00%	51.30%	51.30%	0.00%	239.22%	239.22%
Design G	0.00%	0.01%	0.01%	0.00%	0.01%	0.01%
Design H	0.09%	6.48%	6.38%	0.11%	121.90%	121.65%

The reliability indices for different designs evaluated from the original and the revised Spreadsheet Model are graphically shown in Fig. 3-7 and Fig. 3-8, corresponding to the two cases of common cause factors of 0.1 and 0.5, respectively.

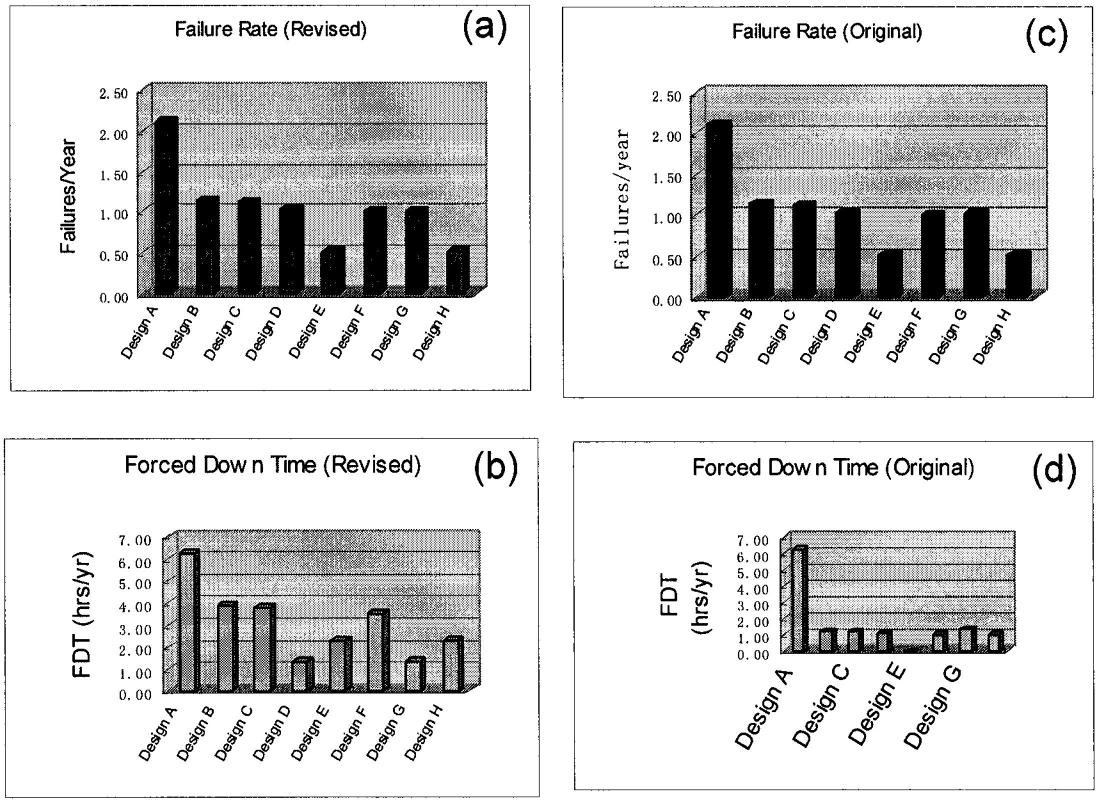


Figure 3-7. Failure Rate and Annual Forced Down Time for the eight typical substation designs when assuming the common cause factor as 0.1: (a) and (b) Failure Rate and Annual Forced Down Time generated by revised model; (c) and (d) Failure Rate and Annual Forced Down Time from the original model.

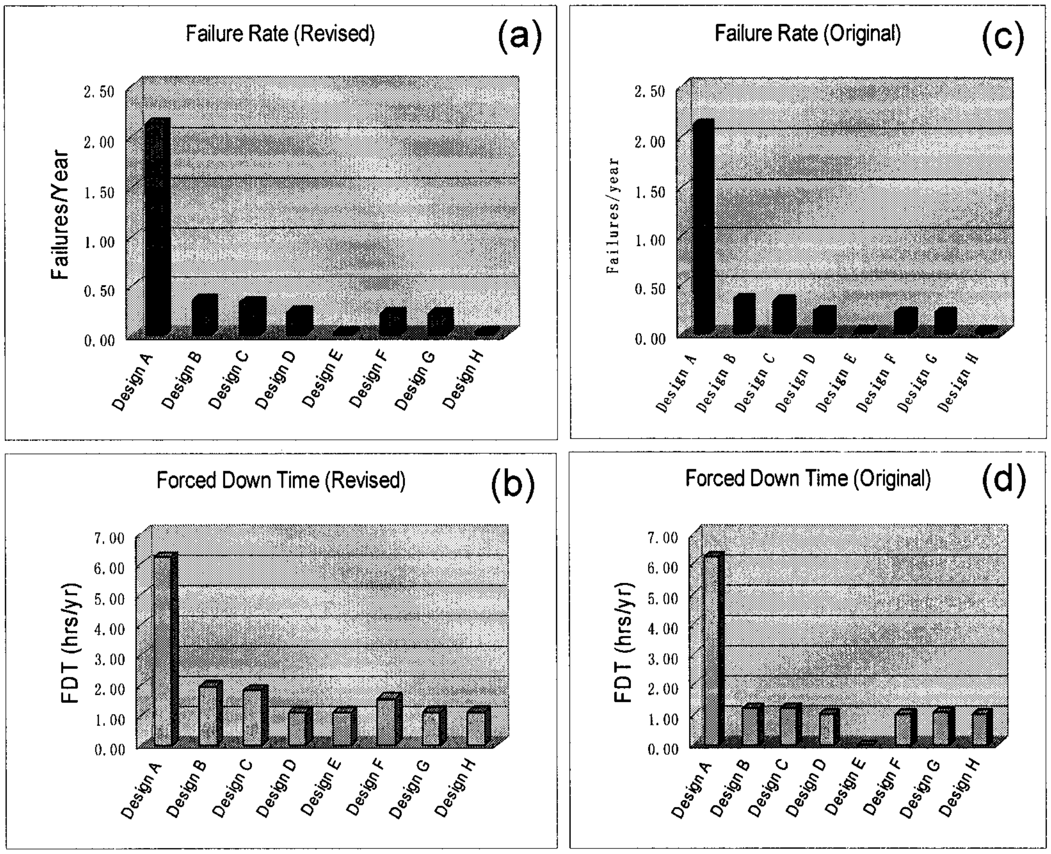


Figure 3-8. Failure Rate and Annual Forced Down Time for the eight typical substation designs when assuming the common cause factor as 0.5: (a) and (b) Failure Rate and Annual Forced Down Time generated by the revised model; (c) and (d) Failure Rate and Annual Forced Down Time from the original model.

Overall, the following observations regarding the different designs may be obtained from the modeling results according to the revised model:

(1) Designs with dual supply system always have higher reliability and smaller forced downtime than a single supply system
(2) The installation of a Closed Tie Breaker results in a lower failure rate and a smaller forced downtime by isolating the two supply utilities when one of them fails. This can be identified by comparing design "C" and "B".
(3) The installation of an Open Tie Breaker (Switch) results in a smaller forced downtime by reducing the MTTR. This is because the user may be switched to an alternative supplying circuit branch rather than waiting for the restoration of the failed one. This fact may be identified by comparing design "D" and "C" or comparing "G" and "F".
(4) Adding one more parallel level may greatly improve the reliability as may be seen from design "E" and design "H".
(5) With a design characteristic such that the common cause factor is high, the advantages of using parallel configuration are greatly suppressed.

Chapter 4

Cut Set Methodology - Modifications and Applications

Starting with a simple speculated network to illustrate the concept and process of the Cut-Set Model, this chapter modifies the equations used in this model. A direct solution for 3^{rd} order parallel configuration is derived with consideration of common cause failure mode. The new set of equations for 3^{rd} order parallel configuration together with the equations for 2^{nd} order parallel configuration derived in Chapter 3 are applied to revise the model which omits the common cause factor. The revised model is applied to a standard network as published in IEEE Gold Book.

4.1 Cut-Set Methodology with an Example

A cut set is a set of components that, if removed or "cut" out of the system, interrupts the availability of power to the load. A minimal cut set is a cut set that has no other cut set within it as a subset [8]. The process to obtain cut sets based upon a single line diagram (the so-called "top-down" method) was described in Ref. [8]. In the present work, a very similar strategy as in the Spreadsheet methodology is used to develop the cut sets. A logic diagram is then constructed corresponding to the actual relationships among the different sets. An outage at a bus with interest is represented by a logical true condition of a logic gate. Starting from this logic gate the influence of the failure states of each set to the true condition is investigated and represented by a logic diagram with the failure states as initial inputs to the logic gate. Each failure state is assigned as a failure event with a number. A letter is assigned to each logic gate. All cut sets with series relationship between two buses are combined into a single failure event for simplification. These cut sets with physical series relationship don't share common components and are supposed to be independent. Therefore the following equations can be used to combine the cut sets in series into one cut set:

$$\lambda_{equivalent} = \lambda_{CS,1} + \lambda_{CS,2} + \lambda_{CS,3} + \cdots + \lambda_{CS,n} \qquad (4-1)$$

$$r_{equivalent} = \frac{\lambda_{CS,1} \cdot r_{CS,1} + \lambda_{CS,2} \cdot r_{CS,2} + \lambda_{CS,3} \cdot r_{CS,3} + \cdots + \lambda_{CS,n} \cdot r_{CS,n}}{\lambda_{CS,1} + \lambda_{CS,2} + \lambda_{CS,3} + \cdots + \lambda_{CS,n}} \qquad (4-2)$$

According to the logic diagram, a working sheet (refer to the following example) can be constructed to illustrate the relationship by replacing the logic gates with their permutation of the failure events. Two rules are followed when doing the replacement:

- An OR gate is replaced by writing its inputs vertically, increasing the number of cut sets;
- An AND gate is replaced by writing its inputs horizontally, increasing the order of the cut set. We ignore the gate with 4^{th} or higher orders for their extremely small influence on the overall failure rate.

