Reliability Evaluation of Substations Subject to Protection Failures

Master of Science Thesis

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Delft, the Netherlands, July 2012

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Abstract

Reliability evaluation of power system substations is of significant importance when performing asset management. Most of the studies about substation reliability only focus on the substation connectivity. The reaction of protection system is fully neglected, which cannot be true in reality. Failures of the protection system or the circuit breakers do have an effect on the substation reliability.
In this thesis, the substation reliability with respect to protection failures is evaluated using the event tree method. The basic protection principles for substations are explained first. Then, the event tree analysis is also introduced.

Two case studies will be analyzed in this thesis. The effects of different substation configurations on the reliability is analyzed and compared. Then, the reliability of a real substation, Maasvlakte 380kV substation in the Netherlands, will be evaluated using event tree methods. The failure results will be combined with a load flow scenario of Maasvlakte substation in 2020, and indices such as the average lost load, and maximum lost load will be given.

Key words:
Reliability, Substation, Protection Failure, Load Flow Combination, 4/3 Circuit Breakers Substation, One-and-a-Half Circuit Breakers Substation, Typical Double Busbar Substation, Maasvlakte 380kV Substation

Acknowledgement

After finishing this thesis, there is a necessity to express my gratitude to those people who have contributed to this study.

First of all, I would love to express my deepest thanks to the two people who have contributed most to this thesis: Ir. Bart Tuinema and Ir. Ernst Wierenga. Being my daily supervisor at Delft University of Technology and TenneT TSO respectively, they gave great patience and support in my thesis, and we really had many interesting discussions during the last several months.

I am also grateful to my responsible professor Prof. Mart van der Meijden and Dr. ir. Madeleine Gibescu, who have given me many useful guidance.

Besides, I would give thanks to my colleagues at TenneT as well. Maurits van Tol helped me a lot in accessing the protection information, Kees Koreman gave me some support, while Maaike Teunissen helped me a lot in the paper work.

Last but not the least, I wish to thank my friends and parents for their encouragement. Special thanks go to my dearest parents: Wang Shuquan and Shan Chunhua. Their trust, patience and unconditional love are my biggest motion all the time.

Management Summary

In the design and asset management of the power system, reliability evaluation can offer many insights as a reference and is of great significance. Being one of the most important parts in the power system, the high voltage substation is taken as the main study object in this thesis.

There are two main subdivisions for power system reliability analysis: system adequacy and system security. System adequacy mainly focuses on the connectivity of the system while system security considers the protection devices and post-fault phenomena. For now, there have been some reliability studies about the power systems. Only a few of them focus on high voltage substations and basically all of these studies only concentrate on the substation connectivity, which is not realistic. In this thesis, the reliability study including with protection devices is applied to the high voltage substations.

To evaluate the substation reliability, the substation is assumed to be under normal situation at first in this study. Then, an initiating fault is assumed to occur to any component in the substation, such as disconnecting switch, transformer, instrumental transformer, cable or line. After that, both situations where protection succeeds and fails to clear the initiating fault are taken into consideration. Two types of protection failures are taken into account in this study: protection system failures and associated circuit breaker failures. The reliability of this whole process is evaluated for the substation and failure results of lines/generators connected to the substation are given by the reliability evaluation method.

The reliability evaluation method adopted in this study is Event Tree Analysis. Being an inductive graphical method, event tree analysis can demonstrate the power system reliability both qualitatively and quantitatively in a clear structure. The construction and calculation of event trees are executed in Microsoft Excel, which is very useful.

Two case studies are analyzed in this study: the comparison of the reliability of different substation configurations, and Maasvlakte 380kV substation.

For the first case study: the comparison of the reliability for different substation configurations, three mostly used substation configurations are analyzed and compared. These are: 4/3 circuit breakers substation, one-and-a-half circuit breakers substation and typical double busbar substation.

After the protection principles of these substations are listed, the event trees are built and calculated. The failure results have shown that, within one substation, the dominant components in reliability analysis are the lines/cables and the transformers

because of their large failure probability. Besides, for the lines/generators with similar locations and components, the reliability is same. Moreover, the 4⁄3 circuit breakers substation and one-and-a-half circuit breakers substation are the same reliability level, while they are more reliable than the typical double busbar substation.

Maasvlakte 380kV substation is chosen as the second case study because of its complexity. In 2020, there will be five generator plants, four 380kV lines, two 150kV lines and one HVDC cable with double direction power flow connected to this substation. The huge amount of power that flows in this substation makes the reliability evaluation of Maasvlakte 380kV substation of highly importance.

Event trees are built and calculated for the Maasvlakte substation. The result is combined with the substation load flow scenario in 2020. The amount of lost power in MWh is then given, and the corresponding economic losts is also calculated. For the transmission system operator (TSO), the economic losses caused by generator losses when an initiating fault occurs within Maasvlakte 380kV substation are small. In other words, Maasvlakte 380kV substation is highly reliable. Moreover, Maasvlakte is a 4⁄3 circuit breakers substation, which is a good design according to the conclusion of the first case study.

Besides, the effect of increasing unavailability of circuit breakers is also studied, because the circuit breaker unavailability can increase when the load flow amount increases. It can be concluded from the results that, the increase of circuit breaker unavailability will only increase the final failure frequency slightly. However, the frequency of losing multiple lines/generators at the same time is linear proportional to this increase because of circuit breaker failure function.

Having given clear conclusions about the effects of different substation configurations on reliability and the Maasvlakte 380kV substation reliability, this thesis does have some limits. First of all, every component in the substation is considered to be in operation in this thesis, which means that maintenance is not considered. Besides, the failure data such as failure frequency and mean time to repair is taken from the TSO database, which is only general data. Different failure modes of components are not taken into consideration, while the effect of the environment and humans on the component repair time is not considered either.

In the future, maintenance can be involved in the reliability study, and the different failure modes as well as the effect of environment and humans on the component repair time can be also taken into account. Moreover, it will be interesting to study the effects of failures in one substation on the nearby substation's reliability. Applying other reliability evaluation methods such as Sequential Monte Carlo and State Enumeration to the substations, and compare the results of different methods could also be an interesting study topic in the future.

Contents

Chapter 1 Introduction

1.1 Background

Reliability evaluation of power systems can have a significant effect on the design and asset management of the system. Being one of the most important parts of the power system, substations play a key role in the transmission and distribution of electricity, and will be the main subject studied in this thesis.

In a power system substation, when a fault occurs, the post-fault phenomena are dynamic, and are usually involved with the connectivity between the energy source and the load. These post-fault phenomena can be very complex depending on the system structure.

Normally, the protection in the substation should react and isolate the faulted part successfully in this situation. However, there is a possibility that the protection system fails to fulfill its responsibility. These protection failures may lead to cascading failures of the other components in the substation. Therefore, the study of the substation reliability subject to protection failures becomes very meaningful and challenging.

In most of the traditional reliability studies, the protection systems are assumed to be perfect. This assumption makes the analysis and calculations much easier, but may lead to unrealistic results. The reality has shown that failures of the protection can lead to serious outages of the substation. Therefore, the reliability of the substation with protection failures will be the major concern of this study.

In this thesis, it is assumed that the initial fault occurs on the transmission line/cable connected to the substation or the initial fault occurs on the substation components. Then we assume the protection of the substation cannot operate properly. Two main types of failures can then happen.

One type of protection failure is the protection system’s failure. This type of failure mainly refers to the situation where the protection system fails to see the failure within its operating zone or it fails to give a tripping signal to the circuit breakers. The occasions where the busbar protection fails, the telecommunication system fails to send the tripping signals or the current transformers and voltage transformers offer wrong measurements, will all lead to this type of failure.

The other type of protection failure is that the circuit breaker cannot respond to the command in time. For example, the circuit breakers fail to trip, the circuit breakers have a delay that is so long that it is considered to be a failure, or the circuit breakers trip mistakenly.

The reliability of the substation with the two types of protection failures mentioned above will be studied in detail in this thesis.

1.2 State of the art

There are several books and papers that are related to this thesis study.
The basic concepts of power system reliability used in this study are based on *Reliability Evaluation of Power Systems* [1], *Risk Assessment of Power Systems – Models, Methods and Applications* [2] and *Methods for Determining and Processing Probabilities* [3].

In the books [4],[5] and [6], the protection principles of power systems are explained in detail. These books introduce the different protection systems used in different situations, and their characteristics. *Design and Reliability of Integrated Protection and Control Schemes* [7], *Protection System Faults – A Comparative Review of Fault Statistics* [8] and *Reliability of Protection Systems – Operational Experience* [9] have listed some failure modes of protection systems. Paper [8] also demonstrates the main protection failure type using Norwegian and Finnish fault statistics, while [9] uses the Swedish statistics from 1976-2002.

When it comes to further information about reliability evaluation of substations with protection failures, only a few materials are relevant. However, the studies about reliability evaluation of power systems considering protection failures do offer study methods for substations.

Some methods have been presented for the reliability assessment of power systems with protection failures. As has been mentioned in *Relay Coordination and Protection Failure Effects on Reliability Indices in an Interconnected Sub-Transmission System* [10], *Power System Reliability Indices to Measure Impacts Caused by Transient Stability Crises* [11] and *Static and Dynamic Aspects in Bulk Power System Reliability Evaluations* [12], Sequential Monte Carlo is an option for this study topic.
Another method combining event trees and fault trees is applied in *A Method for Analysing the Reliability of a Transmission Grid* [13], *Design and Reliability of Integrated Protection and Control Schemes* [7] and *A Method for the Probabilistic Security Analysis of Transmission Grids* [14] to evaluate the reliability subject to power system protection failures. Papers [13] and [14] specifically come forward with the method that combines reliability evaluation with dynamic simulation of the reaction of the power system after contingencies.

In this thesis, the main method that is used to study the substation reliability is inspired by paper [7] and [8], which is the event tree.

1.3 Aims and Scope

The protection failures that are mainly studied in this thesis are: the protection system fails to see the failure within its operating zone within time, the protection system fails to send a tripping signal to the circuit breakers, the circuit breakers fail to trip, and a circuit breaker has a delay that is too long that the protection system treats it to be failed.

In reality, the protection system and the circuit breakers can fail as well when there is no component failure at all. However, these spontaneous trips of the circuit breakers or the self-failure of the protection system are complicated to be involved in the reliability model. Moreover, they are only 10% of the total failures and are not dominant fault for the system. Because of modeling difficulties and time limitation, these self-failures are not included in this thesis.

There are two main problems studied in this thesis.

First, the reliability of the substation with several configurations will be analyzed.

The 4/3 circuit breakers substation, 3/2 circuit breakers substation and traditional double busbar substation are the studied configurations. Their reliability will be calculated using the event tree method, and the results will be compared. It will be analyzed whether the structure of a substation has a significant effect on the reliability.

Then, the Maasvlakte 380kV substation will be selected as a case study.

Being one of the most complicated substations in the Netherlands, the Maasvlakte 380kV substation will be taken as a case study in the thesis.

Maasvlakte's reliability with respect to protection failures is calculated using the event tree methods. The results will be combined with a load flow scenario for 2020 and the installed capacity to give a general concept of Maasvlakte substation reliability and average loss of energy per year.

1.4 Thesis Outline

This thesis is organized as follows.

Chapter 1 is a general introduction to the project, including the background explanation, project description, literature overview and objective.

Chapter 2 introduces some basic concepts that are used in this thesis. Failure probability, failure frequency and other reliability concepts are explained first. Then an introduction about substation structures is also given.

Chapter 3 discusses the principles of protection of a substation. The three different types of protections that are used in a substation (Differential Protection, Distance Protection and Busbar Protection) are introduced. How they cooperate with each other to protect the substation against component failures is explained as well.

Chapter 4 explains the reliability evaluation methods used for power systems. The fault tree method, which is mainly used to study the static reliability of the power systems, is introduced first. Then the event tree method, which is used in this thesis is explained.

Chapter 5 mainly studies the effect of different substation structures on the substation reliability. A comparison between a 4/3 circuit breakers substation, a 3/2 circuit breakers substation and a typical double busbar substation is given.

Chapter 6 takes the Maasvlakte 380kV substation as a case and analyses its reliability. The reliability results are combined with a load flow scenario for 2020, and the average loss of energy per year is given.

Chapter 7 gives a review of what has been accomplished in this thesis, discusses the conclusions from this research and makes some conclusions.

Chapter 2 Reliability Concepts & Substation Structures

2.1 Reliability Concepts

The main function of the power system is to provide energy to the customers adequately and efficiently. In the normal situation, the power system is demanded to be highly efficient and safe. If any part within the system has failed, the amount of delivered power can be affected and huge economic losses can be induced, not to mention the safety issues that may follow a fault. Consequently, reliability evaluation of the power system is of significant importance.

2.1.1 Reliability Subdivision

There is no strict single definition of the term “reliability” of the power system. According to the function of the power system, we could define that the term reliability indicates the ability of a power system to fulfill its function [15].

According to the characteristics of the power system, the reliability of a power system is divided into two different aspects: system adequacy and system security [15], as shown in the Fig 1.1.

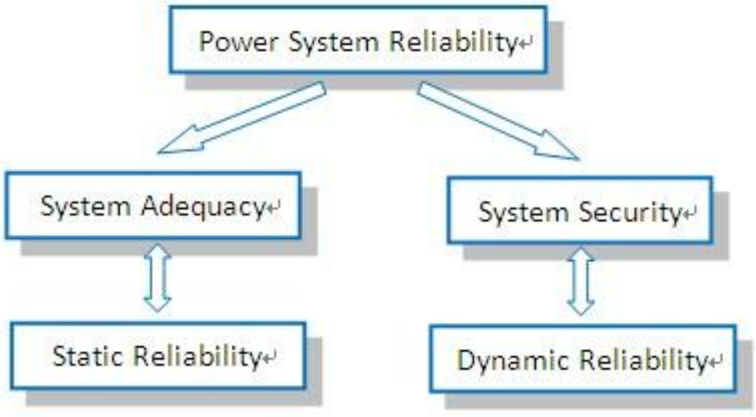


Fig 1. 1 Subdivision of Power System Reliability

System adequacy is related to the static situations. It is used to evaluate whether a system has sufficient devices to ensure it is capable to deliver adequately the energy demanded by the customers. Instead of considering operating situations, the system adequacy focuses more on the system’s designed structure and the installed capacity of the components.

On the other hand, system security evaluates the system’s ability to afford disturbances. It is related to the system transient behavior rather than the system structure only.

The reliability that focuses on the system adequacy is defined as static reliability, while the reliability that concentrates on the system security is called dynamic reliability.

For now, most of the studies about power system reliability, especially substation reliability, are in the static reliability field, i.e. they only consider the connectivity of the system, which is not realistic. Disturbances such as load fluctuation and component outages exist in real world[12]. To involve the system dynamic behavior, such as the protect reaction after a component failure, dynamic reliability evaluation must be applied.

Due to the complexity of the power system protection system, there are only a few studies about dynamic reliability evaluation. Most of these studies take the whole power system instead of a single substation as the case to be studied. In contrast, this thesis will mainly focus on the reliability evaluation of a single substation subject to component-outage disturbances.

The reliability of power systems is mainly dependent on three factors: the incorrect design, incorrect installation and the deterioration in service[6]. In this thesis, the design and installation mistakes are ignored, only the service deterioration will be considered.

2.1.2 Basic Concepts

Before going into the details of reliability evaluation of the substation, there are some basic concepts to defined first. These concepts are described below:

Failure Frequency (f):

The Failure frequency refers to the number of failures that may happen during a time period. In this study, the dimension of the failure frequency is failures per year.

$$f = \frac{\text{Amount of failures}}{\text{Studied period}(\times \text{Circuit length}(\text{for transmission lines/cables}))} \qquad 2 - 1$$

Mean Time to Failure (MTTF):

The average time it takes to the occurrence of a component or system failure measured from t=0.

Mean Time to Repair (MTTR):

The average time it takes to identify the location of a failure and to repair that failure.

Then the relationship between the failure frequency and the Mean Time to Failure is:

$$f = \frac{1}{\text{Mean TIme To Failure+Mean Time To Repair}} \tag{2 - 2}$$

In above equation, the unit for Mean Time to Failure is years.

Reliability (R(t)):

Reliability refers to the probability that a component experiences no failure during a time period, given that it was good at time zero [4].

Failure Probability (Q(t)):

The failure probability is the probability that, under stated conditions, the system or component fails within a stated period. It is identical to unreliability, which is denoted as *F(t)*[4].

$$\mathrm{Q(t)} = 1 - \mathrm{R(t)} \tag{2 - 3}$$

Availability (A):

Availability is the probability that the component is normal at an arbitrary time t, given that it was good at time zero [4].

$$\mathrm{A} = \frac{\mathrm{MTTF}}{\mathrm{MTTF+MTTR}}\text{ [1]} \tag{2 - 4}$$

Unavailability (U):

Unavailability is the probability that the component is down at an arbitrary time t and unable to operate if called upon [4].

$$\mathrm{U} = \frac{\mathrm{MTTR}}{\mathrm{MTTF+MTTR}} = \frac{f \times MTTR}{8760}\text{ [6]} \tag{2 - 5}$$

In the formula above, 8760 in the right part is the total hours of one year, because MTTR is measured in hours.

According to the definition of availability and unavailability:

$$\mathrm{U} = 1 - \mathrm{A} \tag{2 - 6}$$

The concept pairs of reliability/failure probability and availability/unavailability are more or less the same. The difference between them is whether the maintenance of the component is considered. If a healthy component is under maintenance to be checked for its quality, then it is reliable, but unavailable.

The parameters used in this thesis are availability/unavailability. However, taking into account the fact that maintenance time for healthy component in a high-voltage substation is quite small, it is neglected in this thesis.

2.1.3 Reliability Input Data

In the reliability evaluation of power systems, the collection of failure data could be one of the most difficult things because of several reasons.

First, the main subject studied in this thesis is 380kV substation in the Netherlands. The failures of the Dutch power system are stored in the Nestor database. From this database, failure statistics can be derived for the components of the power system. However, the failures of the 380kV system in the Netherlands have only been recorded for the most recent years. Some failure statistics that are recorded in the database are therefore not sufficient enough to be very precise. This is especially the case for EHV cable system components. For system components like overhead lines and transformers, the amount of available failure data is sufficient.

Besides the amount of failures in the data base, the failure modes can also be a reason for impreciseness of the failure statistics. Depending on different failure modes, different environment, and the different operators on field, the repair time of a component can have a very large range. The large range of the repair times can cause an error in the reliability evaluation results as well.

The failure statistics used in this thesis is listed in the table below.

Table 2 - 1 Failure Statistics of Electrical Components Under 380kV

Component	Failure Frequency	failure frequency unit	Data Source	Repair Time (hour)	Unavailability	Data Source
Overhead line(HV)	0.0031	/km	NESTOR(150/110kV,2006-2011)	8	2.83E-06	Equation 2-5
Overhead line(EHV)	0.0022	/km	NESTOR(380/220kV,2006-2011)	8	2.01E-06	Equation 2-5
Cable(Randstad 380) (including joints)	0.0063	/km	CIGRE379(220-500kV)(6 cables/circuit)(+0.006,total for all the terminations)	600	4.32E-04	Equation 2-5
Circuit Breaker	0.003	/comp.	NESTOR(380-110kV,2006-2011)(per set of 3 circuit breakers)	24	8.22E-06	Equation 2-5
Disconnector/ Earthing Switch	0.003	/comp.	NESTOR(380-110kV,2006-2011)(95%-conf.level, per set of three)	8	2.74E-06	Equation 2-5
Busbar	0.003	/comp.	NESTOR(380-110kV,2006-2011)	2	6.85E-07	Equation 2-5
Transformer (EHV)	0.05	/comp.	NESTOR(EHV,2006-2011)	24	1.37E-04	Equation 2-5
Instrument transformer	0.0002	/comp.	NESTOR(380-110,'06-'11)(per phase)	24	5.48E-07	Equation 2-5
Surge arrestor	0.001	/comp.	NESTOR(380-110kV,2006-2011)	2	2.28E-07	Equation 2-5

Compensating Coil	0.004	/comp.	NESTOR(380-110kV,2006-2012)	3	1.37E-06	Equation 2-5
Protection Failure	\	\	\	\	0.0010	VDN(Conditional Probability)
Circuit Breaker Failure	\	\	\	\	0.0015	VDN(Conditional Probability)

As shown in the table above, the voltage level of the listed components is 380kV. For the overhead line, EHV in the table represents for 380/220kV, while HV in the table represents for 150/110kV.

Most of the components' failure frequencies and repair times are derived from the NESTOR database or CIGRE 379 report [16]. Their unavailability is calculated using the equation 2-8.

Failures of the protection system are not recorded separately in the Nestor database. Therefore, for protection system failures, failure data is used from a report published by VDN [17]. For the protection system failures and the circuit breaker failures, a conditional unavailability is given. This conditional probability is the unavailability of the circuit breakers or the protection system, under the condition that a fault has occurred in the system first. In other words, this unavailability does not include unwanted tripping of the circuit breakers, and an overreaction of the protection system.

2.2 Substation Structures

In power systems, substations are used for the transmission and distribution of the electrical power. Generators, transmission lines and distribution lines are connected with the substation for this purpose. There are several different types of substation configurations, as shown in the following figures.

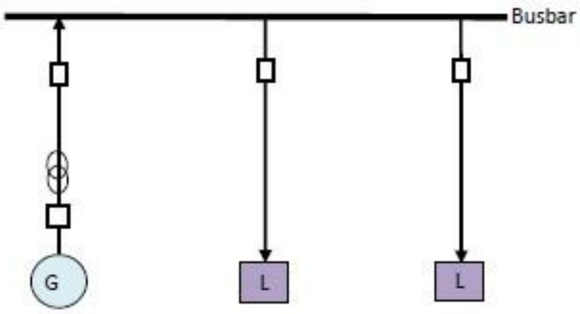


Fig 2. 1 Simplified Single Busbar Substation Configuration

In Fig 2.1, a single busbar substation configuration is shown.

The small block stands for the circuit breakers, purple blocks named “L” represent the loads and blue circles named “G” are the generators. (In the following parts of this thesis, the same symbols are used.)

This single busbar substation has the simplest construction, and its reliability is smaller than the other substation configurations. Normally, in the medium voltage level or the high voltage level, this type of configuration is not used out of reliability consideration.

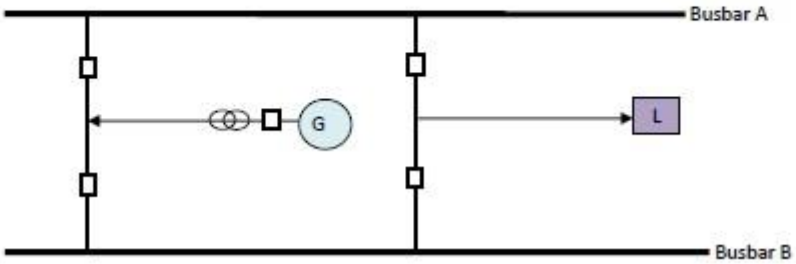


Fig 2. 2 Simplified Two Circuit Breakers Substation Configuration

In Fig 2.2, the two circuit breakers substation configuration is shown.

On each branch, there is only one bay, and two separate circuit breakers are used for the protection of this bay.

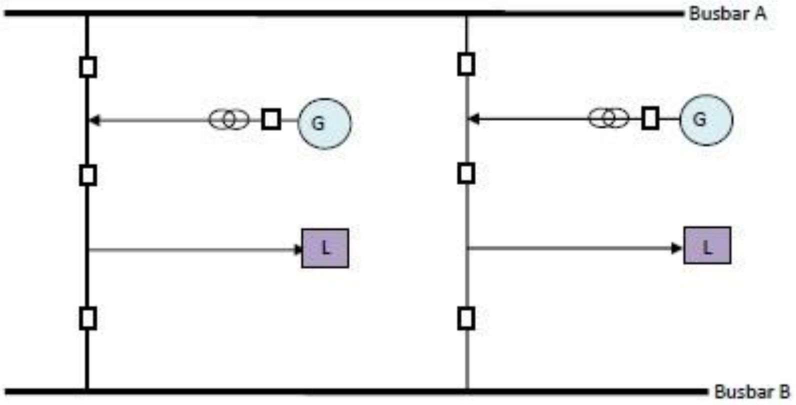


Fig 2. 3 Simplified One-and-a-Half Circuit Breakers Substation Configuration

In Fig 2.3, a one-and-a-half circuit breakers substation configuration is shown.

As can be seen from the figure, on one branch, there are two bays connected with three circuit breakers. Therefore, each bay has 3⁄2 circuit breakers working for itself. That is why this configuration is called one-and-a-half circuit breakers substation.

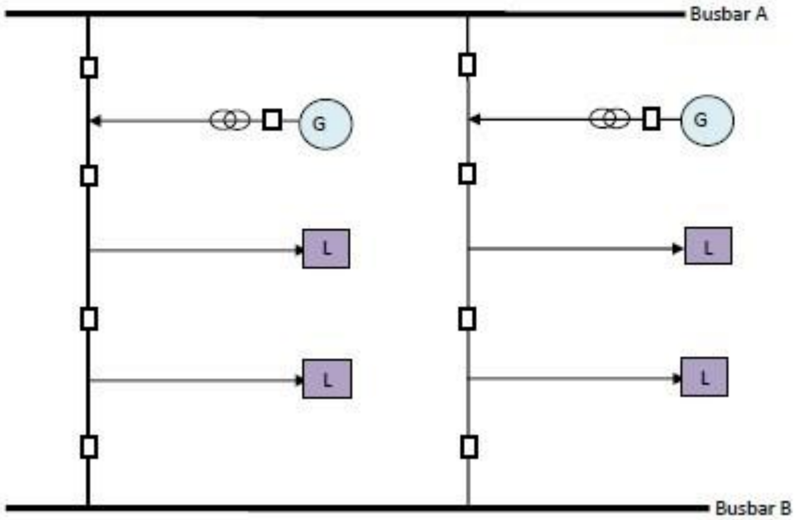


Fig 2. 4 Simplified 4/3 Circuit Breakers Substation Configuration

In Fig 2.4, a 4/3 circuit breakers substation configuration is shown.
This configuration is very similar to the one-and-a-half circuit breakers substation. The only difference is that, on one branch of the 4/3 circuit breakers substation, there are three bays connected with four circuit breakers. Therefore one bay in this configuration shares 4/3 circuit breakers.

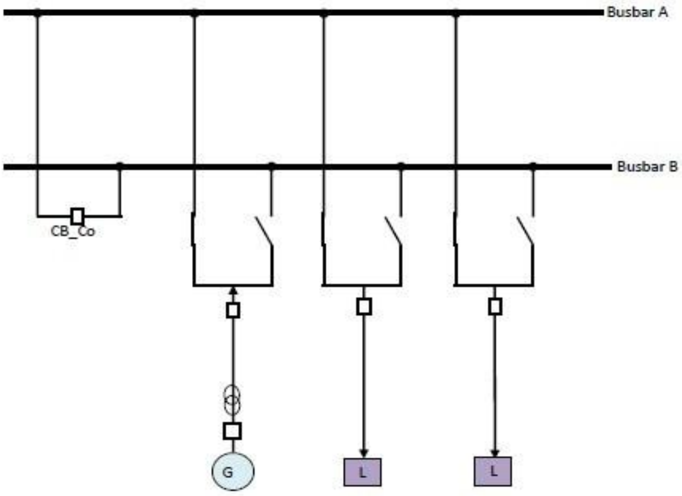


Fig 2. 5 Simplified Typical Double Busbar Substation Configuration

In Fig 2.5, the typical double busbar substation configuration is shown.
Unlike the double/ 4/3 /one-and-a-half circuit breakers substation, a coupling circuit breaker is connected between the two busbars. The loads and the generators are connected to the busbar separately through two disconnecting switches. Under normal situation, only one of the disconnecting switches is closed, therefore the loads and the generators are connected to only one busbar.

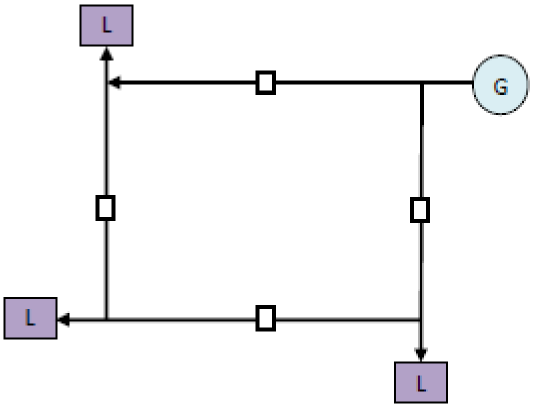


Fig 2. 6 Simplified Ring Substation Configuration

In Fig 2.6, the ring substation configuration is shown.
This substation configuration is connected in a ring shape to improve the reliability, because every load is double fed [18].

In reality, when choosing a substation configuration in the design, there is no absolute right answer. Two main factors have to be taken into account, reliability and costs. However, the substation configuration that is more reliable usually demands higher level protection, and this will lead to an increase of the budget. Moreover, the substation configurations different from the typical double busbar substation are found more difficult to operate by system operators. Therefore, it is necessary for the designers to compare different structures, and try to make a balance between the reliability and costs.