The process described above may be illustrated by an example with a simple circuit topology. Figure 4-1(a) shows a part of a substation with dual supplies connected by a normally closed tiebreaker. Similar to the zones divided for the spreadsheet methodology, the circuit may be divided into events in a way as shown in the figure. An event number instead of a zone number is assigned to each zone. The corresponding logic diagram is shown in Fig. 4-1 (b). A working sheet may be developed based upon the logic diagram and the two rules listed above. Failure rate for each event is evaluated according to the failure rates of the parts associated with that event. The cut set worksheet is shown in Table 4-1. In the "Description" column of the table, the letter "A", "B" or "C" represents the gate as shown in Fig. 4-1(b). The number represents the corresponding event. For example, "A" refers to the "OR" gate that results in the Bus Outage. Any event that makes the output of gate "A" as true will result in an outage at the bus studied. Because the two inputs of gate "A" are event "2" and the output of gate "B", gate "A" maybe replaced by event "2" and gate "B", as described by step 2 in Table 4-1. Because they are two inputs of an "OR" gate, event "2" and gate "B" are put in different rows in the table by following the first rule as discussed above. This means event "2" and gate "B" have an equivalent series relationship, *i.e.*, either of them fails, a failure is resulted at gate "A". When replacing gate "B" as described by step 3, the two inputs (event "3" and the output of gate "C") to an "AND" gate are put in the same row by following the second rule. This means event "3" and gate "C" are in equivalent parallel configuration, *i.e.*, only the simultaneous occurrence of event "3" (failure) and a true output of gate "C" can result in a failure at gate "B". After replacing every gate in the logic diagram with an event number, we may obtain the reliability indices as shown in the last step (step 4 in this case). Because the reliability indices of related events have been determined in advance, the reliability indices for BUS-A Outage (event "1") can be evaluated using the following equation according to step 4 in Table 4-1:

$$\lambda_{BUS-A} = \lambda_2 + \lambda_3\lambda_4 \cdot (r_3 + r_4) + \lambda_3\lambda_5 \cdot (r_3 + r_5) + \lambda_3\lambda_6 \cdot (r_3 + r_6) \qquad (4\text{-}3)$$

The numbers as subscripts in equation (4-3) stand for the event numbers. Approximate equations for parallel configuration without considering common cause factor is used in the example for simplicity. Given the failure rates and duration for events "2" to "6", the failure rate for event "1", *i.e.*, the bus A outage can then be estimated accordingly. A numerical example is shown in Table 4-2. It is obvious that event "2" is the dominant factor to the Bus A Outage because the other events are in parallel relationships.

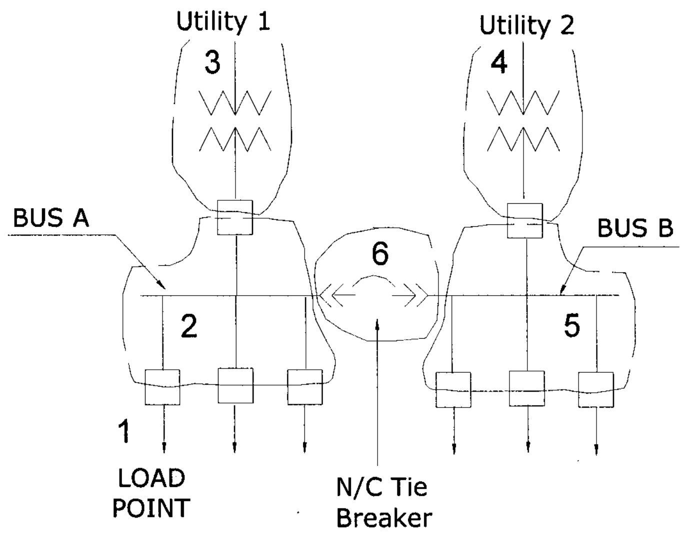


Figure 4-1(a) An example circuit used to illustrate the concept of Cut-Set

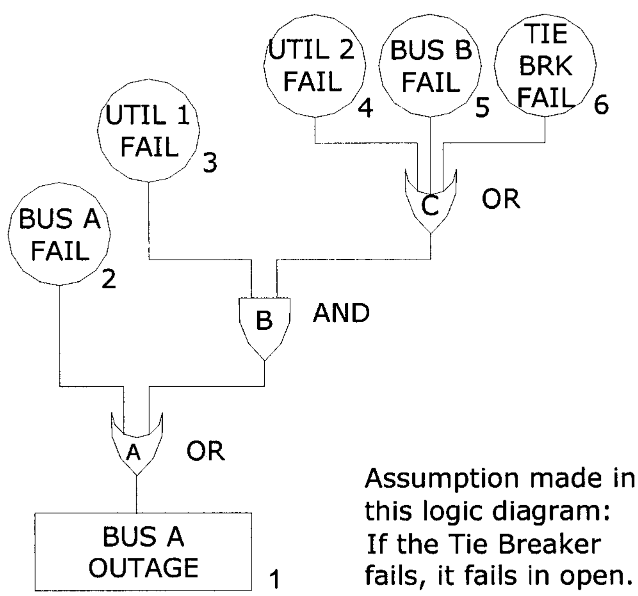


Figure 4-1 (b) Logic diagram developed from the circuit shown in Fig. 4-1 (a)

Table 4-1 Development of Cut Sets for the Outage of Bus A

Step	Description		
1	Start	A	
2	Replace A	2	
		B	
3	Replace B	2	
		3	C
4	Replace C	2	
		3	4
		3	5
		3	6

Table 4-2 A Numerical Example to Illustrate the Cut Set Methodology

Event	λ_i (failures/yr)	r_i (hours)	Cause	$\lambda_{parallel}$	$r_{parallel}$
2	0.008	20	Event 2	0.008	20.00
3	0.005	50			
4	0.005	50	Events 3&4	2.85388E-07	25.00
5	0.008	20	Events 3&5	2.28347E-07	14.29
6	0.03	5	Events 3&6	9.41781E-07	4.55
1			**Bus A Outage**	**0.008001456**	**20.00**

In this example, the parallel configuration only involves two branches. In the original cut-set methodology, the following equations are used for the 2nd order parallel configuration:

$$\lambda_{CS} = \lambda_1 \cdot \lambda_2 \cdot (r_1 + r_2) \tag{4-4}$$

$$r_{CS} = \frac{r_1 \cdot r_2}{r_1 + r_2} \tag{4-5}$$

where (λ_1, r_1) and (λ_2, r_2) are the failure rates and $MTTR_S$ for the two components in parallel, respectively (note: the subscript as a number does not refer to the event number in Fig. 4-1 (b)). It can be seen from the above equations that no common cause factor was considered for the parallel configuration in the original cut-set methodology. From the equations used for third order parallel configuration in the original cut-set methodology, as shown below, the common cause factor was not considered either:

$$\lambda_{CS} = \lambda_1 \cdot \lambda_2 \cdot \lambda_3 \cdot (r_1 r_2 + r_2 r_3 + r_3 r_1) \tag{4-6}$$

$$r_{CS} = \frac{r_1 \cdot r_2 \cdot r_3}{r_1 r_2 + r_2 r_3 + r_3 r_1} \tag{4-7}$$

The failure rates for 4th order and higher parallel configurations are ignored for their extremely small values. Equations (4-4) to (4-7) are revised to consider the common cause failure mode in the following section.

4.2 Improvements for the Calculations

The Cut-Set Model is revised by considering common cause failure mode for parallel configurations. For 2nd order parallel configuration, the equations derived in Chapter 3 are used. For higher ordered parallel configurations, although they have been generally discussed in literature [23], this work takes the effort to deduce a set of practically useful equations for 3rd order parallel connection based upon a model when considering the common cause failure mode. The following demonstrates the process to derive the equations for 3rd order parallel configuration by using Frequency Balancing concept [20].

When three components are connected in parallel, eight possible states may exist with different combinations of UP and DOWN states of the three, plus a state with three parts all at "DOWN" status derived from the first state (all are "UP") by common cause failure mode. There are altogether nine states involved as listed in Table 4-3.

State "8" is derived from one of the states of "5", "6" and "7", whereas state "9" is derived directly from state "1" due to common cause failure. The relationship and transferring rates among the nine states are shown in Fig. 4-2 based upon the following

Table 4-3 The nine possible states for a redundant system with three parallel components

State	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Part 1	U	U	U	D	U	D	D	D	D
Part 2	U	U	D	U	D	U	D	D	D
Part 3	U	D	U	U	D	D	U	D	D
	All up	2 up, 1 down			1 up, 2 down			All down	

Note: "U" and "D" represent an "UP" and "DOWN" status, respectively.