Among the six common substation configurations mentioned above, the single busbar configuration is the simplest and the most unreliable configuration. At medium voltage level and high voltage level networks, it is rarely applied.
The double circuit breakers configuration is more reliable. However, because there are two circuit breakers needed for only one field, the costs of this configuration can be higher than the others. That is why this configuration is also not often applied.
The ring substation has a higher reliability as well, but its complex construction will also increase the costs. Moreover, the complicated construction delivers a higher demand on the substation operators, which may cause more operational mistakes. Consequently, it is also not used frequently in reality.
The remaining three configurations (one-and-a-half circuit breakers substation, 4/3 circuit breakers substation and typical double busbar substation) are mostly used in the high voltage grid design. In chapter 5, a comparison of the reliability of these three configurations is given.

2.3 Conclusion

In this chapter, the subdivision of reliability evaluation of power systems was introduced first. Then, some basic concepts about reliability evaluation, such as reliability, failure probability, failure frequency, mean time to repair, were defined. The failure statistics of power system components in a 380kV system was given.
Moreover, six common substation configurations were listed and explained.

Chapter 3 Protection Principle of the Substation

3.1 Initiating Fault

Inside a Power System Substation, there are several components: generators, step-up transformers, step-down transformers, compensating coils, overhead lines, underground cables, disconnecting switches, circuit breakers, voltage transformers current transformers, and surge arrestors. In this thesis, any fault occurring on those components that will lead to a protection system respond is defined as initiating fault.

An initiating fault can be caused by several different reasons. When there are switching actions or lightning strokes in the substation, some of the components may be subject to transient effects, which could cause an insulation fault. The fault occurring under this situation is called a transient fault. After the fault occurs, the protection system will send the responding circuit breakers a tripping signal to isolate the faulted part. After a short period, the fault path will be cleared and the circuit breakers will perform an auto-reclosure.
Besides, for the components that have been into operation for a long time, the aging of the insulating material can lead to a breakdown mechanism. When a component experiences a breakdown in the last period of its life cycle, this fault is called the permanent fault. Unlike the transient fault, after the tripping of the circuit breakers to isolate the faulted part, there will be no auto-reclosure. After the corrective maintenance or the replacement of the component, the operator on site will put the faulted part back into operation again.
Moreover, the factors in the environment may also cause a component fault, such as birds causing a short circuit or tree branches hitting the line. This type of fault is called semitransient fault [5]. These faults will be removed without maintenance by human.

3.2 Protection Zones

The main responsibility of an electrical power system is to generate and supply energy to the customers. Now that any outage of power can lead to severe interruptions of the whole society’s normal pace, the power system is required to be reliable, efficient and adequate. To assure the power system to be reliable, the protection system of power system has a significantly important role.
According to the IEC standards (IEC 60255-20), the definition of a protection system

is:
A complete arrangement of protection equipment and other devices required to achieve a specified function based on a protection principle.
The protection equipment and devices here refer to equipment such as current transformers, voltage transformers and circuit breakers.

Normally, the responsibility of protection systems is to detect the fault that occurs in the power system and then demand the trip of the responding circuit breakers to isolate the fault area.
When a fault occurs in the power system, to isolate the fault area and prevent the neighboring parts from being affected by this fault, the protection system is designed to use different zones. Normally, to prevent that any part of the power system is left without being protected, the protection zones are arranged to overlap with each other. The boundary of different protection zones are usually defined according to the position of current transformers.

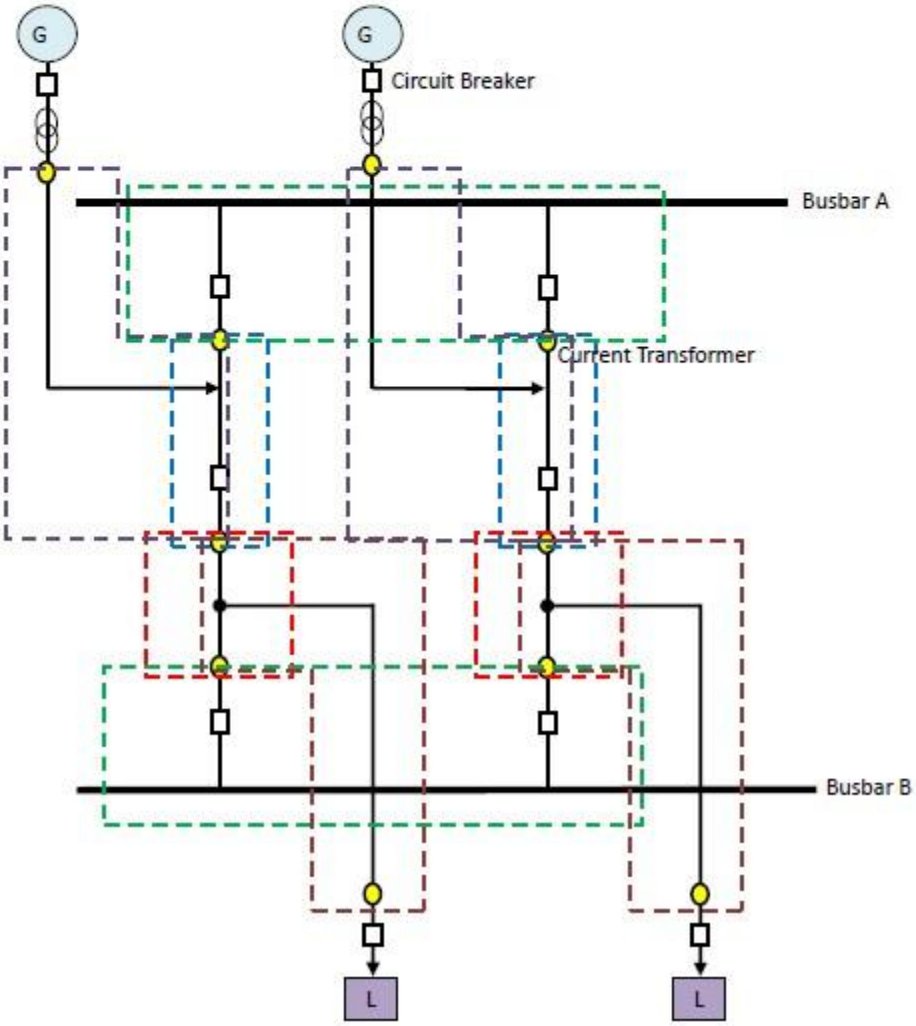


Fig 3. 1 Protection Zones of a Substation

The boundary of protection zones are explained in the Fig 3.1.
In the figure, the small blocks stand for circuit breakers, while the small yellow circles stand for the current transformers. (In the following chapters of this thesis, the same symbols are used.)
The generators are connected to the substation through a step-up transformer and a circuit breaker. The lines are connected to the other substations, and these neighboring substations are assumed to be one single circuit breaker and one current transformer only. In other words, the neighboring substations are assumed to be perfect.

As mentioned above, the boundaries of protection zones are located according to the connection points between protection and power system, which means the position of current transformer. In Fig 3.1, each colored block with dotted lines represents one protection zone. All the area within and outside the substation is covered, and some areas are located in the overlap of two zones.

3.3 Main Protection Principles

There are three main types of protection applied in power system substations: Differential Protection, Distance Protection and Busbar Protection. These coordinate with each other, and offer the substation the ability to withstand initiating faults.

3.3.1 Differential Protection

Differential Protection is based on Kirchhoff's first law. The sum of the current flows into a circuit should be equal to the sum of the current flows out. This protection checks the difference between input and output current for electrical components. If the difference of the current is beyond the normal value, the differential protection will see the fault, and send a trip signal to the corresponding circuit breakers through the telecommunication channel. Consequently, the tripping circuit breakers will isolate the faulted components from the healthy part.
According to the principle of differential protection, at least two current transformers are needed to provide the current measurement, while a telecommunication channel is used to transmit these values.

Based on the components that a differential protection protects, differential protection can be further classified into several types.
In Fig 3.2, the field differential and line differential protection schemes are shown.
There are two substations connected with one overhead line in the figure. On the left side, the red and blue blocks with dotted lines represent the bay differential

protection zones. When a fault occurs within the zone, it will trip the corresponding circuit breakers. For example, if a fault occurs within the red block area, the three current transformers will offer the measurements, which have a larger difference than in the normal situation. The field differential protection will then see the fault, and send the trip signal to circuit breakers CB_A and CB_B. The faulted part then is isolated from the other part of the system.

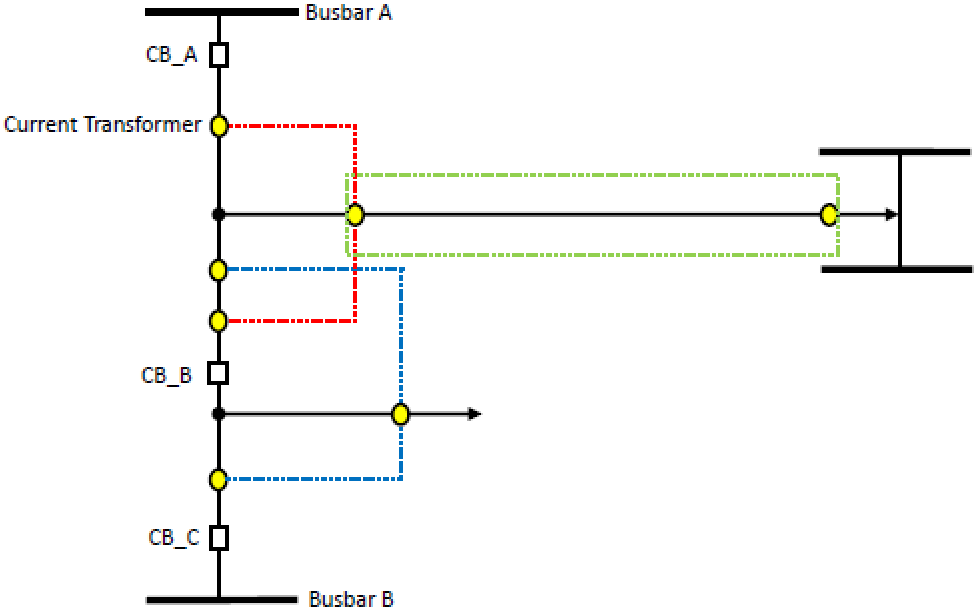


Fig 3. 2 Bay Differential Protection & Line Differential Protection Scheme

The green block with a dotted line in Fig 3.2 represents the line differential protection. If a fault occurs on this line, the two current transformers' measurements will have a larger difference than under normal operation. Then the line differential protection will see the fault and send a trip signal to the corresponding circuit breakers, i.e. circuit breaker CB_A, CB_B and the circuit breaker in the other substation.

Attention has to be paid that, in this scheme there are two current transformers in the middle of the branch, and the protection zones overlap with each other. However, only one current transformer will be installed here in reality out of cost issues. Then there is no overlapping of the field differential protection zone, but every part of the substation is still covered by the differential protection.

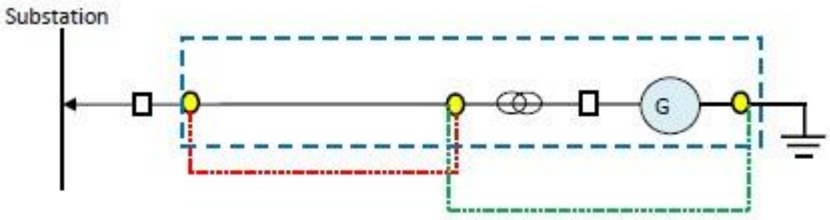


Fig 3. 3 Generator Field Differential Protection Scheme

For a generator that is connected to the substation through a step-up transformer, the differential protection scheme is shown in Fig 3.3.

Usually a generator is connected to the substation by an underground cable in the high voltage design. If a fault occurs in this cable, the fault should lie in the red block area with the dotted lines. The generator field differential protection should see the fault and trip the two nearby circuit breakers shown in the figure.

The transformer and the generator are protected by the combined differential protection. There is a current transformer connected to the neutral ground point of the generator. If any fault occurs in the green block with dotted lines, this combined differential protection should also see the fault and trip the two neighboring circuit breakers shown in the figure.

Therefore, the effect of a fault occurring in the red block and the green block are the same. Combining the red block and the green block, the generator/step-up transformer differential protection zone will be the blue block. Any fault occurring in the blue block area will lead to the reaction of generator/step-up transformer differential protection.

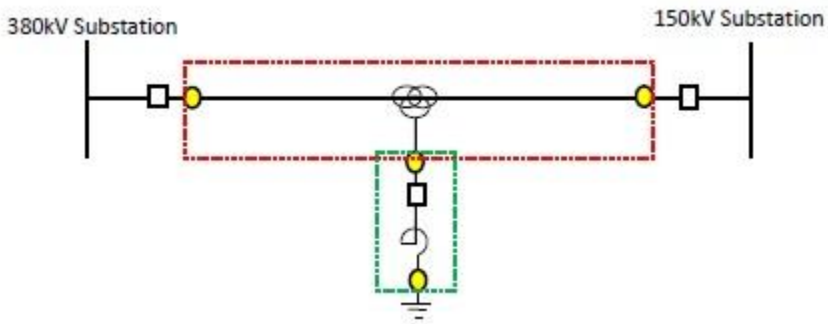


Fig 3. 4 Transformer field differential protection scheme

In some of the substations, a transformer is used to step down the voltage level. As shown in the Fig 3.4, the transformer's voltage level is 380/150/50 kV. On the 50kV side of the transformer, a compensating coil is used.

If a fault occurs in the red block area, the transformer field differential will react and trip all the three circuit breakers shown in the figure. If the compensating coil has failed, the fault lies in the green block, and the differential protection will only trip the circuit breaker on the 50kV side. This fault does not have a big influence on the operation of the transformer.

In brief, there are four types of differential protection used in the substation: field differential protection, line differential protection, generator/step-up transformer differential protection, and transformer field differential protection. Any fault occurring in the protection zone will lead to the reaction of the differential protection, and the nearest circuit breakers will be tripped to isolate the fault.

3.3.2 Distance Protection

Unlike differential protection, the distance protection uses two input parameters to detect the faults: the voltage and current at one point of the line.