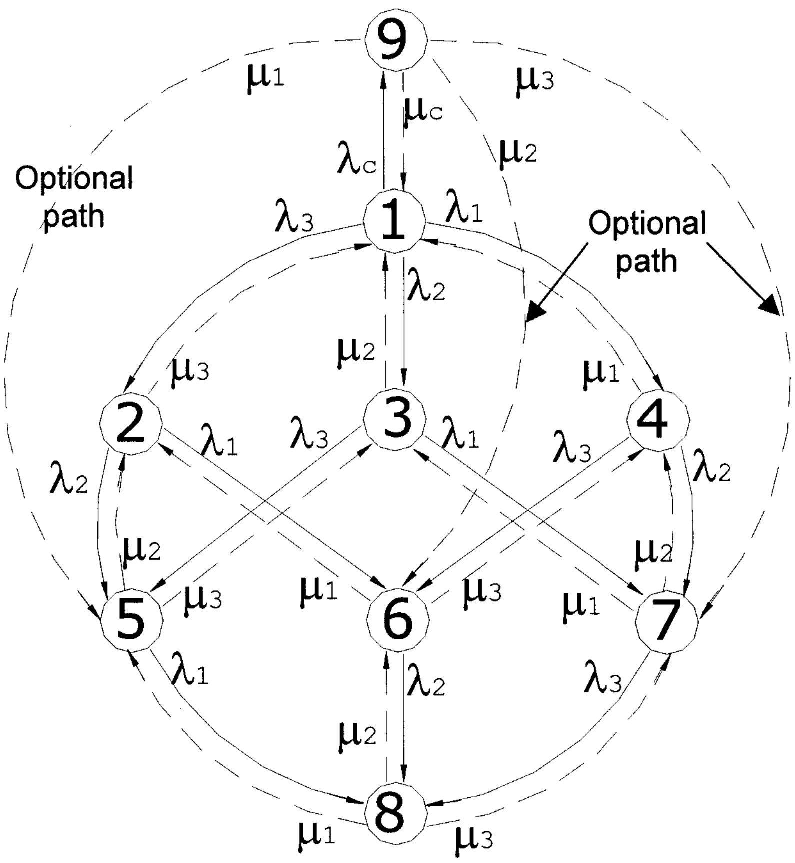


Figure 4-2 State diagram for a three-component parallel redundant system

assumptions:

- The component that fails individually is repaired one at a time and returned to service as soon as the repair is finished. Therefore the state with failing component(s) can transfer back to a neighboring state with a repaired component.
- The components that fail due to common cause factor are repaired one by one and therefore state "9" has the chance to go back to states "5", "6" or "7", while the rate for transfering back to state "1" is the reciprocal of the total repairing time for the three components.

Other assumptions may also be reasonable as discussed below. The symbols in Fig.4-2 that represent the transfering rates among differents states have the following meaning:

λ_i – Failure rate for component i;

μ_i – Repairing rate for component i. It equals to $1/r_i$, where r_i represents the MTTR for component i;

For the common cause mode failure parameters, we suppose the failure rate as:

$$\lambda_c = C \cdot \min(\lambda_1, \lambda_2, \lambda_3) \qquad (4\text{-}8)$$

where C is the common cause factor coefficient. Based upon the assumptions made above, the repairing rate back to state "1" from state "9" is:

$$\mu_C = 1 / (r_1 + r_2 + r_3) \qquad (4\text{-}9a)$$

Based upon the different realistic situation, the assumptions for repairing can be made in some other ways, *e.g.*, state "9" will only be returned to state "1" with a simultaneous repair for the three failed components, while the rates for returning back to states "5", "6" and "7" are all zero (as indicated by "optional path" in Fig. 4-2). In this case the repairing rate back to state "1" will be:

$$\mu_C = 1 / \max(r_1, r_2, r_3) \qquad (4\text{-}9b)$$

where the repairing rate is restricted by the lowest repairing rate among the three. We tried both two assumptions and found the 3rd order failure rate generated by the two sets of assumptions are close enough to be regarded as identical. The difference is the overall MTTR. By cutting the repairing rates for the optional paths to zero, the overall MTTR is increased to about twice. This observation may prove that the first assumption we have made is a better scheme and it is used in this thesis.

According to the state space diagram, applying the Frequency Balance Method, and assuming the probability for state "*i*" is P_i, an equation set with respect to P_i can be derived as following:

i) $P_1(\lambda_1 + \lambda_2 + \lambda_3 + \lambda_c) = P_2\mu_3 + P_3\mu_2 + P_4\mu_1 + P_9\mu_c$

ii) $P_2(\lambda_1 + \lambda_2 + \mu_3) = P_1\lambda_3 + P_5\mu_2 + P_6\mu_1$

iii) $P_3(\lambda_1 + \mu_2 + \lambda_3) = P_1\lambda_2 + P_5\mu_3 + P_7\mu_1$

iv) $P_4 (\mu_1 + \lambda_2 + \lambda_3) = P_1 \lambda_1 + P_6 \mu_3 + P_7 \mu_2$

v) $P_5 (\lambda_1 + \mu_2 + \mu_3) = P_2 \lambda_2 + P_3 \lambda_3 + P_8 \mu_1 + P_9 \mu_1$

vi) $P_6 (\mu_1 + \lambda_2 + \mu_3) = P_2 \lambda_1 + P_4 \lambda_3 + P_8 \mu_2 + P_9 \mu_2$

vii) $P_7 (\mu_1 + \mu_2 + \lambda_3) = P_3 \lambda_1 + P_4 \lambda_2 + P_8 \mu_3 + P_9 \mu_3$

viii) $P_8 (\mu_1 + \mu_2 + \mu_3) = P_5 \lambda_1 + P_6 \lambda_2 + P_7 \lambda_3$

ix) $P_9 (\mu_1 + \mu_2 + \mu_3 + \mu_c) = P_1 \lambda_c$

Rearranging the above equations and writing them into vector format, we get:

$$\boldsymbol{A} \cdot \boldsymbol{P} = \boldsymbol{0} \qquad (4\text{-}10)$$

Where $\boldsymbol{A}$ and $\boldsymbol{P}$ are a coefficient matrix and a column vector, respectively, *i.e.*,

$$A = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} & a_{15} & a_{16} & a_{17} & a_{18} & a_{19} \\ a_{21} & a_{22} & a_{23} & a_{24} & a_{25} & a_{26} & a_{27} & a_{28} & a_{29} \\ a_{31} & a_{32} & a_{33} & a_{34} & a_{35} & a_{36} & a_{37} & a_{38} & a_{39} \\ a_{41} & a_{42} & a_{43} & a_{44} & a_{45} & a_{46} & a_{47} & a_{48} & a_{49} \\ a_{51} & a_{52} & a_{53} & a_{54} & a_{55} & a_{56} & a_{57} & a_{58} & a_{59} \\ a_{61} & a_{62} & a_{63} & a_{64} & a_{65} & a_{66} & a_{67} & a_{68} & a_{69} \\ a_{71} & a_{72} & a_{73} & a_{74} & a_{75} & a_{76} & a_{77} & a_{78} & a_{79} \\ a_{81} & a_{82} & a_{83} & a_{84} & a_{85} & a_{86} & a_{87} & a_{88} & a_{89} \\ a_{91} & a_{92} & a_{93} & a_{94} & a_{95} & a_{96} & a_{97} & a_{98} & a_{99} \end{bmatrix}, \quad P = \begin{bmatrix} P_1 \\ P_2 \\ P_3 \\ P_4 \\ P_5 \\ P_6 \\ P_7 \\ P_8 \\ P_9 \end{bmatrix}$$

We would be able to get a non-zero solution for vector $\boldsymbol{P}$ if and only if the matrix A is not a positive definite matrix, *i.e.*, at least one of its eigenvalues should be zero to get a non-zero solution for the probability vector $\boldsymbol{P}$. By substituting the parameters in the above equation with actual numbers to check matrix $\boldsymbol{A}$, it is found that the rank for this matrix is always 8, *i.e.*, one less than its order. Equivalently, there is always one and only one of its nine eigenvalues is zero. The probability vector $\boldsymbol{P}$ may then be determined corresponding to the zero eigenvalue.

After solving $\boldsymbol{P}$ and applying one more restriction to normalize it:

$$\sum_{i=1}^{n} P_i = 1.0 \text{ (with } n = 9 \text{ in this case)} \qquad (4\text{-}11)$$

the unique solution for probability vector ***P*** can be determined. Consequently the reliability for the parallel system can be expressed by:

$$R_S = P_1 + P_2 + P_3 + P_4 + P_5 + P_6 + P_7 \quad \text{(4-12a)}$$

$$Q_S = P_8 + P_9 \quad \text{(4-12b)}$$

Based upon the transferring rates among different states as shown in Fig. 4-2, the frequency for the system being down can be represented as:

$$\begin{aligned} f_{down} &= P_9 (\mu_1 + \mu_2 + \mu_3 + \mu_c) + P_8 (\mu_1 + \mu_2 + \mu_3) \\ &= (\mu_1 + \mu_2 + \mu_3)(P_9 + P_8) + P_9 \mu_c \\ &= (\mu_1 + \mu_2 + \mu_3) Q_S + P_9 \mu_c \end{aligned} \quad \text{(4-13)}$$

$$\begin{aligned} MTTR_S &= Q_S / f_{down} \\ &= Q_S / [(\mu_1 + \mu_2 + \mu_3) Q_S + P_9 \mu_c] \\ &= 1 / [(\mu_1 + \mu_2 + \mu_3) + P_9 \mu_c / Q_S] \end{aligned} \quad \text{(4-14)}$$

Then the failure rate for the third order redundant parallel configuration can be determined by applying the Frequency Balance equation between the overall operational and failure states:

$$R_S \cdot \lambda_S = Q_S \cdot \mu_S$$

$$i.e., \lambda_S = Q_S \cdot \mu_S / R_S = Q_S / (R_S \cdot MTTR_S) \quad \text{(4-15)}$$

Equations (4-14) and (4-15) are used in this work to solve third order parallel configuration in the Cut Sets methodology.

4.3 Applying to the IEEE Gold Book Standard Network

4.3.1 The IEEE Gold Book Standard Network

A great number of reliability estimation methodologies for power system networks are available nowadays. In order to compare and valuate these methodologies, it would be convenient to define a standard network based upon which the outputs of reliability indices can be obtained corresponding to different methodologies. After considerable examinations of actual industrial and commercial power system network configurations, a network was defined and has been commonly accepted as a standard one. It was published in IEEE Gold Book as shown in Fig. 4-3. The equipment reliability data for each labeled component of the network are also defined and listed in Table 4-4. More details on the development of the standard system configuration and the basis for selection of component indices can be found in [6]. When analyzing the Gold Book Standard Network, some assumptions are necessary in order to make the results for different methodologies to be meaningful:

- Actual Cable Lengths, as indicated on the drawings, affect the failure rate in Table 4-4. Example: Cable Failure Rate per rated length X% of Actual Cable Length indicated on drawing.
- Manual switching operation is allocated 15 minutes for activation.
- 2 out of 4 of the Generators are required for the demand load.
- The UPS are redundant.
- The PDU Transformers are redundant.
- Terminations, while normal for all systems, are not included on the drawings. Terminations or splices are not included in the reliability calculations for this analysis either.
- For Breaker Failure Modes assume 50% opened and 50% shorted.