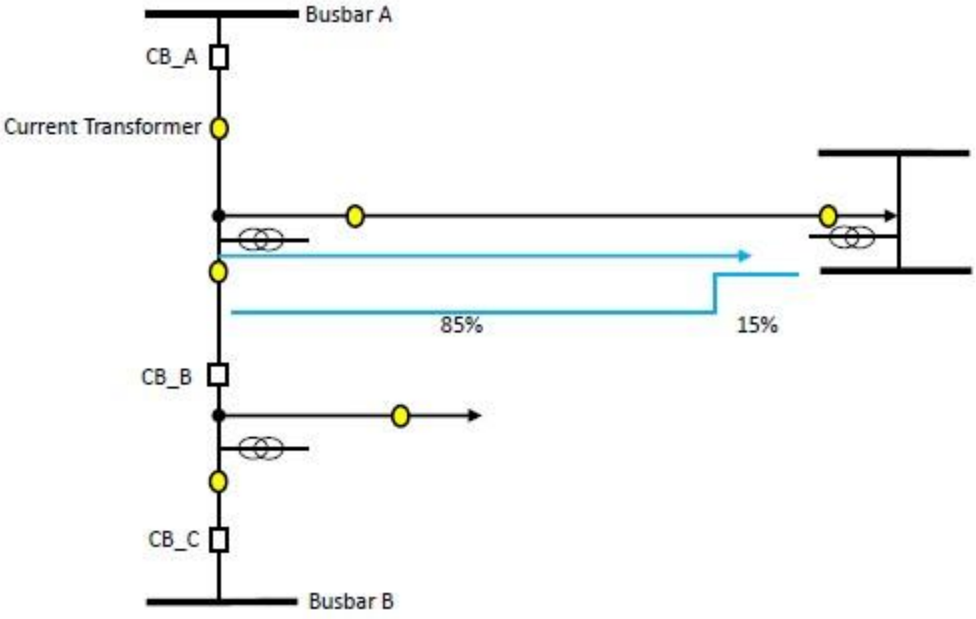


Fig 3. 5 Distance Protection Scheme

Fig 3.5 gives an example of the distance protection scheme for a line.

At the starting point of the blue arrow, there is one current transformer and one voltage transformer. These measure the current and voltage at this point, which is called the relaying point. After getting the measurements, the ratio between the voltage and the current is calculated. The result is equivalent to the line impedance. Rather than depending on the actual values of voltage and current, an ideal distance protection only compares the ratio with actual line impedance [5]. If the measurements do not fit with the expectation, the distance protection will see the fault and clear it by tripping the circuit breakers at both end of the line.

In Fig 3.5, the distance protection starts from the relaying point and reaches the end of the line in the direction of the blue arrow. The first 85% of the line is cleared by the distance protection immediately after the fault occurs, while it takes 230 ms delay before clearing a fault in the last 15% of the line. On the other side of this line, a same distance protection with opposite direction is also available. If the fault occurs on this line, both distance protections should see the fault. If the protection system in the neighboring line does not work, the distance protection on this side will act as a back-up protection for the neighboring side after 440ms.

3.3.3 Busbar Protection

In the power system substation, the busbar is often not protected separately, especially in the low voltage network. There are three reasons that can explain this. First of all, unlike other components such as the transformers, the busbar has a high degree of reliability. Besides, the busbar protection system is expensive. Considering the busbar's high reliability, the risk is sometimes affordable. Moreover, the mistaken operation of the busbar protection can lead to a widespread substation outage. Because of the reasons mentioned above, the busbar protection is not frequently applied in the low voltage substations.

However, in the high voltage substation, to assure the system's reliability and safety, the busbar protection is applied.

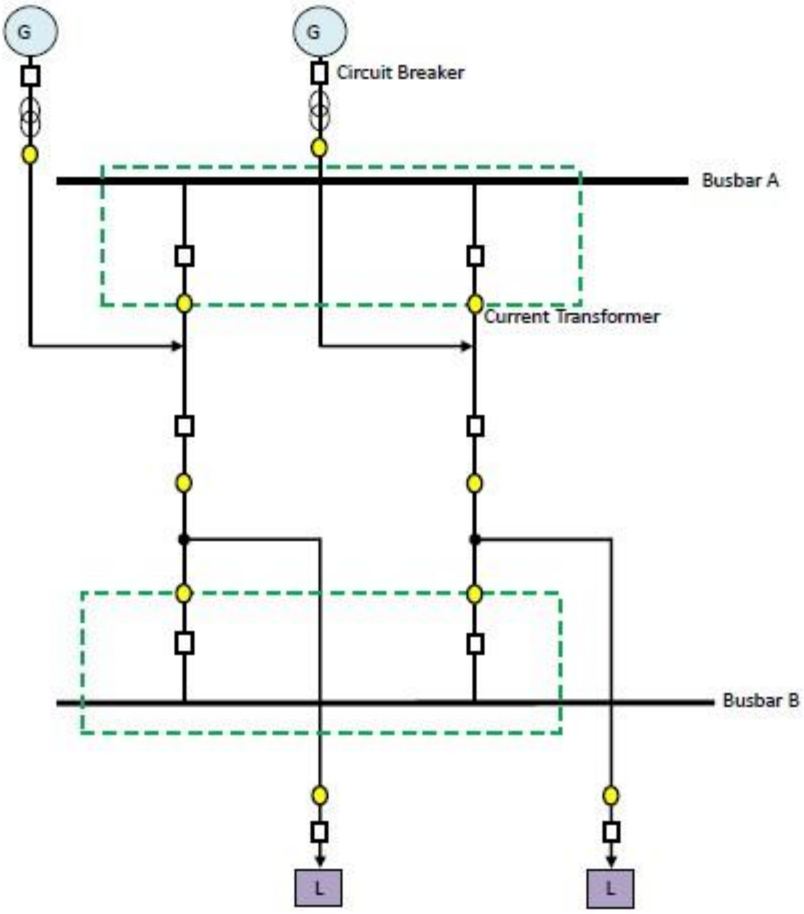


Fig 3. 6 Busbar Protection Scheme

The Fig 3.6 shows the scheme of a busbar protection.

Similar to the differential protection, the busbar protection takes the current transformers' measurements as reference. When a busbar fault occurs, it should be in the green block with the dotted lines in Fig 3.6. Consequently, the two current transformers will give different measurements of the currents, and the busbar protection will see the fault and clear it by tripping the two circuit breakers in the green block.

3.4 Protection Failures

In chapter 3.3, three types of protections were introduced. These coordinate with each other in a substation, and trip the corresponding circuit breakers to isolate the fault area.

In most of the reliability studies of power systems, the protection systems are assumed to be perfect because of modeling difficulty. The protection system consists of current transformers, voltage transformers, circuit breakers and so on. Each of them has a probability to fail, which makes protection failures to be an interesting and challenging subject to study.

3.4.1 Protection System Failures

The protection system is used to protect the power system from having a widespread fault. However, the protection system itself can also fail. If the current transformers or the voltage transformers fail, it is possible that they offer the wrong measurements to the protection system and the protection system may fail to see the fault. Besides, the comparison of the measurements is enabled by the telecommunication channel. A failure of this telecommunication channel can lead to a protection system failure as well. Moreover, after the protection system finds out the fault successfully, it has to send a signal to the associated circuit breakers, which can also fail.

To prevent widespread outages caused by failures of the protection system, in power systems, each component must be protected by two completely separated protection systems. If the primary protection does not work successfully, the back-up protection will fulfill this responsibility. The back-up protection can be regarded as either local or remote [6].

In Fig 3.7, an example of a primary protection and local back-up protection is given.

The line that is connected between two substations is covered by the red block and green block with the dotted lines. This line is protected by the field differential and line differential protection as primary protection. If the differential protection fails, the distance protection from the left side substation will react as a back-up protection after a time delay, usually 170ms.

If the back-up protection fails to fulfill this responsibility, both distance protections at

both line ends should react.
In this thesis, the back-up protection is assumed to be perfect, i.e. it will never fail.

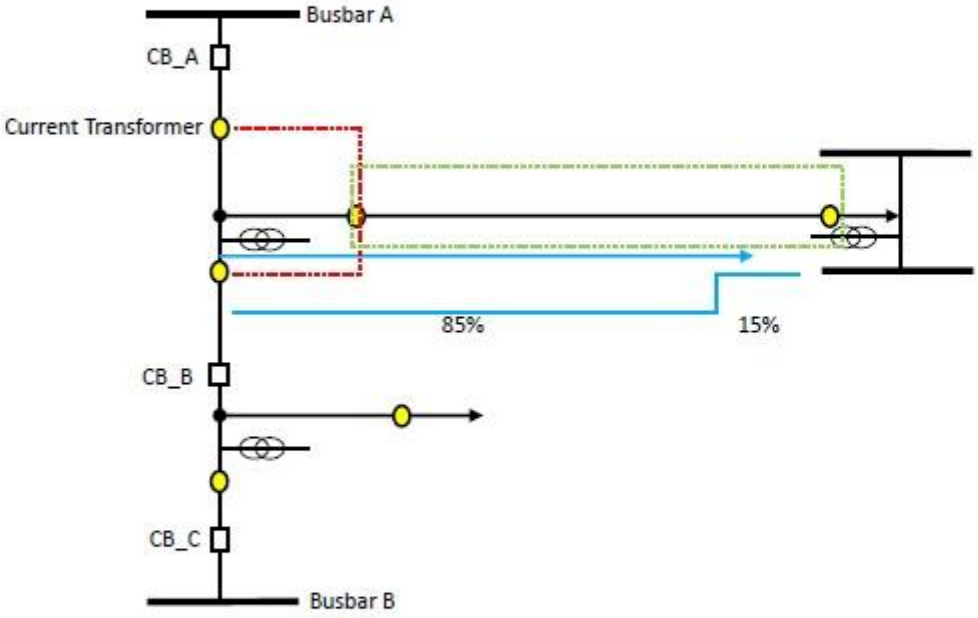


Fig 3. 7 Primary protection and Local Back-up Protection Scheme

3.4.2 Circuit Breaker Failures

After a protection system successfully detects the fault in the system, it will send a signal to the associated circuit breakers. The circuit breakers will then respond to the command and trip. In reality, there is a chance that the circuit breakers refuse to trip, or have such a long delay that the protection system considers it to be failed.

When having a circuit breaker failure, a function called circuit breaker failure function is applied to make sure that the faulted part is isolated. In the Netherlands, this circuit breaker failure function is called SRBV, which is short for “Schakelaar Reserve Beveiliging”.

There are two criteria that have to be satisfied to activate the circuit breaker failure function:
Criteria 1: Both the primary protection and the back-up protection see the fault.
Criteria 2: In one of the protections the circuit breakers are not tripped successfully.

Take the line in Fig 3.7 as an example.
The line is protected by two different protection systems. The primary protection is the differential protection, while the back-up protection is the distance protection in the direction of the blue arrow.

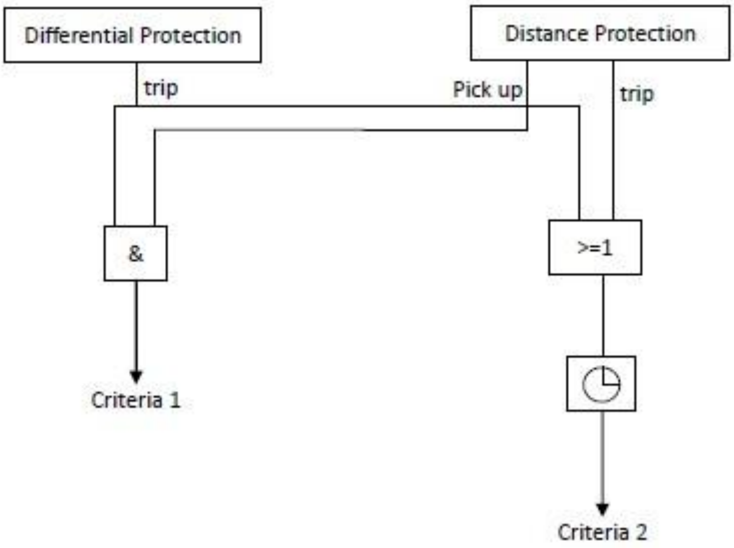


Fig 3. 8 Circuit Breaker Failure Function Principle

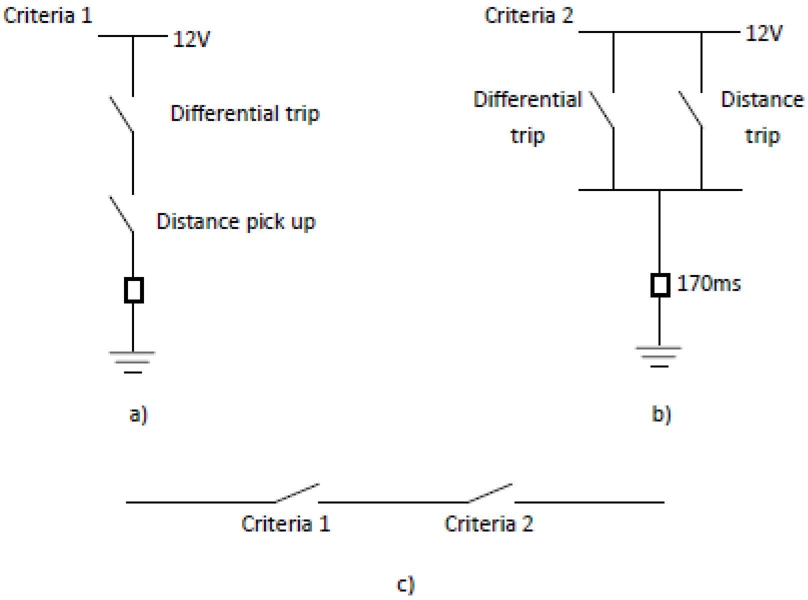


Fig 3. 9 Circuit Breaker Failure Function Criteria

The two criteria are shown in Fig 3.8 and Fig 3.9. Fig 3.8 explains the circuit breaker failure function by the AND Gate and OR Gate, while Fig 3.9 explains the same principle by a series and parallel circuit connection.

As can be seen from the Fig 3.8, for the differential protection, when it sees the fault, it will pick up the fault and trip at the same time. For the distance protection, the pick-up and trip process can happen at a different time.

The two criteria are in series connection, which is shown in Fig 3.9 c). This demonstrates that the circuit breaker failure function will only be activated when the two criteria are satisfied at the same time.

If a fault occurs on the line in Fig 3.7, the differential protection and distance protection should all pick-up the fault at the same time, and the differential protection will trip immediately. The criterion 1 is satisfied. As shown in Fig 3.8 a).
At the same time, criteria 2 will also be satisfied after a time delay (170ms), as shown in Fig 3.8 b).

If the circuit breakers that are associated with the differential protection system work successfully, the fault will be cleared within 170ms. Then criteria 1 will not be satisfied and the circuit breaker failure function will not be activated.

If the circuit breakers tripped by the differential protection system fail, the fault will remain in the system after 170ms. The criteria 1 and criteria 2 will both be satisfied and the circuit breaker failure function will be activated.

Care has to be taken that the circuit breaker failure function will only be activated when the circuit breakers fail. If the protection system fails, the criterion is not satisfied and the circuit breaker failure function will not react.