The standard network is supplied by two independent 15kV primary distribution feeders. There are four diesel engine generators as backup where two out of four generators are required to meet the network load demands at all times. The reliability indices of some specific load points are to be evaluated by both the cut-set

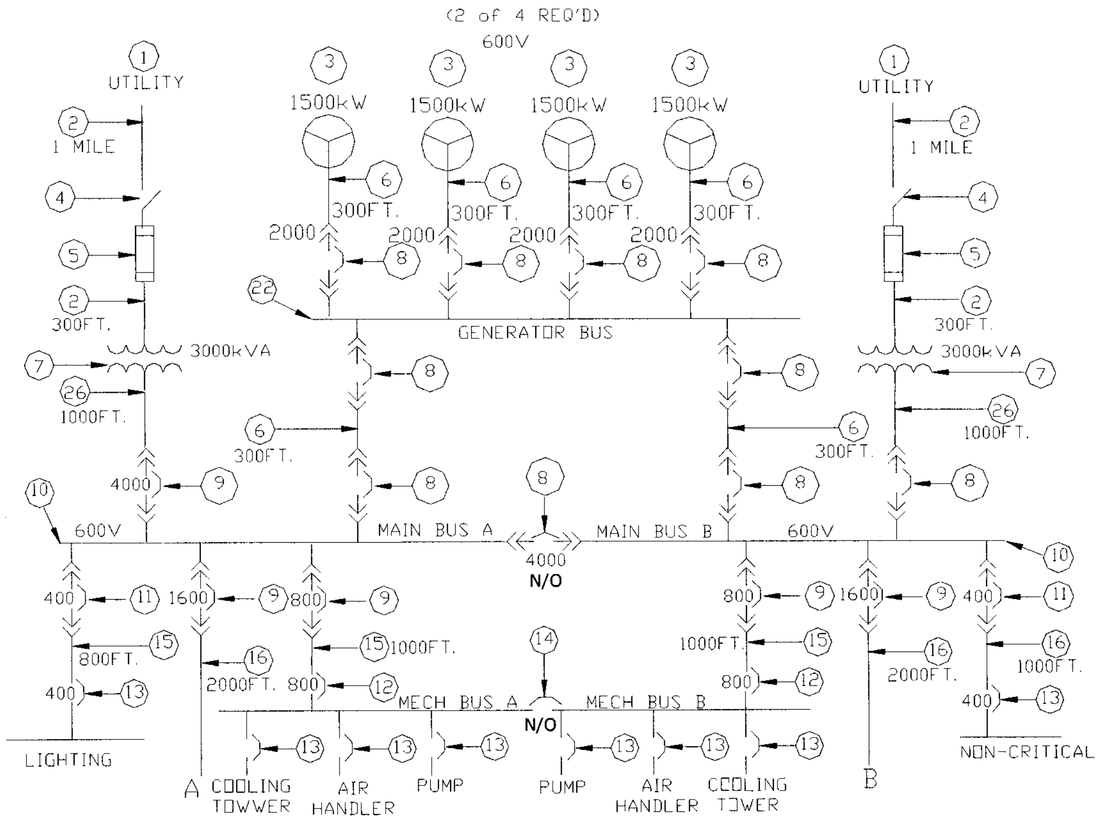


Figure 4-3 the Standard Network as published in IEEE Gold Book

and spreadsheet methodologies. The following reliability indices need to be solved:

(1) Frequency of load point interruptions (interruptions per year, refers to as Failure rate).

(2) Annual duration of load point interruptions (hours per year, refers to as Forced Down Time per year).

(3) Average duration of load point interruptions (hours per interruption, refers to as Mean Time To Repair).

(4) Availability level of power supply to the load point.

Table 4-4 Equipment reliability data for the Gold Book Standard Network configuration

REF #	ITEM DESCRIPTION	PREP ITEM #	INHERENT RELIABILITY	MTTR (hours)	FAILURE RATE failure/ year	Calculated Reliability
	Single Circuit Utility Supply, 1.78 failures/unit years, A =0.999705, Gold Book p. 107	N/A	0.99970500	1.32	1.956000	
2	Cable Arial, < 15kV, per mile	32	0.99999022	1.82	0.047170	
3	Diesel Engine Generator, Packaged,Stand-by, 1500kW	98	0.99974231	18.28	0.123500	
4	Manual Disconnect Switch	187	0.99999980	1.00	0.001740	
5	Fuse, 15kV	117	0.99995363	4.00	0.101540	
6	Cable Below Ground in conduit, < 600V, per 1000 ft	47	0.99999743	11.22	0.002010	
6A	Cable Below Ground in conduit, < 600V - 300 feet			11.22	0.000603	0.999999228
7	Transformer, Liquid, Non Forced Air, 3000kVA	208	0.99999937	5.00	0.001110	
8	Ckt. Breaker, 600V, Drawout, Normally Open, > 600 Amp	68	0.99999874	2.00	0.005530	
8A	Ckt. Breaker, 600V, Drawout, Normally Open, > 600 Amp	68		2.00	0.276500	0.999999369
9	Ckt. Breaker, 600V, Drawout, Normally Closed,>600 Amp	69	0.99999989	0.50	0.001850	
9A	Ckt. Breaker, 600V, Drawout, Normally Closed,>600 Amp	69		0.50	0.000925	0.999999947
10	Switchgear, Bare Bus, 600V	191	0.99999210	7.29	0.009490	
11	Ckt. Breaker, 600V Drawout, Normally Closed, < 600 Amp	67	0.99999986	6.00	0.000210	
11A	Ckt. Breaker, 600V Drawout, Normally Closed, < 600 Amp	67		6.00	0.000105	0.999999928
12	Ckt. Breaker, 600V, Normally Closed, > 600 Amp, Gold Book p. 40	63	0.99998948	9.60	0.009600	
12A	Ckt. Breaker, 600V, Normally Closed, > 600 Amp, Gold Book p. 40	63		9.60	0.004800	0.999994740
13	Ckt. Breaker, 3 Phase Fixed, Normally Closed, < 600Amp	61	0.99999656	5.80	0.005200	
13A	Ckt. Breaker, 3 Phase Fixed, Normally Closed, < 600 Amp, Gold Book p. 40	61		5.80	0.002600	0.999998279
14	Ckt. Breaker, 3 Phase Fixed, Normally Open, > 600 Amp	62	0.99998532	37.50	0.003430	
14A	Ckt. Breaker, 3 Phase Fixed, Normally Open, > 600 Amp	20		37.50	0.001715	0.999992658
15	Cable, Above Ground, No Conduit, < 600V, per 1000 ft.	20	0.99999997	2.50	0.000120	
15A	Cable, Above Ground, No Conduit, < 600V, per 1000 ft.	20		2.50	0.000096	0.999999973
16	Cable, Above Ground, Trays, < 600V, per 1000 ft., Gold Book p.105		0.99999831	10.50	0.001410	
16A	Cable, Above Ground, Trays, < 600V, per 1000 ft., Gold Book p.105			10.50	0.002820	0.999996620
22	Switchgear, Insulated Bus, < 600V		0.99999953	2.40	0.001700	0.999999534
26	Bus Duct, Gold Book p.206, per Circuit foot		0.99999982	12.90	0.000125	0.999815959
26A	Bus Duct, Gold Book p.206, per 1000 Circuit feet		0.99999982	12.90	0.125000	0.999815959

4.3.2 Applying the Cut Set Methodology

When applying the Cut-Set Methodology, steps for calculating the reliability indices for the output can be summarized as following:

1) As introduced in section 4.1, cut sets are developed based upon the single line diagram.
2) Determine the indices for all the events (refer to Table 4-5 that calculates and lists the reliability indices corresponding to each event).
3) Develop logic diagrams corresponding to the reliability evaluation requirement for each output (refer to Fig. 4-4 for the outage at Main Bus A as an example).
4) Develop a working sheet to reflect the logic configuration by using the two rules stated in section 4-1. As an example, Table 4-6 shows the process to obtain the final logic configuration for the involved events (refer to step 10) corresponding to Fig.4-4.
5) Applying the series and parallel equations for reliability calculation, the reliability indices for each load point can be obtained.

Table 4-5 Events indices

Event #	Item	Description	Lambda (per year)	MTTR (hours)	FDT (hours)
1,2	Switchgear (Main) Bus Fault				
	10	Bare Bus 600V	0.0094900	7.29	0.0691821
	9A (3)	Drawout CB	0.0027750	0.50	0.0013875
	8A (2)	Drawout CB	0.0055300	2.00	0.0110600
	11A (1)	Drawout CB	0.0001050	6.00	0.0006300
	SubTotal		**0.0179000**	**4.595508**	**0.0822596**
3	Tie Breaker Failure				
	8A (specifically fails in open)		**0.0027650**	**2**	**0.0055300**
4,5	Utility Service to Switchgear Bus				
	1	Utility supply	1.9560000	1.32	2.5819200
	2	Aerial Cable, 15kV	0.0471700	1.82	0.0858494
	4	Disconnect, 15kV	0.0017400	1.00	0.0017400
	5	Fuse, 15kV	0.1015400	4.00	0.4061600

Table 4-5 Events indices

(continued)