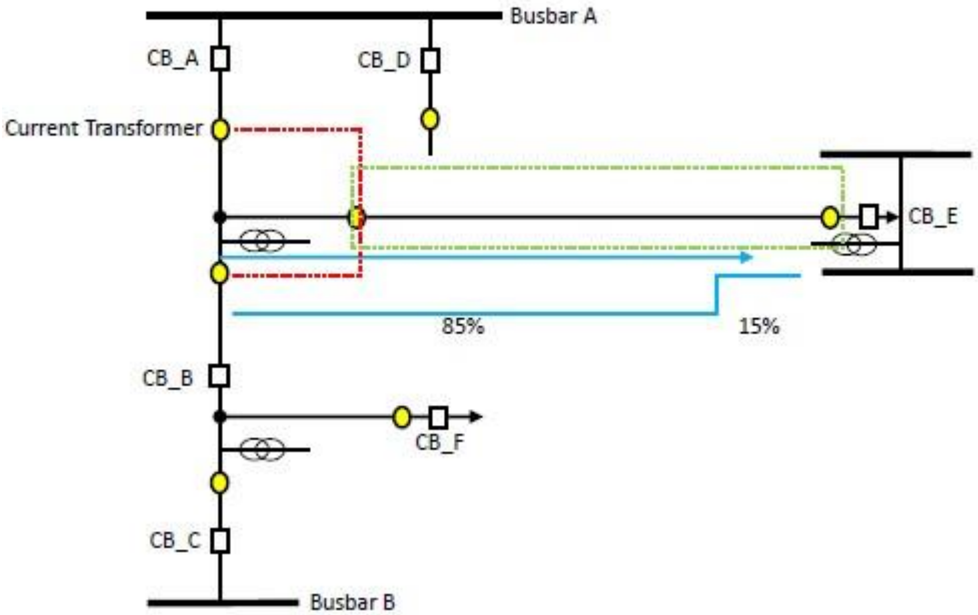


Fig 3. 10 Example of Circuit Breaker Failure Function

After the circuit breaker failure function is satisfied, it will trip the most nearby circuit breakers.
Still take the line in Fig 3.7 as an example. The circuit breakers are added in Fig 3.10.

When a fault occurs on the line, the differential protection should see the fault and send the circuit breakers CB_A, CB_B, and CB_E a tripping signal. CB_E belongs to the other substation and it is assumed to be perfect in this thesis. If one of CB_A and CB_B fails to trip, the circuit breaker failure function will be activated. Because there is no way to identify exactly which circuit breaker fails in a short time, all the circuit breakers that are next to these three circuit breakers will be tripped, i.e. CB_C, CB_D, CB_F.

In brief, when a fault occurs and one of the circuit breakers fails to trip, the circuit breaker failure function will trip all the neighboring circuit breakers to isolate the fault.

3.4.3 Non-system Faults

The task of a protection system is to detect the initiating fault and trip the associated circuit breakers. However, an unwanted operation of protection system which leads to a system disturbance happens sometimes, for example, the spontaneous tripping of circuit breakers. The unwanted operations are called non-system faults. According to [9], about 25.3% of the power system faults are non-system fault.

Due to the modeling difficulties and time limitation, the non-system faults will not be studied in this thesis, but they do have an effect on the system reliability.

3.5 Conclusion

In this chapter, the basic protection principles of power system substation were introduced.

The three main types of protection system: differential protection, distance protection and busbar protection were explained first. Then the relationship between primary protection and back-up protection was discussed. The circuit breaker failure function was explained as well.

Chapter 4 Methods for Reliability Evaluation in Power Systems

4.1 Introduction

There are several methods that can be used for the reliability evaluation of the power system. The mostly used methods are fault tree analysis, event tree analysis, Monte Carlo simulation and State enumeration. To study the static reliability, fault tree analysis, Monte Carlo simulation and State enumeration are used frequently. When it comes to the dynamic reliability evaluation, event tree analysis and Sequential Monte Carlo are better choices.

The major subject of this thesis is the high voltage substation reliability considering protection failures, which belongs to the dynamic reliability evaluation field. The method chosen in this thesis is the event tree method combined with the fault tree method.

In the following part of Chapter 4, a detailed introduction of the fault tree method and the event tree method will be given, while the Monte Carlo method is also introduced briefly.

4.2 Fault Tree Analysis (FTA)

4.2.1 Basic Concepts

Fault tree analysis was originally developed in the 1960s by Bell Laboratory [19]. Since then, it is used widely spread in many different fields for the purpose of reliability evaluation.

Being a traditional anti-causal evaluation method, fault tree analysis can build a diagram of all the elements that may contribute to a system failure, and then trace back the groups of elements that will necessarily lead to the system’s undesired situation[20]. The relationship between basic components and the undesired situation can be clearly demonstrated by this oriented graph.

An example of a fault tree is shown in the figure below.

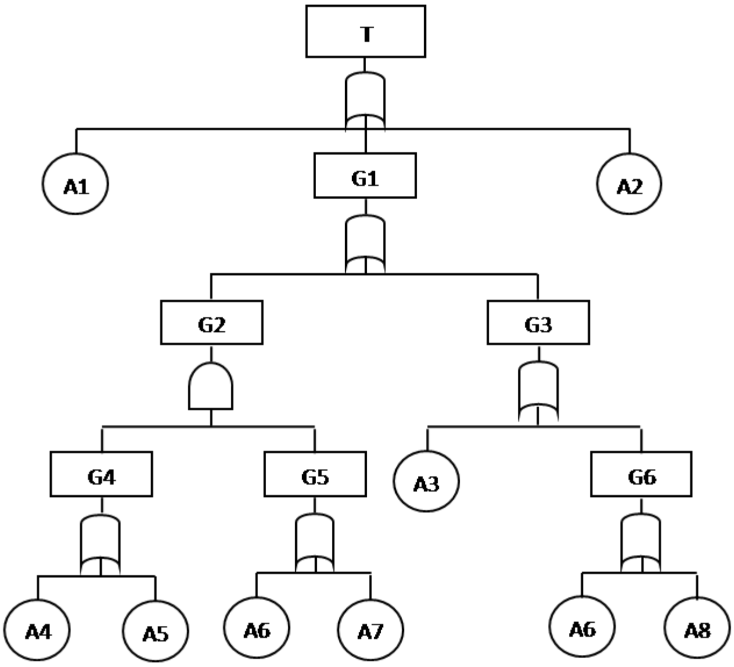
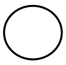


Fig 4. 1 an example served for demonstration of the fault tree principle

There are four types of symbols in the example given above:

Basic Event:

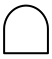


A Basic Event refers to a single initiating fault that could not be developed any further. Basic Events must be independent from each other.

Intermediate Event:

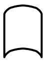
An Intermediate Event refers to an event that is caused by two or more antecedent events acting through logic gates.

AND Gate:



An AND Gate means that when all the input faults occur, the output fault event will occur.

OR Gate:



An OR Gate means that when one or more than one of the input faults occurs, the output fault event will occur.

The fault tree needs to be read from top to bottom.

Set Fig 4.1 as an example. In this fault tree, the rectangle marked as “T” in the top represents the top event. It refers to the undesired situation which is caused by the

basic events acting through the AND Gates and OR Gates.
In this case, the top event is connected to A1, G1 and A2 through an OR Gate, that means when one or more than one of A1, A2 and G1 occurs, the top event will occur. G1 is connected to G2 and G3 through an OR Gate, therefore G1 will occur when one of or both G2 and G3 occur. G2 is connected to G4 and G5 through an AND Gate. Then G2 will not occur until both G4 and G5 occur. Repeat these steps until all the logical relationships have been covered.

For the small series system shown in the following figure, the fault tree is drawn in Fig 4.3.

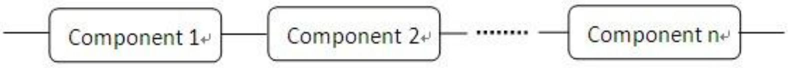


Fig 4. 2 A Series Connection System

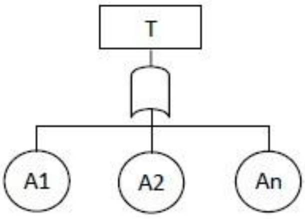


Fig 4. 3 Fault Tree for the Series Connection System

For the series connection system, if any component within the system fails, the system will fail. Therefore, a simple fault tree with one stage using an OR Gate is built. In Fig 4.3, A1, A2, and A3 refer respectively to the fault of component 1, 2, and 3. If one or more than one component fault occurs, the top event T – system failure will occur.

For the small parallel system shown in the following figure, the fault tree is shown in Fig 4.5.

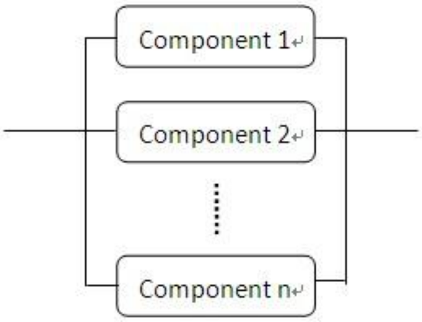


Fig 4. 4 A Parallel Connection System

For the parallel system, the system will fail only when all of the components fail.

Therefore it has a simple fault tree with only one stage using an AND Gate. Similar to the series system mentioned above, A1, A2, and A3 refer respectively to the faults of component 1, 2, and 3. The top event – system failure will not occur until all of the component faults occur.

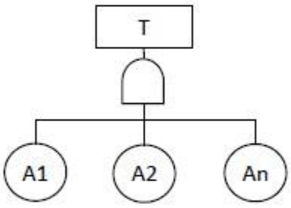


Fig 4. 5 Fault Tree for the Parallel Connection System

4.2.2 Fault Tree Calculation

After the construction of the fault tree has been accomplished, the problem how to calculate the fault tree both qualitatively and quantitatively comes forward.

For a fault tree with more than one stage, the cut set method is applied to solve this problem. A cut set is any set of basic events that together will lead to the top event. A minimal cut set is any set of basic events that causes the top event. Those basic events cannot be reduced any further. According to the minimal cut sets of a system, the probability of the undesired situation can be easily calculated. Moreover, the weakness of a system can be easily revealed by minimal cut sets, which has a significant meaning in reliability analysis.

Boolean Algebra is the method used to calculate the minimal cut sets[20]. The relationship between the top event and the basic events is expressed by formulas through Boolean algebra. Since the fault trees that are used in this thesis consist of one stage only, the Boolean algebra will not be introduced here in detail.

For the fault tree with only one stage, the calculation is very simple.

For the fault tree of the series connection system shown in Fig 4.3:

$$\mathrm{R(system)} = \mathrm{R(1)} \times \mathrm{R(2)} \times \ldots \mathrm{R(n)} \quad [21] \qquad 4-1$$

$\mathrm{R(n)}$ means the probability that component n is functioning in a given period[1].

For the fault tree of the parallel connection system shown in Fig 4.5:

$$\mathrm{Q(system)} = \mathrm{Q(1)} \times \mathrm{Q(2)} \times \ldots \times \mathrm{Q(n)} \qquad 4-2$$

$$\mathrm{R(system)} = 1 - \mathrm{Q(system)} \qquad 4-3$$

$Q(n)$ refers to the failure probability of component n in a given period.

The availability/unavailability use the same equations as shown in 4-1, 4-2, 4-3.

4.3 Event Tree Analysis

4.3.1 Basic Concepts

When applying the fault tree analysis in the reliability evaluation of power systems, it is mostly focused on the connectivity of the system, which is static reliability. For the reliability evaluation that includes protection failures, event tree analysis offers a better solution.

The event tree analysis method is frequently used in nuclear power plants to assure safety. Being an inductive analytical diagram, the event tree presents the system possible outcomes after the injection of an initiating event. The logical process of the system's response to the initiating event is demonstrated by the event tree both qualitatively and quantitatively.

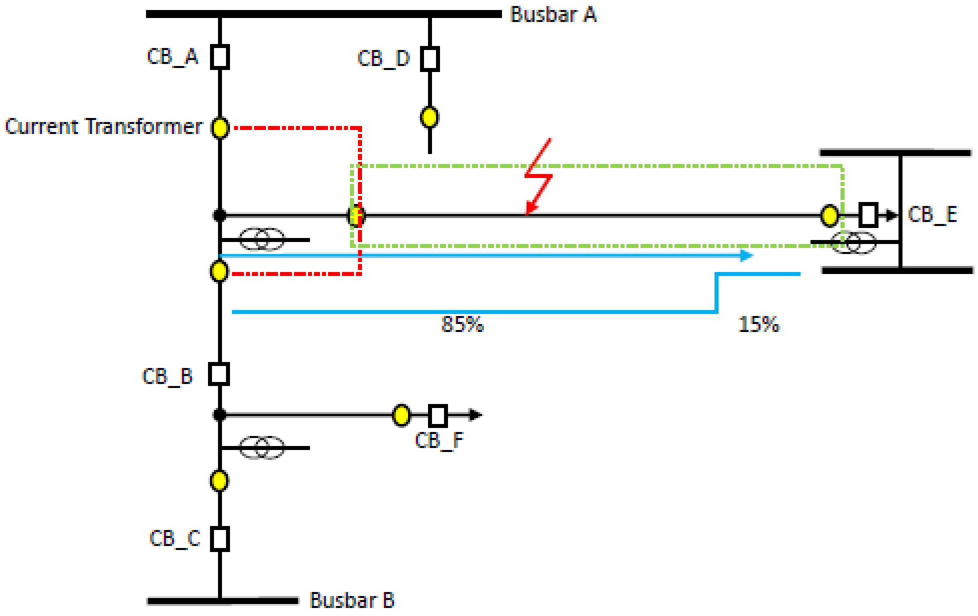


Fig 4. 6 Example of Line Fault near a Substation

In Fig 4.7, the event tree example for the line fault in Fig 4.6 is given. Some colored blocks are added to demonstrate the structure of the event tree clearly.

The event tree should be read from the left to the right. And each event branch has two outputs, which represent the failure and success of this event.

The blue, pink, purple and yellow blocks on the left side of the tree represent different events. The blue block named ‘initiating event’, refers to the line fault in this case. The pink block represents the primary protection, which is the line differential protection in this case. If the primary protection works successfully, the associated circuit breakers should trip as the next step, which is represented by the purple block. If the primary protection fails, no circuit breakers will be tripped. Instead, the back-up protection (distance protection in the direction of the blue arrow in this case) should react, represented by the yellow block.

The green and red blocks on the right side of the tree represent the end state. Success refers to no protection failures, and vice versa for a failure. When both the primary protection and circuit breakers function well, there is no protection failure, and the fault will be cleared successfully, namely state 1. If the primary protection sees the fault, but the associated circuit breakers fail, the circuit breaker failure function will be activated and trips the circuit breakers next to the firstly associated ones. When the primary protection fails, but the back-up protection works successfully, the fault will be cleared after a time delay. For the situation where both the primary protection and the back-up protection fail, the chance is so small that it is not considered in this thesis.

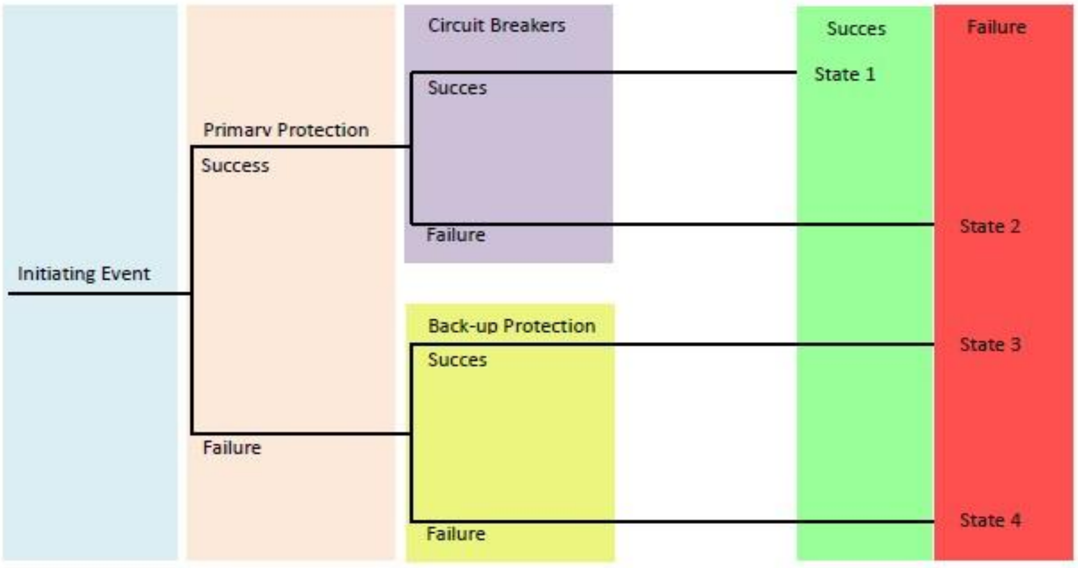


Fig 4. 7 Event Tree Example for the Line Fault in Fig 4.6

The end state of this tree is described in the following table.

Table 4 - 1 End State Description of the Event Tree in Fig 4.7

State Number	State description
1	Primary protection (Line Differential Protection) works successfully; Associated circuit breakers(CB_A,CB_B,CB_E) trip successfully; Fault cleared immediately; Only the faulted line/generator will be isolated;
2	Primary protection (Line Differential Protection) works successfully; One or more than one of the associated circuit breakers(CB_A,CB_B,CB_E) fails to trip; The circuit breaker failure function is activated, the next level circuit breakers (CB_D, CB_C,CB_F and the circuit breakers within the other substation) are tripped; Fault cleared after a time delay; Besides the faulted line/generator, the neighboring lines/generators are isolated because of the circuit breaker failure function.
3	Primary protection (Line Differential Protection) fails; Back-up protection (distance protection) works successfully; Fault cleared after a time delay; Normally, only the faulted line/generator will be isolated because back-up protection trips the same circuit breakers as the primary protection does.
4	Primary protection (Line Differential Protection) fails; Back-up protection (distance protection) fails; Not considered;

4.3.2 Event Tree Calculations

There are several commercial software packages for the construction and calculation of event trees, such as Risk Spectrum. However, for event trees with events that are independent from each other, the calculation is quite simple, and could be done by Microsoft Excel[22].

Still use the event tree in Fig 4.7 as an example, its calculation with Excel is shown in the following figure.

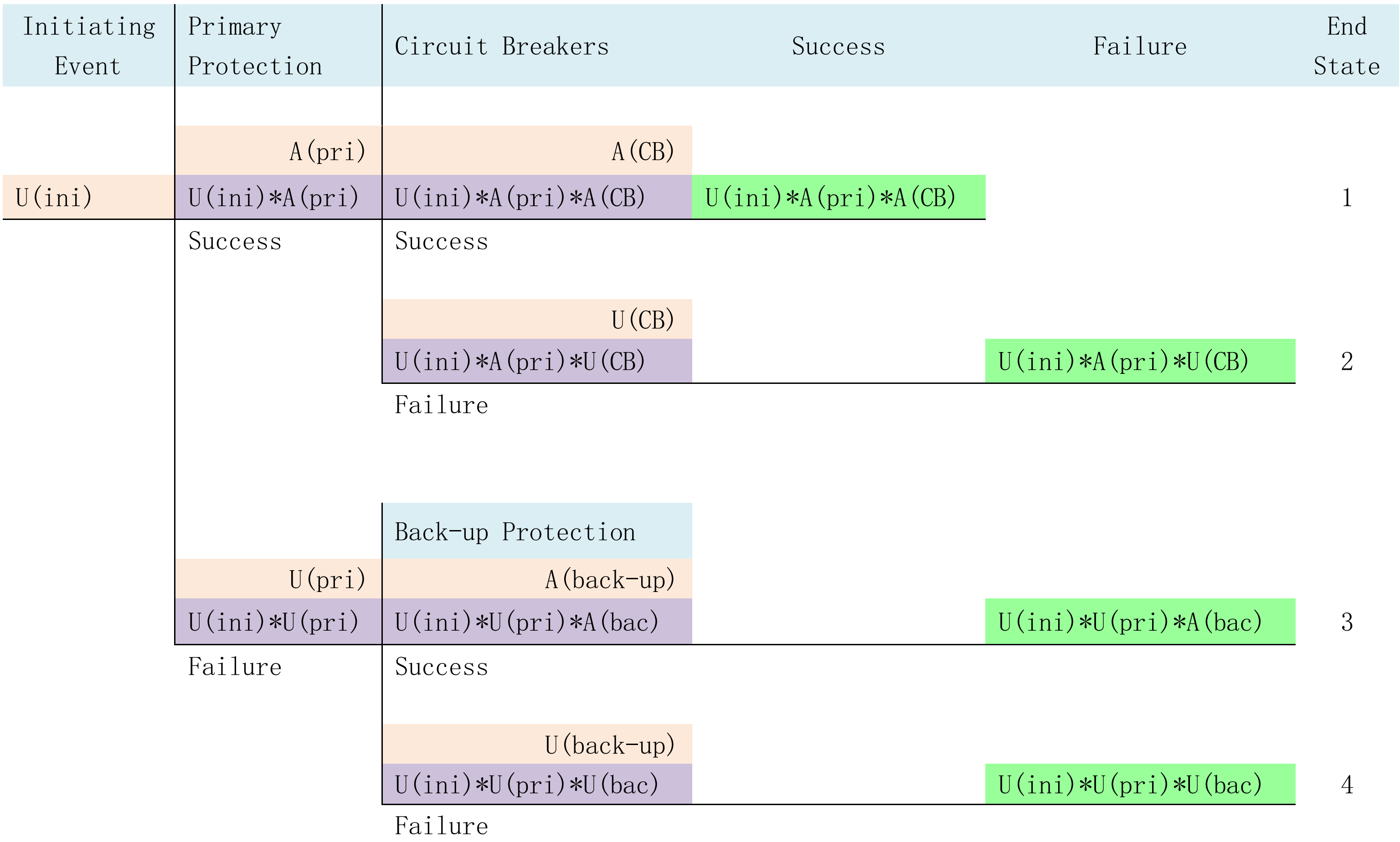


Fig 4. 8 Example for the Event Tree Calculation

In Fig 4.8, the blue blocks are the event names. The pink blocks stand for the input data, the purple blocks stand for the calculation process, while the green blocks show the output.

U(X) represents the unavailability of the event X.

A(X) represents the availability of the event X.

When the events are independent of each other, the event trees can be calculated simply with the products of the probabilities along the tree branch.

Take the end state 1 as an example.

When both the primary protection and the circuit breakers work successfully, state 1 will be reached. The input on this branch is U(ini), A(pri), and A(CB). These refer to the probabilities of the initiating failure event, a working primary protection, and working circuit breakers respectively. The probability of state 1 can be calculated by multiplying the probability of each event along the tree branch, i.e.

P(state 1) = U(ini)*A(pri)*A(CB) 4 - 4

If we change the input data of the initiating event from its unavailability to its failure frequency while keeping the conditional probabilities of a protection failure and a circuit breaker failure, the output of the tree will also change to a failure frequency.

Still use end state 1 as an example.
The input data of the initiating event now is the failure frequency, f(ini). The expected frequency that state 1 happens is:
$f(\text{state 1}) = f(\text{ini})*R(\text{pri})*R(\text{CB})$ 4 - 5

4.4 Combination of Initiating Events

Event tree analysis is the main method used in this thesis. However, fault tree analysis is also applied to get the input of the event trees.
There are many components in power system substations and a failure of the components that are located in the same protection zone will cause the same effect. Therefore, to reduce the amount of event trees, components in the same protection zone will be combined into one unit. When one or more than one of the components in this zone fails, the protection system will react. Consequently, the fault tree analysis is needed to calculate the unavailability of this “unit”. The result will be the initiating event probability for the event tree.

This combination of event tree analysis and fault tree analysis will be further explained by a case study in Chapter 5.

4.5 Conclusions

There are several methods that can be used for reliability evaluation of power systems. In this thesis, event tree analysis is combined with fault tree analysis to evaluate the reliability of a high voltage substation with protection failures.
The principle of fault tree analysis and event tree analysis was explained in detail in this chapter. The calculation of both methods was demonstrated by examples. Last but not the least, the reason for combining fault tree and event tree analysis in this thesis was explained.

Chapter 5 Comparison between the Reliability of Different Substation Constructions

5.1 Introduction and Assumptions

As has been mentioned in Chapter 2.2, when designing a substation, several different configurations can be used. The substation must transport and distribute electricity power to the customers, not only adequately, but also safely.
Currently, there are only a few studies that focus on the reliability of substations including protection failures. To give a general feeling about the effect of a substation configuration on the reliability, three mostly used substation configurations (4/3 circuit breakers substation, one-and-a-half circuit breakers substation and typical double busbar substation) are analyzed in this Chapter. The results of their reliability evaluation are compared.

Before analyzing the reliability of the substations, several assumptions are made first.

a. The substation is operating at 380kV.
b. The earthing switches and surge arrestors inside the substation do not have a significant effect on the substation reliability and are neglected in this chapter.
c. The generators do not belong to the substation. Therefore, generator failures are not considered in this study.
d. In this chapter, the components that are considered to have a chance to fail are: busbar, circuit breaker, disconnecting switch, current transformer, voltage transformer, step-up transformer, step-down transformer, line connected to the substation, cable connected to the substation.
e. In this study, the line and cable connected to the nearby substation is involved in the reliability model, i.e. the line/ cable fault will lead to a protection reaction.
f. The neighboring substations are assumed to be perfect for modeling convenience. These are assumed to consist of one perfect circuit breaker which will never fail.
g. For all three types of substation configurations, there are six generators/lines connected to the substation: two generators and four lines. Two of the lines are connected to 150kV substations. Their detailed description is shown below in Table 5 - 1.
   The data of the line or cable length is derived by using real data of a 380kV substation in the Netherlands (Maasvlakte 380kV substation) as a reference.
h. The back-up protection systems and the back-up circuit breakers are assumed to be perfect in this study.

Table 5 - 1 Description of the Generators/Lines Connected to the Substation

Name	Description	Data
G1	Connected to the substation through a high voltage cable.	Cable length: 5km
G2	Connected to the substation through a high voltage cable.	Cable length: 5km
L1	Connected to another 380kV substation	Line length: 20km
L2	Connected to another 380kV substation	Line length: 20km
L3	Connected to a 150kV substation through a 380kV/150kV/50kV step-down transformer. 380kV side: cable 150kV side: line	380kV side cable length: 0.5 km 150kV side line length: 0.3 km
L4	Connected to 150kV grid through a 380kV/150kV/50kV step-down transformer. 380kV side: cable 150kV side: line	380kV side cable length: 0.5 km 150kV side line length: 0.3 km

5.2 Reliability Evaluation for the 4/3 Circuit Breakers Substation

5.2.1 Substation Configuration

In Fig 5.1, the configuration of a 4/3 circuit breakers substation is shown.
The blue circles named "G" represent the generators, while the purple blocks named "L" refer to the lines.
For the 4/3 circuit breakers substation, on each branch there are three fields. Therefore, two branches are needed to satisfy the assumption of "2 generators and 4 lines connected to the substation".

The generators are not connected directly to the same busbar in this configuration, in case of circuit breaker failure. If there is a busbar fault, and one of the circuit breakers associated with the busbar protection fails, the neighboring circuit breakers should be tripped to isolate the fault. Then the line/generator connected directly to this busbar will be isolated for a period. If all the generators are connected to the same busbar, these will be lost at the same time in this situation. To ensure that there is always a power input in the substation, the generators must be connected to different busbars.

As mentioned above in the chapter 5.1, the neighboring substations are assumed to consist of one perfect circuit breaker. Take line 1 as an example. CB_L1 represents the neighboring substation and the studied substation is connected to CB_L1 through line 1. On the neighboring substation side, there is also a current transformer to realize the line differential protection of line 1, which is considered to have a chance to fail.

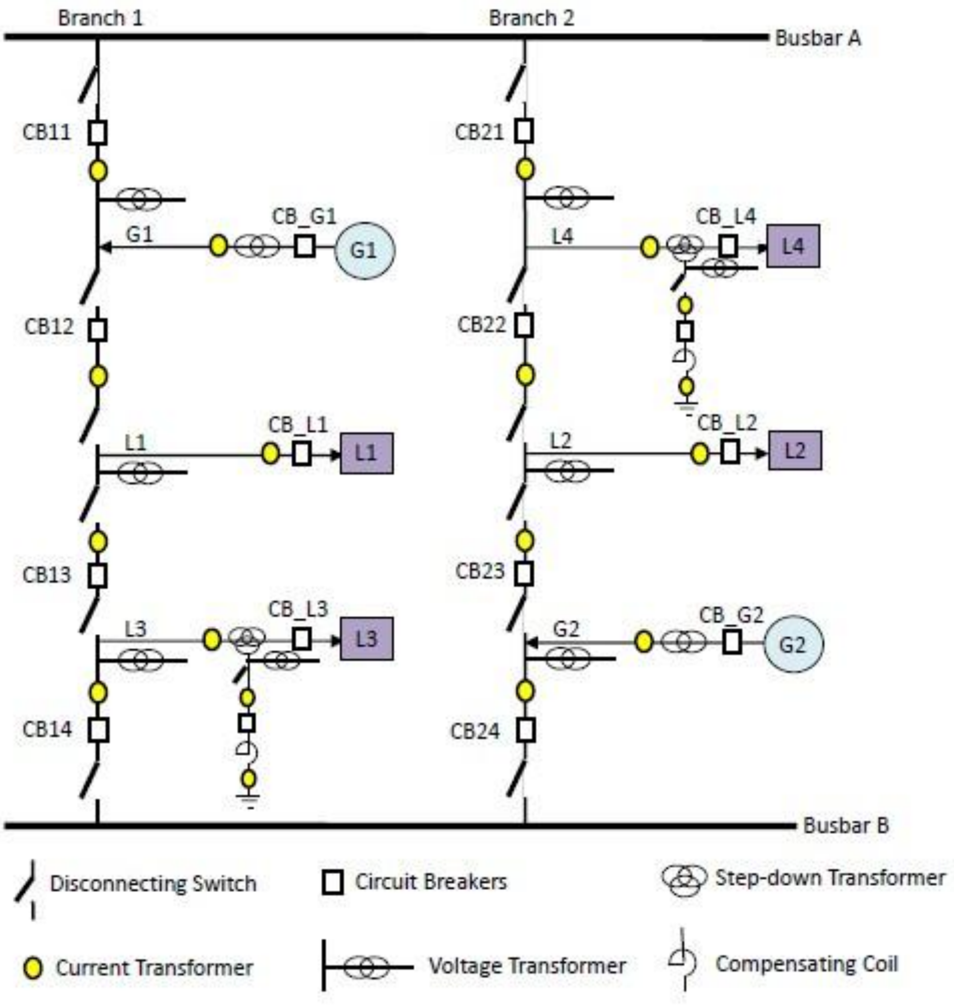


Fig 5. 1 4⁄3 Circuit Breakers Substation Configuration

5.2.2 Protection Principles and Event Trees

In the substation, differential protection, distance protection and the busbar protection coordinate with each other to ensure safety. Which of these protection systems reacts to the component fault mainly depends on the fault location.