	2A	300ft out of 1mile	0.0026800	1.82	0.0048776
	7	Transformer, OA	0.0011100	5.00	0.0055500
	26	Bus duct, 1000 ft	0.1250000	12.90	1.6125000
	9A	Drawout CB	0.0009250	0.50	0.0004625
	SubTotal		**2.2361650**	**2.101392**	**4.6990595**
6	Generator Bus				
	A. Reliability of Each Gen set				
	3	Engine Generator	0.1235000	18.28	2.2575800
	6	300ft 600V Cable	0.0006030	11.22	0.0067657
	8A	Drawout CB	0.0027650	2.00	0.0055300
	SubTotal for each Gen set		0.1268680	17.89163	2.2698757
	B. calculated at Gen Bus				
	22	Insulated Bus	0.0017000	2.40	0.0040800
	8A (6)	Drawout CB	0.0165900	2.00	0.0331800
		Generators group Fail	0.0253565	5.367562	0.1361026
	Gen Bus totals:		***0.0436465***	***3.97197***	***0.1733626***
7,8	Feeder Brk (GenBus to Switchgear)				
	8A (2)	Drawout CB	0.0055300	2.00	0.0110600
	6	1000ft * 0.3 Cable	0.0006030	11.22	0.0067657
	SubTotal:		**0.0061330**	**2.906516**	**0.0178257**
10,11	Mechanical Switchgear Bus Fault				
	10	Bare Bus 600V	0.0094900	7.29	0.0691821
	12A	Drawout CB	0.0048000	9.60	0.0460800
	13A (3)	Drawout CB	0.0078000	5.80	0.0452400
	14A	Drawout CB	0.0017150	37.50	0.0643125
	SubTotal:		**0.0238050**	**9.444008**	**0.2248146**
12	Tie Breaker Failure				
	14A	Drawout CB	**0.0017150**	**37.5**	**0.0643125**
13,14	Feeder Brk (MainBus to MechBus)				
	9A	Drawout CB	0.0009250	0.50	0.0004625
	15	Above Ground Cable	0.0001200	2.50	0.0003000
	12A	Circuit Breaker >600A	0.0048000	9.60	0.0460800
	SubTotal:		**0.0058450**	**8.014115**	**0.0468425**

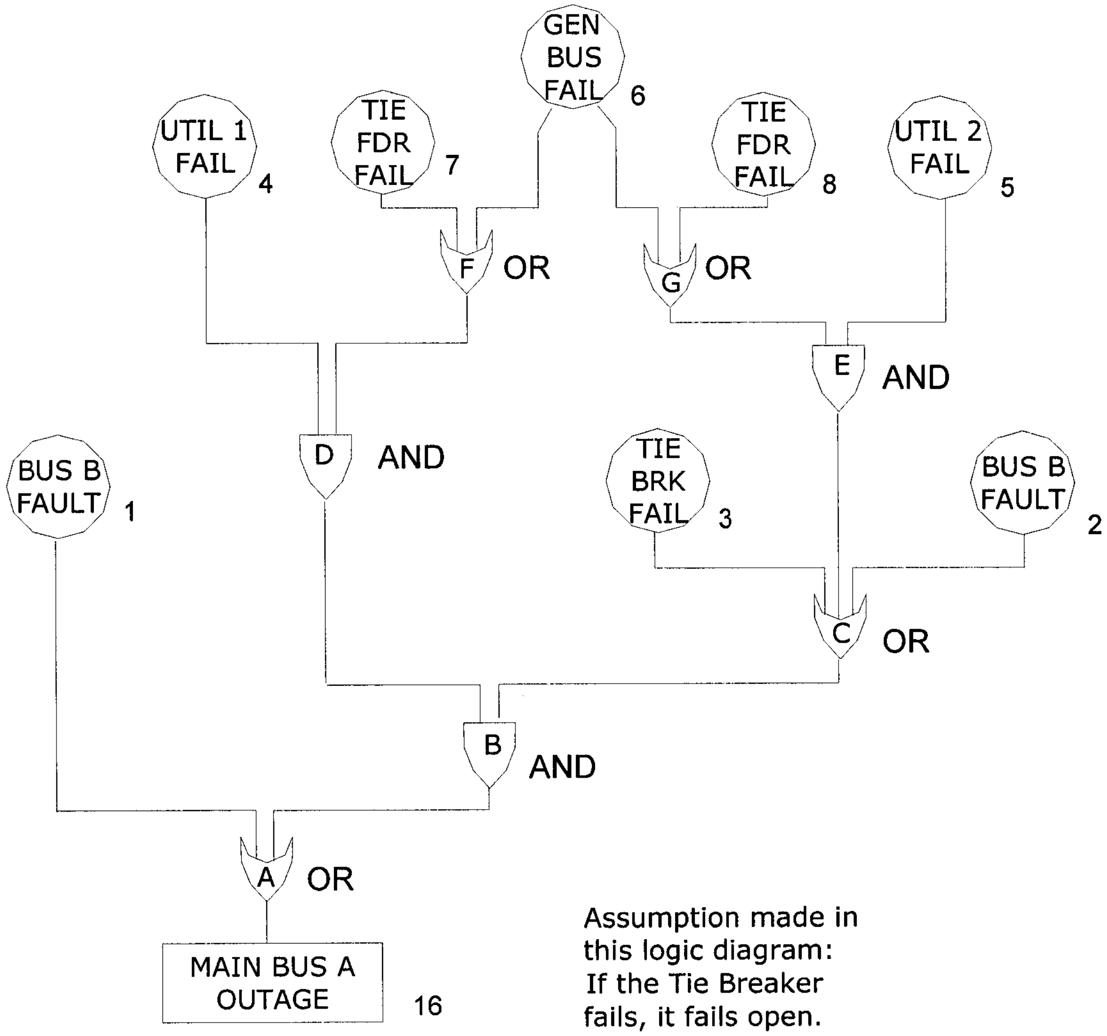


Fig. 4-4 Logic Diagram for figuring out the outage at Main Bus A

Table 4-6 Development of cut sets for the outage of Main Bus A

Step	Description				
1	Start	A			
2	Replace A	1			
		B			
3	Replace B	1			
		C	D		
4	Replace C	1			
		2	D		
		3	D		
		E	D		
5	Replace D	1			
		2	4	F	
		3	4	F	
		E	4	F	
6	Replace E	1			
		2	4	F	
		3	4	F	
		5	G	4	F
7	Replace F	1			
		2	4	6	
		2	4	7	
		3	4	6	
		3	4	7	
		5	G	4	6
		5	G	4	7
8	Replace G	1			
		2	4	6	
		2	4	7	
		3	4	6	
		3	4	7	
		5	6	4	6
		5	8	4	6
		5	6	4	7
		5	8	4	7

Table 4-6 Development of cut sets for the outage of Main Bus A (continued)

9	Eliminate Duplicates	1			
		2	4	6	
		2	4	7	
		3	4	6	
		3	4	7	
		5	4	6	
		5	8	4	6
		5	6	4	7
		5	8	4	7
10	Eliminate Supersets	1			
		2	4	6	
		2	4	7	
		3	4	6	
		3	4	7	
		5	4	6	
		5	8	4	7

Two new items of Duplicates and Supersets appear in Table 4-6 other than the example as in Table 4-1. The elimination of Duplicates in step 9 means the fourth row from bottom in step 8 that contains the same event #6 is eliminated. The "Supersets" eliminated in step 10 refer to two rows in step 9 (5-8-4-6 and 5-6-4-7). This is because the contributions from Events #7 and #8 may be substituted by only one event - Event #6. This fact is clear by referring to the logic diagram in Fig. 4-4. The outage at Main Bus A is calculated by applying the first, second and third order equations to the events as listed in Table 4-6. The indices for each individual event are obtained from Table 4-5. The fourth and higher orders are ignored in calculations for their extremely small effects on the overall failure rate. Referring to step 10 in the above table, the final reliability calculations for Main Bus A involve the reliability indices for Event #1 that

Table 4-7 Calculations of the Main Bus A Outage

(Overall Failure rate, MTTR and FDT)

Event #	Event description	Component indices			Calculated cut set indices		
		failure Rate (per year)	MTTR (hours)	FDT (hrs/year)	Failure Rate (per year)	MTTR (hours)	FDT (hrs/year)
1	Switchgear Bus A	0.0179	4.595508	0.08226			
		First order			0.0179	4.595508	0.08226
2	Switchgear Bus B	0.0179	4.595508	0.08226			
4	Utility 1	2.236165	2.101392	4.69906			
6	Generation group	0.043646503	3.97197	0.173363			
		Third order			8.95E-04	0.962512	0.000861
2	Switchgear Bus B	0.0179	4.595508	0.08226			
4	Utility 1	2.236165	2.101392	4.69906			
7	Gen Feeder	0.00613	2.902447	0.017792			
		Third order			3.06E-04	0.875528	0.000268
3	Switchgear Tie Brk	0.002765	2	0.00553			
4	Utility 1	2.236165	2.101392	4.69906			
6	Generation group	0.043646503	3.97197	0.173363			
		Third order			1.38E-04	0.739926	0.000102
3	Switchgear Tie Brk	0.002765	2	0.00553			
4	Utility 1	2.236165	2.101392	4.69906			
7	Gen Feeder	0.00613	2.902447	0.017792			
		Third order			1.38E-04	0.683445	9.44E-05
5	Utility 2	2.236165	2.101392	4.69906			
4	Utility 1	2.236165	2.101392	4.69906			
6	Generation group	0.043646503	3.97197	0.173363			
		Third order			0.002180577	0.754259	0.001645
16	**Totals for Switchgear Bus A**				**0.021558066**	**3.953529**	**0.08523**

has been calculated in Table 4-5, plus the four 3rd order parallel configurations for different combinations of Events #2 to #7. The 3rd order parallel configuration is solved by a self-coded MatLab script and a numeric solution is available as presented in Table 4-7.

Following the same procedure as described above, the outages at other locations can also be determined. Results for the other locations are collected and shown in Chapter 5 when comparison is made with the results generated by the Spreadsheet Model. The revised Cut-Set Model and the revised Spreadsheet Model are mutually validated by applying them to the same Standard Network as shown in the next chapter.

Chapter 5

Comparison of the Two Methodologies

The two revised models are validated by applying them to an identical Standard Network in IEEE Gold Book. Closely comparable results are obtained from the two revised models for the same network. Influence of the failure modes of circuit breakers on the reliability indices output for the Standard Network is investigated by using the proficient and accurate revised Spreadsheet Model. The influence of the tie breaker status (N/C or N/O) on system reliability is also discussed for the power distribution substation designs.

5.1 Applying Spreadsheet Model to the Gold Book Standard Network

In order to apply the spreadsheet model, different zones are obtained (as shown in Fig. 5-1) according to our discussion in Chapter 2. The quantities of every component for each zone are entered into the spreadsheet model, where the relationship among the different zones are defined in the area of "Zone Table", as also shown in Table 5-1. Reliability indices for the required load points can be extracted from the PointTable in the Spreadsheet Model. For comparison, these results are collected and given in comparison with the results generated by the revised Cut-Set Model (refer to section 5.2).

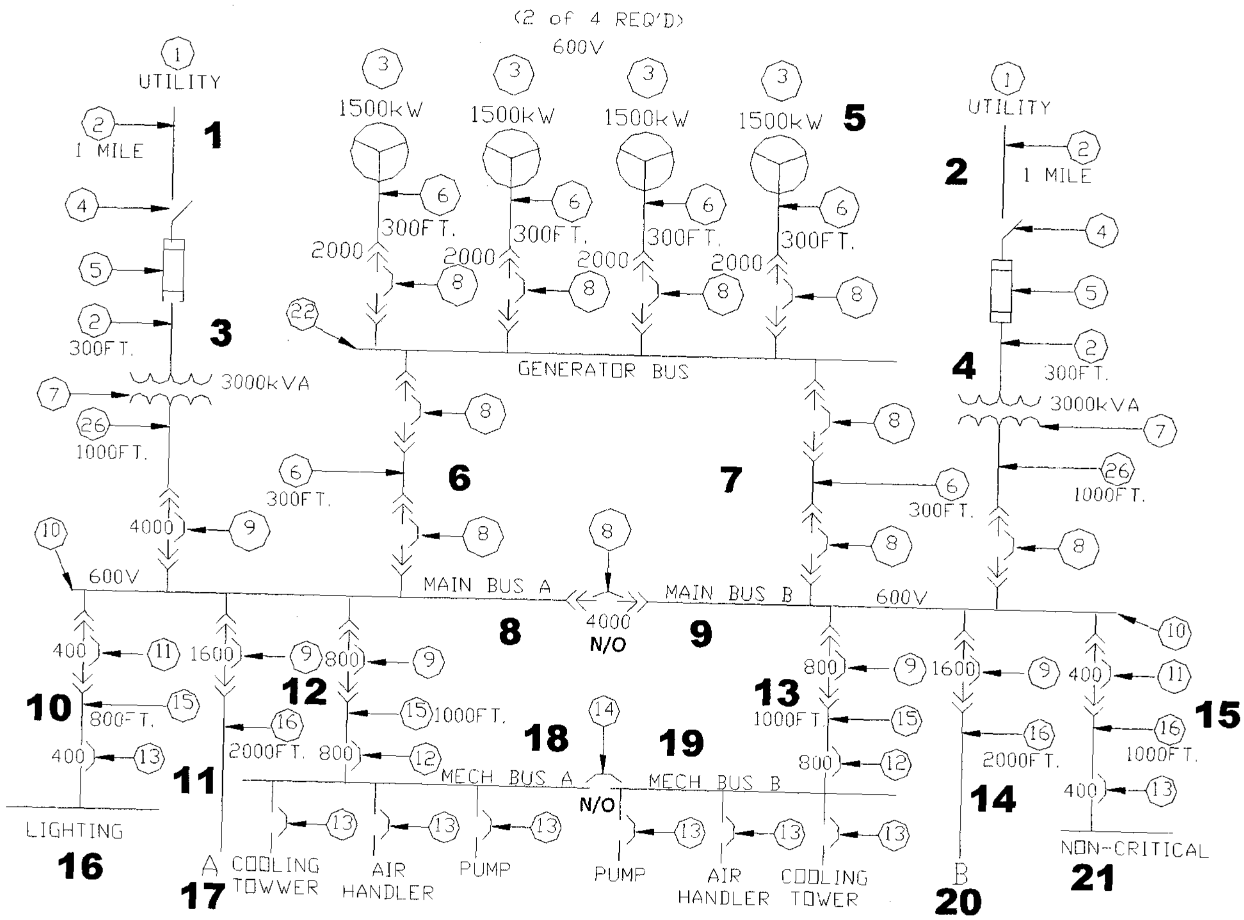


Fig. 5-1 A schematic showing the different zones in the IEEE Standard Network

Table 5-1 Zone Table used in the Spreadsheet model to define the zone configurations

Point Number	Zone Table				
	Series		Parallel		
	Zone	Point	CZone	Point "1"	Point "2"
Point 1	1	0	0	0	0
Point 2	2	0	0	0	0
Point 3	3	1	0	0	0
Point 4	4	2	0	0	0
Point 5	5	0	0	0	0
Point 6	6	5	0	0	0
Point 7	7	5	0	0	0
Point 8	0	0	8	3	6
Point 9	0	0	9	4	7
Point 10	10	8	0	0	0
Point 11	11	8	0	0	0
Point 12	12	8	0	0	0
Point 13	13	9	0	0	0
Point 14	14	9	0	0	0
Point 15	15	9	0	0	0
Point 16	16	10	0	0	0
Point 17	17	11	0	0	0
Point 18	18	12	0	0	0
Point 19	19	13	0	0	0
Point 20	20	14	0	0	0
Point 21	21	15	0	0	0

5.2 Comparing the Two Methodologies

By studying the procedures of the original Cut-Set and original Spreadsheet methodologies, we find that they applied different concepts when dealing with parallel connections. In the Spreadsheet model, the common cause factor (*CCF*) is considered in failure rate estimation, although not considered in MTTR and availability estimations. When *CCF* is considered, it always assumes that the component with the greatest failure rate dominates the failure rate with common cause mode. In the Cut-Set methodology, the *CCF* is ignored and consequently results in unreasonably low failure rates when parallel connection is involved. These differences account for the totally different results for the reliability indices generated by the two original methodologies. Table 5-2 shows the different results generated by the original Cut-Set and Spreadsheet methodologies when they are applied to the IEEE Gold Book standard circuit. Table 5-2 (a) shows the reliability indices generated by the original Cut-Set Model; (b) is generated by the original Spreadsheet Model. The relative differences corresponding to different reliability indices are shown in Table 5-2 (c). Compared with the reliability indices from the Spreadsheet Methodology, except for the outage at the Generation Bus, the failure rate and MTTR from the Cut-Set methodology are too small and too large, respectively. The reliability indices at the Generation Bus are calculated using the same strategy for the two methodologies and have the same results for the two models, because there is no way to evaluate the "2 out of 4" reliability by using the Spreadsheet methodology.

After modifying the two models by considering the common cause factor and the protective circuit devices' failure modes, we achieve two sets of comparable results for the reliability indices corresponding to the revised Cut-Set Model and the revised Spreadsheet Model, as shown in Table 5-3.

Table 5-2 Comparisons of the two ***original*** models

(a) Results generated by the original Cut-Set Model:

Output Location	Failure Rate per year	MTTR (hours)	FDT per year	Inherent Availability
Main Switchgear Bus A	0.017895008	4.595114239	0.082229606	0.999990613
Main Switchgear Bus B	0.017895008	4.595114239	0.082229606	0.999990613
Generation Bus	0.015530000	2.043786220	0.031740000	0.999996377
Mechanical Switchgear Bus A	0.023841493	9.484818415	0.226132232	0.999974186
Mechanical Switchgear Bus B	0.023841493	9.484818415	0.226132232	0.999974186
Lighting Bus	0.020696008	4.743891002	0.098179606	0.999988792
Non-Critical Bus	0.012315000	7.387812026	0.090980905	0.999989614

(b) Results generated by the original Spreadsheet Model:

Output Location	Failure Rate per year	MTTR (hours)	FDT per year	Inherent Availability
Main Switchgear Bus A	0.239951656	0.000427235	0.000102516	0.999999988
Main Switchgear Bus B	0.239951656	0.000427235	0.000102516	0.999999988
Generation Bus	0.015530000	2.043786220	0.031740000	0.999996377
Mechanical Switchgear Bus A	0.269601656	1.008016666	0.271762963	0.999968978
Mechanical Switchgear Bus B	0.269601656	1.008016666	0.271762963	0.999968978
Lighting Bus	0.245352656	0.126888967	0.031132545	0.999996446
Non-Critical Bus	0.245376656	0.127121079	0.031192545	0.999996439

(c) Differences between the two original models:

Output Location	Failure Rate per year	MTTR (hours)	FDT per year	Inherent Availability
Main Switchgear Bus A	1240.8860%	-99.9907%	-99.8753%	0.0009%
Main Switchgear Bus B	1240.8860%	-99.9907%	-99.8753%	0.0009%
Generation Bus	0.0000%	0.0000%	0.0000%	0.0000%
Mechanical Switchgear Bus A	1030.8086%	-89.3723%	20.1788%	-0.0005%
Mechanical Switchgear Bus B	1030.8086%	-89.3723%	20.1788%	-0.0005%
Lighting Bus	1085.5072%	-97.3252%	-68.2902%	0.0008%
Non-Critical Bus	1892.5023%	-98.2793%	-65.7153%	0.0007%

Table 5-3 Comparisons of the two ***revised*** models

(a) Results generated by the revised Cut-Set Model:

Output Location	Failure Rate per year	MTTR (hours)	FDT per year	Inherent Availability
Main Switchgear Bus A	0.021558066	3.953529415	0.085230447	0.999990271
Main Switchgear Bus B	0.021558066	3.953529415	0.085230447	0.999990271
Generation Bus	0.043646503	3.971969900	0.173362595	0.999980210
Mechanical Switchgear Bus A	0.048563893	5.997778578	0.291275476	0.999966750
Mechanical Switchgear Bus B	0.048563893	5.997778578	0.291275476	0.999966750
Lighting Bus	0.026959066	4.312480565	0.116260447	0.999986728
Non-Critical Bus	0.026983066	4.310868460	0.116320447	0.999986722

(b) Results generated by the revised Spreadsheet Model:

Output Location	Failure Rate per year	MTTR (hours)	FDT per year	Inherent Availability
Main Switchgear Bus A	0.020119304	3.875628263	0.077974943	0.999991099
Main Switchgear Bus B	0.020119304	3.875628263	0.077974943	0.999991099
Generation Bus	0.043646503	3.971969900	0.173362595	0.999980210
Mechanical Switchgear Bus A	0.049769304	4.647599936	0.231307813	0.999973596
Mechanical Switchgear Bus B	0.049769304	4.647599936	0.231307813	0.999973596
Lighting Bus	0.025520304	4.271302755	0.109004944	0.999987557
Non-Critical Bus	0.025544304	4.269638542	0.109064944	0.999987550

(c) Differences between the two revised models:

Output Location	Failure Rate (%)	MTTR (%)	FDT (%)	Inherent Availability (%)
Main Switchgear Bus A	7.15%	2.01%	9.30%	0.00%
Main Switchgear Bus B	7.15%	2.01%	9.30%	0.00%
Generation Bus	0.00%	0.00%	0.00%	0.00%
Mechanical Switchgear Bus A	-2.42%	29.05%	25.93%	0.00%
Mechanical Switchgear Bus B	-2.42%	29.05%	25.93%	0.00%
Lighting Bus	5.64%	0.96%	6.66%	0.00%
Non-Critical Bus	5.63%	0.97%	6.65%	0.00%

Table 5-3 (a) lists the reliability indices from the revised Cut-Set Model; (b) is generated by the revised Spreadsheet Model, and the relative differences between the two revised models are greatly suppressed as shown in Table 5-3 (c). From this table it is clear that the two sets of reliability indices generated by the two revised models are comparable when they are applied to an identical network. By this comparison, the two revised models are mutually validated, *i.e.*, if one of the revised models is practical, then the other is practical, too.

By comparing the evaluation process of the two models, the Spreadsheet Model is relatively flexible and convenient in use. After improving its accuracy by using self-deduced equations, the revised Spreadsheet Model can be a good choice of our convenient methodology with enough accuracy. The revised Spreadsheet Model is used to address the open or short failure modes of circuit breakers in the next section.

5.3 Influence of Failure Modes on the Overall Reliability

The failure rate and mean time to repair of a circuit breaker may be obtained from statistical observations, but a circuit breaker may have different probabilities of failure as open or failure as short under different environment, *e.g.*, a circuit breaker may more likely fail as short under higher voltage compared to lower voltage applied across it.

According to our discussion in section 3.2.3 ("Dealing with Breakers"), a failed circuit breaker affects its neighboring zone (either upstream or downstream) depending upon its connection with other breakers. Therefore the different failure modes of a circuit breaker has different influence on the reliability indices of related load points. It is of significant practical meaning to study the relationship between the reliability and failure modes of circuit breakers. By investigating the Spreadsheet Model, we found that this model may be used to evaluate the effect of failure modes of circuit breakers in a convenient way. As long as the ratio of short to open failure mode is given, the corresponding reliability indices at different load points of the system may be determined. Figure 5-2 shows the dependence of the system's failure rate on the percentage of the short-circuit failure mode of circuit breakers. At different load points, as represented by different legends in Fig. 5-2, the failure rate always increases with the increased ratio of failure as short. This indicates that the short-circuit failure mode has a more significant influence on the system, as expected from speculation. Consequently the influence on forced down time (FDT) related to each load points has the same pattern as for the failure rate, as shown in Fig. 5-3.

The detailed results for reliability indices corresponding to different failure modes are listed in Tables 5-4 (A) to (E)

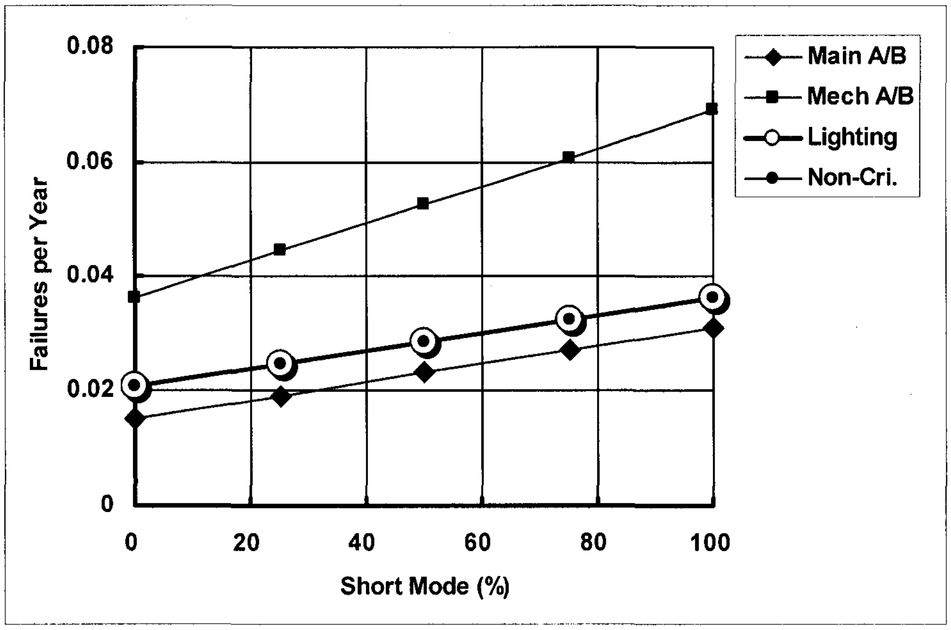


Figure 5-2 Influence of the failure mode on failure rate at different locations of the IEEE standard network

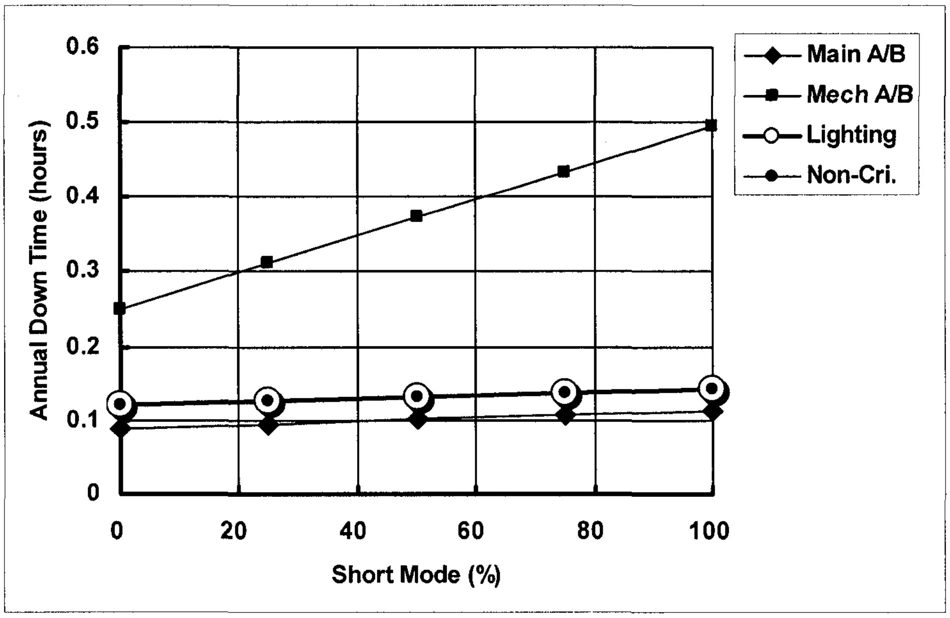


Figure 5-3 Influence of the failure mode on Forced Down Time per year at different locations of the IEEE standard network

Table 5-4 (A) Reliability indices at different load points with failure mode of: Open = 100%, Short = 0%

Output Location	Failure Rate (failures/year)	MTTR (hours)	FDT (hrs/year)	Inherent Availability
Main Switchgear Bus A	0.015131	5.842663	0.088403	0.999990
Main Switchgear Bus A	0.015131	5.842663	0.088403	0.999990
Mechanical Switchgear Bus A	0.036191	6.934694	0.250971	0.999971
Mechanical Switchgear Bus A	0.036191	6.934694	0.250971	0.999971
Lighting Bus	0.020637	5.817964	0.120063	0.999986
Non-Critical Bus	0.020661	5.814110	0.120123	0.999986

Table 5-4 (B) Reliability indices at different load points with failure mode of: Open = 75%, Short = 25%

Output Location	Failure Rate (failures/year)	MTTR (hours)	FDT (hrs/year)	Inherent Availability
Main Switchgear Bus A	0.019067	5.008625	0.095498	0.999989
Main Switchgear Bus A	0.019067	5.008625	0.095498	0.999989
Mechanical Switchgear Bus A	0.044422	7.037358	0.312612	0.999964
Mechanical Switchgear Bus A	0.044422	7.037358	0.312612	0.999964
Lighting Bus	0.024520	5.172998	0.126843	0.999986
Non-Critical Bus	0.024544	5.170384	0.126903	0.999986

Table 5-4 (C) Reliability indices at different load points with failure mode of: Open = 50%, Short = 50%

Output Location	Failure Rate (failures/year)	MTTR (hours)	FDT (hrs/year)	Inherent Availability
Main Switchgear Bus A	0.022993	4.413477	0.101481	0.999988
Main Switchgear Bus A	0.022993	4.413477	0.101481	0.999988
Mechanical Switchgear Bus A	0.052643	7.088066	0.373140	0.999957
Mechanical Switchgear Bus A	0.052643	7.088066	0.373140	0.999957
Lighting Bus	0.028394	4.666794	0.132511	0.999985
Non-Critical Bus	0.028418	4.664964	0.132571	0.999985

Table 5-4 (D) Reliability indices at different load points with failure mode of: Open = 25%, Short = 75%