For the components that are within one protection zone, the effects on the protection will be the same. Therefore, the whole substation is divided into several zones. In the 4⁄3 circuit breakers substation, there are five types of zones. This can be explained as follows.

a. Busbar Zone

When the initiating fault is located in the zone of the busbar protection, as shown in Fig 5.2, the busbar protection should react first, and trip the circuit breakers: CB11 and CB 21. If any of these two circuit breakers fails, the circuit breaker failure function will be activated, and trip CB12, CBG1, CB22, CBL4, and CB_L4low. There is no back-up protection within the substation. If the busbar protection fails, the fault will not be seen by the distance protection within this substation. It will be the distance protection from the nearby substation that clears the fault. Therefore, the whole substation is assumed to be down.

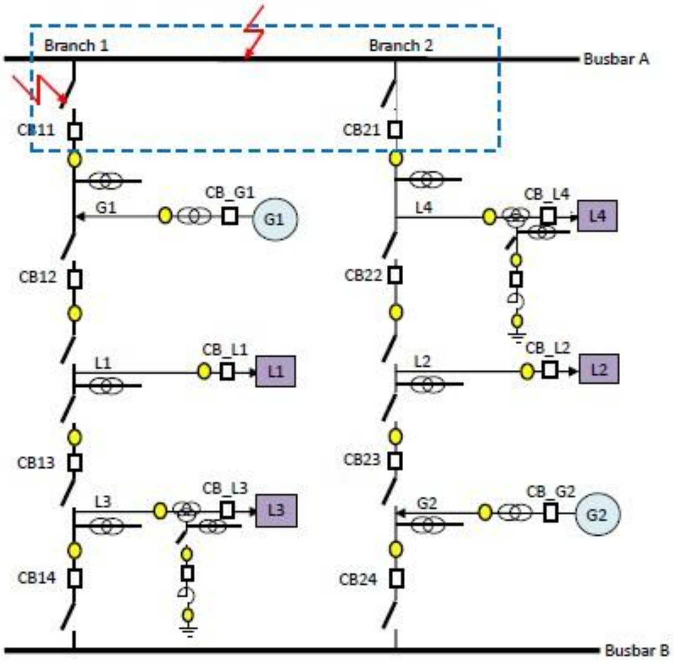
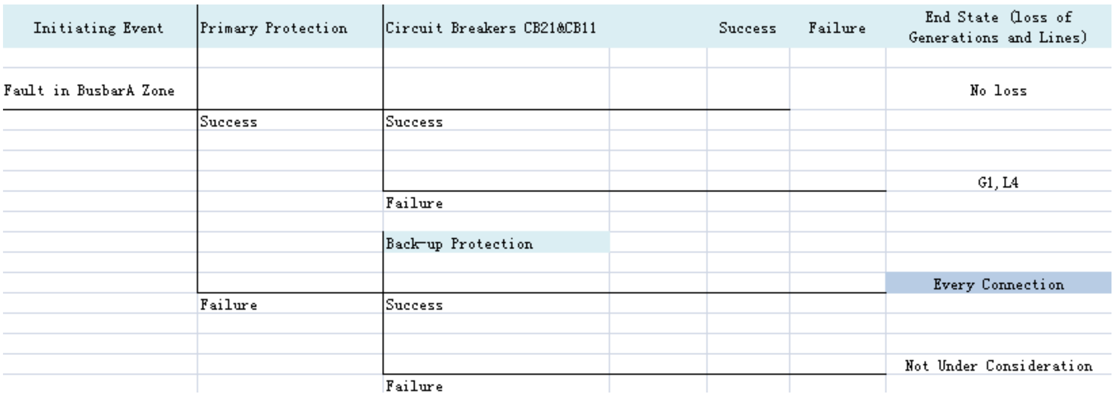


Fig 5. 2 Busbar Zone of 4/3 Circuit Breakers Substation

The Event tree for a fault within busbar A zone is shown below.



Initiating Event	Primary Protection	Circuit Breakers CB21&CB11	Success	Failure	End State (loss of Generations and Lines)
Fault in BusbarA Zone					No loss
	Success	Success			
					G1, L4
		Failure			
		Back-up Protection			
					Every Connection
	Failure	Success			
					Not Under Consideration
		Failure			

Fig 5. 3 Event Tree for a Fault in Busbar A Zone

As shown in Fig 5.3, when both the primary protection (busbar protection) and the associated circuit breakers react successfully, there will be no generators/lines isolated. When the primary protection works successfully, but one of the associated circuit breakers fails to trip, the next level of circuit breakers will be tripped by the circuit breakers failure function. Generator 1 and Line 4 will be isolated in this case. If the busbar protection fails to see the busbar fault, the whole substation will be down. The situation where both primary protection and back-up protection fail is neglected, because the back-up protection is assumed to be perfect in this study.

b. Generator Zone

As shown in Fig 5.4, when a fault occurs on the branch, the primary protection is the field differential protection. If the fault occurs on the line, the line differential protection will be the primary protection. If the fault occurs on the step-up transformer, the primary protection is the generator field differential protection. Although the primary protection systems are slightly different from each other, the associated circuit breakers are the same. Now a fault that lies in these three types of zones has same effect on the reliability study, the three zones are combined into one.

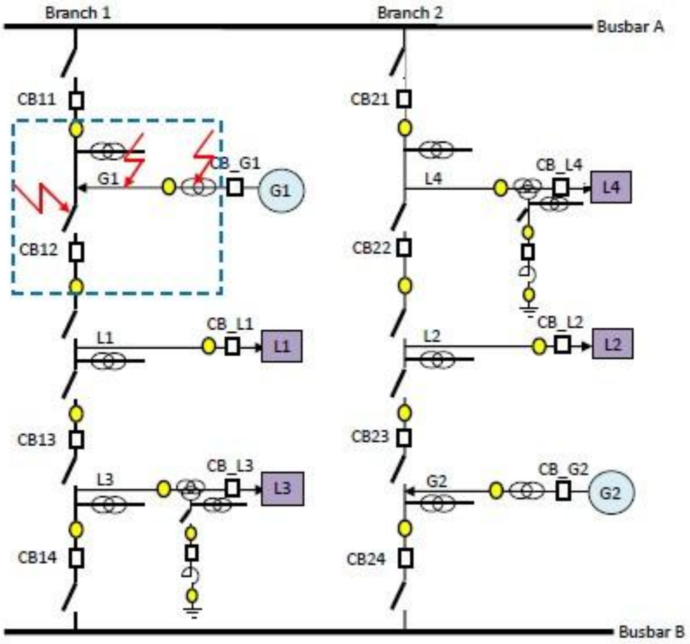


Fig 5. 4 Generator Zone of 4⁄3 Circuit Breakers Substation

The event tree for the fault lies in G1 zone is shown in Fig 5.5.

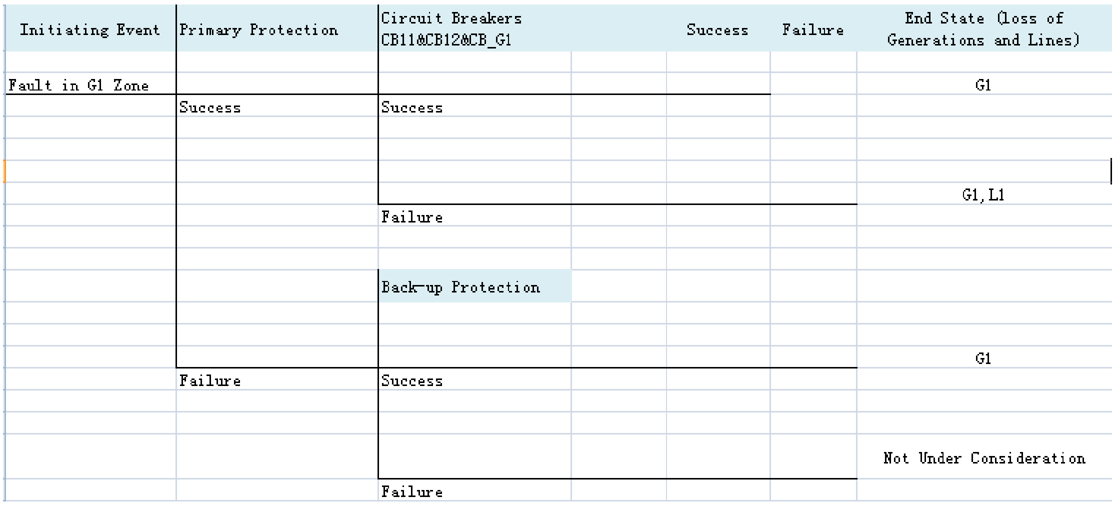


Fig 5. 5 Event Tree for the Fault in G1 Zone

When the initiating fault occurs in the G1 zone, such as a short-circuit within or an explosion of the step-up transformer, the differential protection should react first, and trip circuit breakers CB 11, CB12 and CB_G1. If one of these circuit breakers fails, the circuit breaker failure function will trip the neighboring circuit breakers, which are: CB13, CB_L1 and CB21. Therefore, G1 and L1 will be isolated.

When the primary protection does not work successfully, the back-up protection will react after a time delay. In this case, the back-up protection is the distance protection of the line, CB_G1, CB11 and CB21 will be tripped and G1 will be isolated.

The situation where the primary protection and back-up protection both fail is not considered.

c. Line Zone

In Fig 5.6, a fault occurring within a line zone is shown.

When a fault occurs on the branch, the field differential protection should react first. If the initiating fault is a line fault, the line differential protection is the primary protection. Since the protection system for those two faults will trip the same circuit breakers, they do not have a different effect on the reliability study. Therefore, these two zones are combined into one line zone.

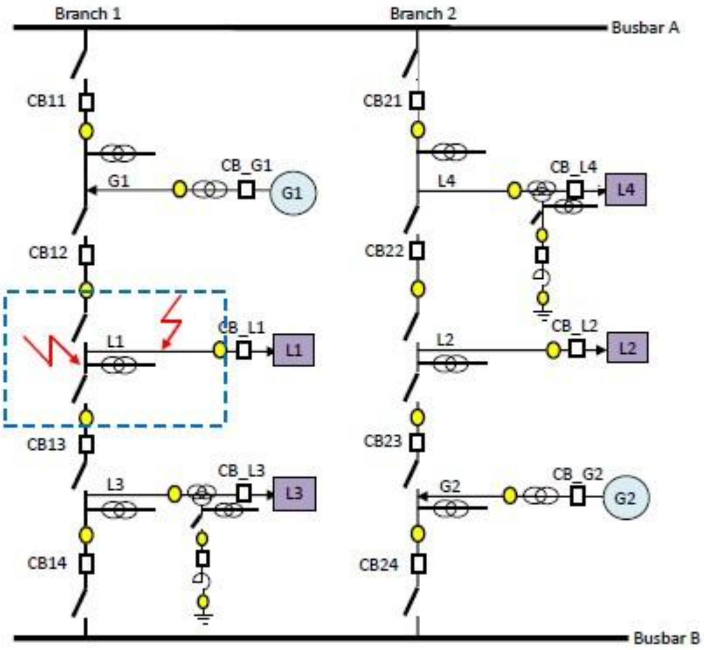


Fig 5. 6 Line Zone of 4/3 Circuit Breakers Substation

The Event Tree for the Line 1 Zone is shown below.

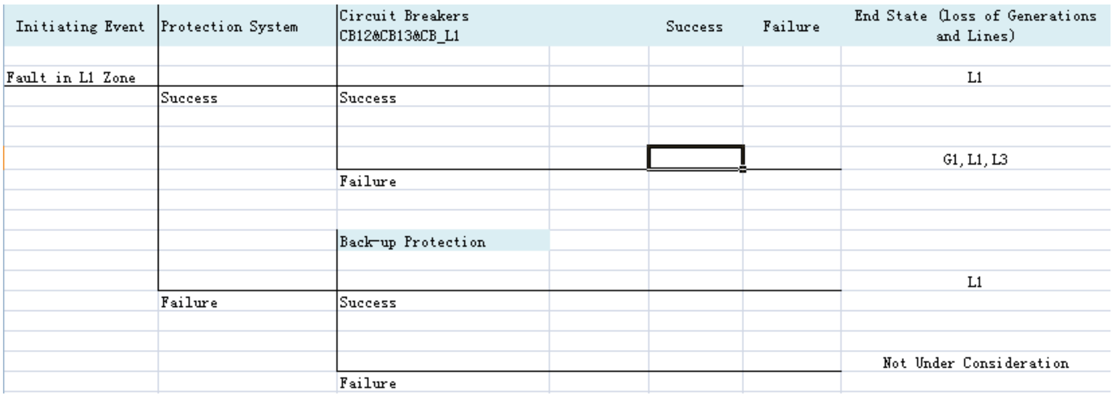


Fig 5. 7 Event Tree for the Fault in L1 Zone

When the fault occurs in the L1 zone, the primary differential protection should react and trip circuit breakers CB12, CB13 and CB_L1. When all these circuit breakers work successfully, only L1 will be isolated for some time. If one of the circuit breakers fails, the circuit breaker failure function will trip CB11, CB_G1, CB14, CB_L3, CB_L3low. Then G1, L1, L3 will be isolated.

When the differential protection fails to see the fault, the distance protection on the line should react, and trip CB12, CB13, CB_L1. Only L1 will be isolated in this case.

d. Step-down Transformer Zone

The step-down transformer zone is shown in Fig 5.8.

If the fault is located on the branch, the field differential will react first. If the fault is a line fault, the line differential protection is the primary protection. A fault lying in the transformer zone is protected by the transformer field differential protection. These different types of primary protection systems will trip the same circuit breakers. Therefore the three different zones are combined into one.