Output Location	Failure Rate (failures/year)	MTTR (hours)	FDT (hrs/year)	Inherent Availability
Main Switchgear Bus A	0.026920	3.991932	0.107464	0.999988
Main Switchgear Bus A	0.026920	3.991932	0.107464	0.999988
Mechanical Switchgear Bus A	0.060865	7.125059	0.433669	0.999950
Mechanical Switchgear Bus A	0.060865	7.125059	0.433669	0.999950
Lighting Bus	0.032269	4.282124	0.138179	0.999984
Non-Critical Bus	0.032293	4.280800	0.138239	0.999984

Table 5-4 (E) Reliability indices at different load points with failure mode of: Open = 0%, Short = 100%

Output Location	Failure Rate (failures/year)	MTTR (hours)	FDT (hrs/year)	Inherent Availability
Main Switchgear Bus A	0.030847	3.677695	0.113447	0.999987
Main Switchgear Bus A	0.030847	3.677695	0.113447	0.999987
Mechanical Switchgear Bus A	0.069087	7.153229	0.494197	0.999944
Mechanical Switchgear Bus A	0.069087	7.153229	0.494197	0.999944
Lighting Bus	0.036143	3.979907	0.143847	0.999984
Non-Critical Bus	0.036167	3.978925	0.143907	0.999984

5.4 Proficiency of Open/Closed Tie Breakers

As shown in the above section, the Spreadsheet Model can be conveniently used to conduct sensitivity test, *i.e.*, by changing the reliability indices of any components or changing the configuration of the connection, the influence of the changes may be easily reflected from the final results. This feature can be used to identify the most critical issue regarding the design so that the most cost-effective design may be achieved. Another example for sensitivity test by using the Spreadsheet Model is conducted to study the different proficiencies of Open Tie Breaker and Closed Tie Breaker. Recalling the eight typical designs of the power distribution substation discussed in Chapter 3, we have treated the tie breaker that links the two utility suppliers always as Closed Tie Breaker (as in Designs C, D, and E). A comparison calculation is done here by assuming each of them as an Open Tie Breaker. The

Table 5-5 The influence of tie breaker status on the load point reliability indices

Design	Status of Tie Breaker Linking Utility Suppliers	Failure Rate (failures/year)	Forced Down Time (hours/year)	MTTR (hours/failure)
Design C	N/C	0.330406	1.836304	5.557723
Design C	N/O	2.105615	1.846403	0.877080
Design D	N/C	0.232013	1.101627	4.739032
Design D	N/O	2.007210	1.543506	0.769120
Design E	N/C	0.026487	1.089900	41.148523
Design E	N/O	2.004075	1.527540	0.762350

difference in reliability indices resulted from the N/C or N/O status of the tie breakers in Designs C, D and E are collected in Table 5-5. It is clear that a normally closed tie breaker greatly improves the reliability of the system by greatly decreasing the failure rate, while a normally open tie breaker improves the reliability by effectively suppressing the MTTR. The annual forced down times are comparable by using either a closed or an open tie breaker, although the closed tie breaker generates a slightly smaller forced down time. This fact can be understood by realizing the following mechanism: a parallel configuration connected using a N/C tie breaker is a redundant system with one of the components as an immediate backup of the suppliers, and a parallel configuration connected using a N/O tie breaker actually "shorten" the MTTR by switching to the other supplier when one of them fails. This is consistent with the observations as obtained in Chapter 3 for the reliability indices of different designs.

Chapter 6

Conclusions

6.1 Circuit Breaker and Failure Modes

Serving as one type of protection device in the power system, a circuit breaker is supposed to isolate a fault from the system as soon as the fault occurs. If a circuit breaker fails, it could trip its neighboring breaker(s). A circuit breaker failure can be either open or short. It is one of the main contributions of this thesis to attribute the failure rates (corresponding to different failure modes) to different circuit zones. Furthermore, the interaction of the failure modes and the configuration of the circuit breakers (series, parallel or serving as tie breaker) results in different mechanisms for the network to respond to a fault. By evaluating the reliability indices for the IEEE Standard Network with different failure modes (open to short ratio), it was found that the circuit breaker that fails short has the biggest influence on the reliability of the network. The different proficiencies of using N/C and N/O tie breakers are also identified. They improve the system reliability by effectively suppressing the failure rate and MTTR, respectively.

6.2 Reliability of Parallel Configurations

Mathematically, a parallel system with two or more independent components, greatly improves the system reliability when it is compared with either of the components that serves the network individually. In practice, it is hard to obtain absolute independent components to compose a parallel system. This results in a common mode failure that dramatically lowers the parallel system reliability, although it is still much better than each individual component. In this work, models for both 2nd and 3rd order parallel systems were built and solved by using Frequency Balancing Approach. For the 3rd order parallel system, based upon the model developed in this work, a nine-order matrix equation was obtained with the form of $\boldsymbol{A} \cdot \boldsymbol{P} = \boldsymbol{0}$. Realistic system parameters always result in the rank of the matrix $\boldsymbol{A}$ being 8, the significance of which is that this generates a corresponding and unique non-zero solution.

6.3 Spreadsheet Model: Improvements and Application

The original Spreadsheet model is investigated by uncovering the equations and processes involved in the model. It greatly underestimates MTTR when a failure from parallel configuration is involved. When the equations and the evaluating procedure are both modified, the resulting revised model can be applied to obtain one optimized power distribution station amongst eight typical design possibilities. The effectiveness of using dual suppliers, tie breakers, and parallel design level are explicitly illustrated:

- Designs with dual supply systems always have higher reliability and smaller forced down time.
- A closed tie breaker improves the reliability of the system by effectively lowering the failure rate.
- An open tie breaker improves the reliability at the related load points by effectively decreasing MTTR when a fault occurs.
- It is always an effective way to improve reliability by adding one more parallel level between the suppliers and the load points. With a design characteristic in which the common cause factor is high, the advantages of using parallel configuration are greatly suppressed.

6.4 Cut Set Model: Improvements and Applications

No common cause factor was considered in the original Cut Set model. Due to the characteristics of this model, high orders (3^{rd}, 4^{th}, 5^{th}) of parallel configuration are usually derived from the logic diagram. Effort is taken in this thesis to determine the reliability indices (failure rate and MTTR) for a 3^{rd} order parallel configuration. The failure rates for 4^{th} order and higher parallel configurations are ignored for their extremely small values. The revised model is applied to the IEEE Gold Book Standard Network.

6.5 Comparison and Validation of the Two Revised Models

The IEEE Standard Network is chosen to validate the two revised models. By using the two *original* models, the reliability indices for the network differed greatly. Modifications to the two models resulted in comparable performance indices when applied to the same network. The similarities in results obtained with the two *revised* models validate, to a certain extent, each of the models. The revised Spreadsheet Model is a convenient methodology with sufficient accuracy.

6.6 Future Research Work

(a) The Monte-Carlo principle has been applied in evaluating electrical network reliability. It would be a practical and meaningful project to conduct a comparison study of the evaluation methodologies discussed in this thesis with the Monte-Carlo methodology.

(b) The Spreadsheet Model cannot handle the parallel configuration with three or more components. It would be an interesting project to revise the model further by coding to solve the higher order parallel configuration events involved in the Spreadsheet Model.

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Related Publications

Two papers have been published in accordance with the content of this thesis:

1. Don Koval, Xinlie Zhang, John Propst, Timothy Coyle, "Reliability methodology applied to the IEEE Gold Book Standard Network", *IEEE Transactions on Industry Applications*, **9** (1), 32-41 (2003)
2. Zhenfu Dong, Don Koval, John Propst, "Reliability of various industrial substations", Accepted by *IEEE Transactions on Industry Applications*, (2004)

out. Resurrecting three South American heroes from the nineteenth century – Bolívar himself, Bolívar's revolutionary teacher, Simón Rodríguez, and Ezequiel Zamora, leader of the peasants against the landed oligarchy in the federal wars of the 1840s and 1850s – Chávez began to sketch the outline of a politics of revolutionary nationalism, destined to have considerable popular appeal. From the country in Latin America that has been most deeply immersed in North American culture and politics, he launched a fierce counter-attack on the programme of globalization imposed on the world by the United States in the aftermath of the Cold War. Soon he was topping the polls of public opinion.

Chávez is a master communicator. He speaks every Sunday morning on his own radio programme, and everyone is familiar with his pedagogic formulations. He talks like a teacher and listens like a teacher, picking up an implicit question and throwing it back at the questioner. On the radio, he is at his didactic best, illustrating, explaining and arguing, with all the sophistry at his command. As the child of two teachers, this is a world with which he has always been familiar, and it is no accident that one of his great nineteenth-century heroes, Simón Rodríguez, organized a radical programme of education for the poor, the Indians and the blacks. It is difficult to overestimate the impact that his broadcasts make on the largest and poorest section of the Venezuelan population.

On television, he will often appear to be speaking to an invited audience immediately in front of him. Then he will suddenly turn, as though to another camera, to address the real audience out there in the rural areas and the shanty towns. It is always an electrifying performance, for he speaks as though he is in instant communion with his own people, the people who understand what he is trying to say and do.

The privileged middle class in Caracas, and a plethora of hostile newspaper columnists, complain about his rough and simple language – he is accused of sounding dull and provincial. They fail to grasp that he is talking to people with whom he has a close rapport, who appreciate what he is doing, and are buoyed up by a feeling of expectancy

that something is going to happen, something is going to be done, and that things are going to change. He conveys this sense of excitement in a way that the middle classes are unable to capture, for they are tuned in to a different wave-length. Throughout his first year in office, the old Venezuelan political and cultural elite, grossly overblown by oil rent and petro-dollars, and enmired in corruption, stood back aghast and horrified, hypnotized by the activities of this messianic officer whose interests and preoccupations were not theirs.

Chávez's support comes from the impoverished and politically inarticulate section of society, in the shanty towns of Caracas, and in the great forgotten regions of the interior of the country. He speaks to them every day, in words that they understand, in the vivid, often biblical, language of the evangelical preacher. God and Satan, good and evil, pain and love are the combinations that he often uses. As a result, the mass of the *pueblo* are with Chávez, just as, in other countries of Latin America and at other times, they have been with Perón, with Velasco, with Torríjos, with Allende and with Fidel.