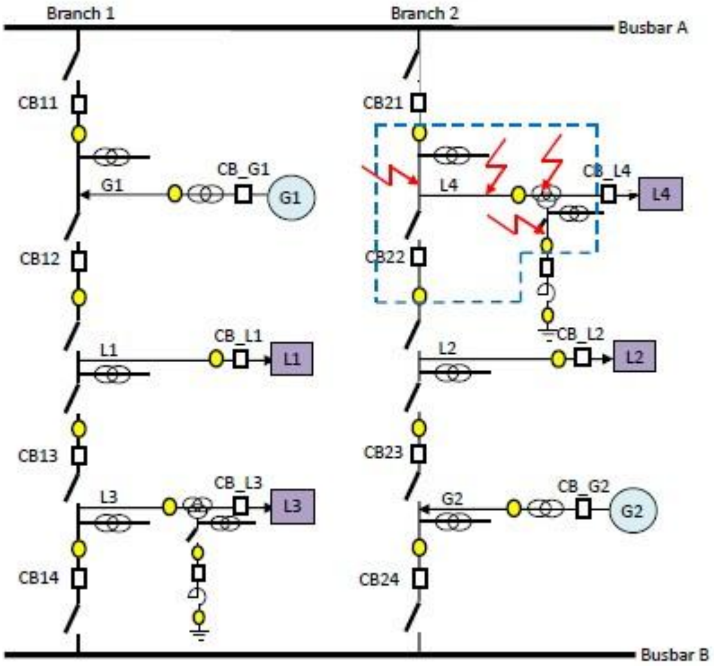


Fig 5. 8 Step-down Transformer Zone of 4/3 Circuit Breakers Substation

The event tree for the fault within the L4 zone is shown in Fig 5.9.

If an initiating fault occurs within this zone, the primary differential protection will trip CB21, CB22, CB_L4, and CB_L4 low. If all the circuit breakers work successfully, only L4 will be isolated. If one of those circuit breakers fails, CB11, CB23, CB_L2 will be tripped by the circuit breaker failure function. Both L2 and L4 will be isolated.

When the primary protection fails, the distance protection should react and isolate L4.

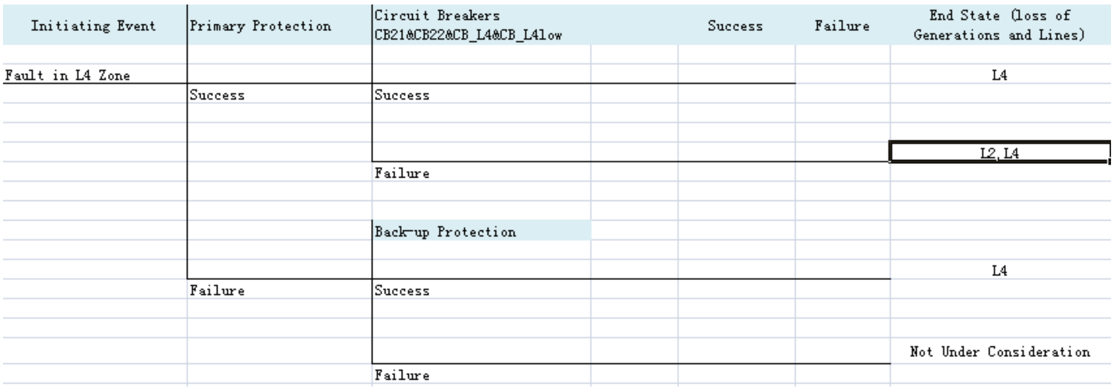


Fig 5. 9 Event Tree for the Fault in L4 Zone

e. Step-down Transformer 50kV Side Zone

A compensating coil is used at the 50kV side of the 380/150/50 kV transformer. There are two current transformers and one circuit breaker at this side, as shown in Fig 5.10. If the compensating coil experiences a fault, the circuit breakers at this side will be tripped, and the line is not affected.

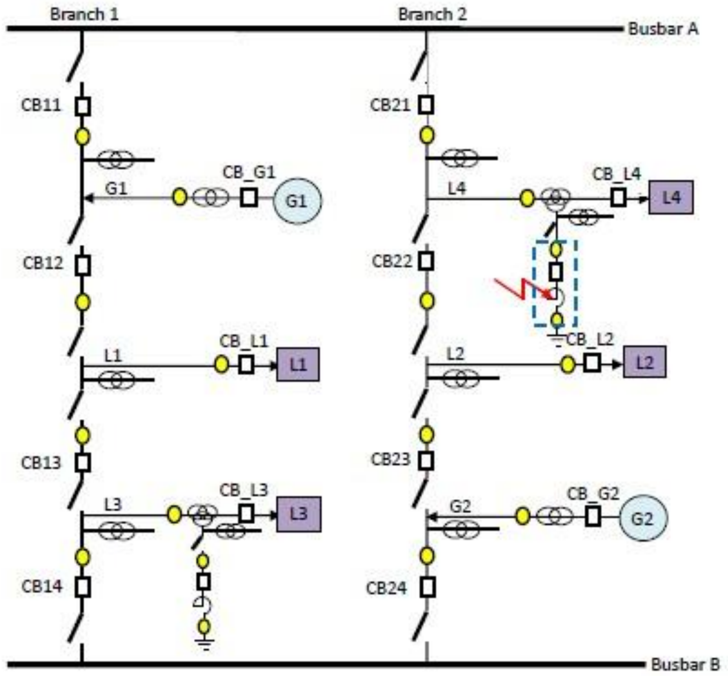


Fig 5. 10 Step-down Transformer 50kV Side Zone of 4/3 Circuit Breakers Substation

The event tree for the fault occurring at the L4 low side is given in Fig 5.11.

When there is an initiating fault, the differential protection should trip the CB_L4low, and no line will be isolated. If this circuit breaker fails, CB21, CB22 and CB_L4 will be tripped and L4 will be isolated.

If the primary differential protection system fails, the distance protection at this side should react and trip CB_L4low. No line will be isolated.

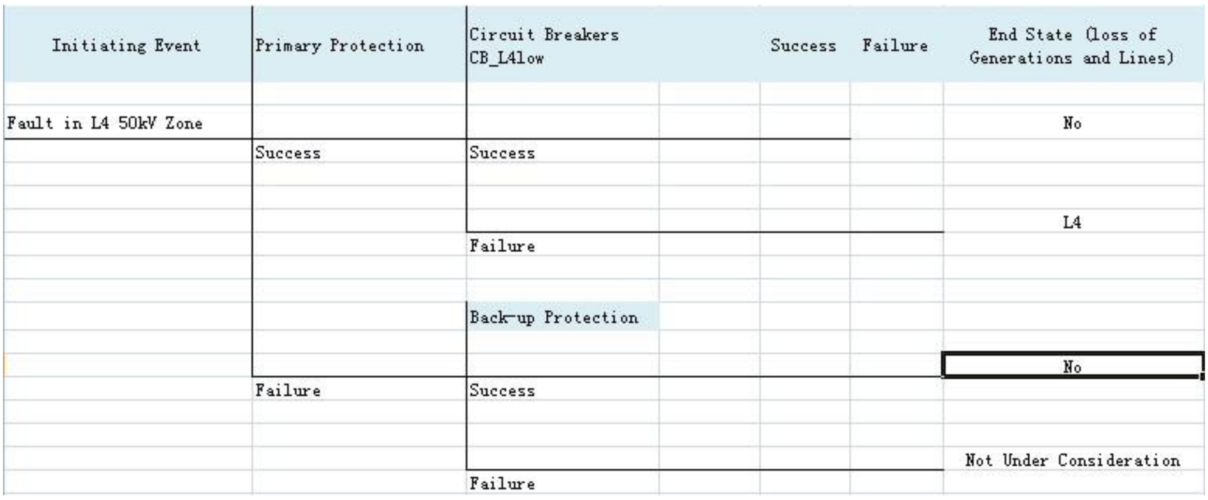


Fig 5. 11 Event Tree for Fault in L4 50kV Side Zone

According to the 5 types of protection zones introduced above, the protection principles for the 4⁄3 circuit breakers are summarized in Table 5-2.

The first column refers to the zone in which the initiating fault occurs.
For the three columns named by “Protection System failures”, the first column is the primary protection responding to the initiating faults in the different zones. The back-up protection is written in the second column. The third column refers to the lost generators/lines because of a primary protection system failure.
The three columns named by “Circuit Breaker Failures” are based on the condition that the primary protection system works successfully. The first column shows the circuit breakers that should be tripped by the primary protection. The second column shows the circuit breakers tripped by the circuit breaker failure function if one of the main circuit breakers fails. The third column shows lost generators/lines caused by circuit breaker failures.

According to this table, ten event trees can be built in total. The event trees can be found in the Appendix.
Each event tree has several states, and each state’s probability or frequency can be calculated by the event tree. By adding the probability or frequency of the same states of the ten trees, the final reliability result of 4⁄3 circuit breakers substation can be calculated.

Table 5 - 2 Protection Principle for the 4⁄3 Circuit Breakers Substation

	Protection System Failures			Circuit Breaker Failures		
Fault Zone	Primary Protection	Back-up Protection	Consequences	Main circuit breakers	CB tripped by Circuit Breaker Failure Function	Consequences
G1	Differential	Distance	Lost G1	CB11	CB21,CB13,CB_L1	Lost Generation:G1 Lost line:L1
				CB12		
				CB_G1		
G2	Differential	Distance	Lost G2	CB_G2	CB22,CB_L2,CB14	Lost Generation: G2 Lost line:L2
				CB23		
				CB24		
L1	Differential	Distance	Lost L1	CB_L1	CB11,CB_G1,CB14,CB_L3, CB_L3low	Lost Generation: G1 Lost line:L1,L3
				CB12		
				CB13		
L2	Differential	Distance	Lost L2	CB_L2	CB21,CB_L4,CB_L4low, CB24,CB_G2	Lost Generation: G2 Lost line:L2,L4
				CB22		
				CB23		

L3	Differential	Distance	Lost L3	CB_L3 CB_L3low CB13 CB14	CB12,CB_L1,CB24	Lost Generation:No Lost line:L1,L3
L3 lowside	Differential	Distance	Lost L3	CB_L3low	CB13,CB14,CB_L3	Lost Line: L3
L4	Differential	Distance	Lost L4	CB_L4 CB_L4low CB21 CB22	CB11,CB23,CB_L2	Lost Generation:No Lost line:L4,L2
L4 lowside	Differential	Distance	Lost L3	CB_L4low	CB21,CB22,CB_L4	L4
Busbar A	Busbar	Distance	Everything	CB11 CB21	CB12,CB_G1,CB22,CB_L4, CB_L4low	G1,L4
Busbar B	Busbar	Distance	Everything	CB14 CB24	CB13,CB_L3,CB_L3low, CB23,CB_G2	L3,G2

5.2.3 Event Tree Calculations

To calculate the resulting probabilities and failure frequencies from the event tree, the unavailability and failure frequency of the initiating events must be calculated first. This can be done by using a small fault tree.

As explained in Chapter 5.2.2, each zone consists of several components that can fail. The components together build a zone. Their failure statistics are shown in Table 5-3. The source of these failure statistics was already given in Table 2-1.

When one or more than one of the components within a zone fails, this zone will be regarded as failed, which offers the initiating fault for the event trees. Therefore, every zone can be regarded as a small series connection system.

The unavailability of the zone can be calculated by equations 4-1 and 4-3.

The failure frequency of the zone can be calculated using the equation below.

$$f(\text{system}) = f(1)+ f(2)+\ldots+ f(\text{n}) \tag{5 - 1}$$

The results are listed in the Table 5-3.

Table 5 - 3 Zone Data for the 4/3 Circuit Breakers Substation

Zone Name	Zone Construction	Zone Data		Components Failure Frequency	Components Unavailability	Zone's Failure Frequency	Zone's Unavailability
		Data	Unit				
G1	disconnecting switch	1	-	0.003	2.74E-06	0.0851	2.30E-03
	current transformer	2	-	0.0002	5.48E-07		
	voltage transformer	1	-	0.0002	5.48E-07		
	G1 Cable	5	km	0.0063	4.32E-04		
	transformer	1	-	0.05	1.37E-04		
G2	current transformer	2	-	0.0002	5.48E-07	0.0851	2.30E-03
	disconnecting switch	1	-	0.003	2.74E-06		
	voltage transformer	1	-	0.0002	5.48E-07		
	transformer	1		0.05	1.37E-04		
	G2 Cable	5	km	0.0063	4.32E-04		
L1	disconnecting switch	2	-	0.003	2.74E-06	0.0508	8.64E-03
	voltage transformer	1	-	0.0002	5.48E-07		
	current transformer	3	-	0.0002	5.48E-07		
	L1 line	20	km	0.0022	4.32E-04		
L2	voltage transformer	1	-	0.0002	5.48E-07	0.0508	8.64E-03
	current transformer	3	-	0.0002	5.48E-07		
	L2 line	20	km	0.0022	4.32E-04		
	disconnecting switch	2	-	0.003	2.74E-06		
L3	current transformer	2	-	0.0002	5.48E-07	0.0609	3.61E-04
	voltage transformer	2	-	0.0002	5.48E-07		
	disconnecting switch	2	-	0.003	2.74E-06		
	L3 cabl	0.5	km	0.0063	4.32E-04		
	transformer	1	-	0.05	1.37E-04		
	L3 150kV line	0.3	km	0.0031	2.83E-06		
L3 50kV	compensating coil	1	-	0.004	1.37E-06	0.0042	1.92E-06
	current transformer	1	-	0.0002	5.48E-07		
L4	current transformer	2	-	0.0002	5.48E-07	0.0609	3.61E-04
	voltage transformer	2	-	0.0002	5.48E-07		
	L4 cable	0.5	km	0.0063	4.32E-04		
	transformer	1	-	0.05	1.37E-04		
	L4 150kV line	0.3	km	0.0031	2.83E-06		
	disconnecting switch	2	-	0.003	2.74E-06		
L4 50kV	current transformer	1	-	0.0002	5.48E-07	0.0042	1.92E-06
	compensating coil	1	-	0.004	1.37E-06		
Busbar A	disconnecting switch	2	-	0.003	2.74E-06	0.0092	6.71E-06
	busbar	1	-	0.003	6.85E-07		
	voltage transformer	1	-	0.0002	5.48E-07		

Busbar B	busbar	1	-	0.003	6.85E-07	0.0090	6.16E-06
	disconnecting switch	2	-	0.003	2.74E-06		

Now, the failure frequency and unavailability of the initiating events is known. The unavailability of the circuit breakers and protection systems was already given in Table 2-1. The event trees can be calculated using the method introduced in Chapter 4.3.2.

By adding the failure statistics of the same end states, the frequency and probability of losing lines/generators can be calculated. The results are listed in section 5.5.

5.3 Reliability Evaluation for the One-and-a-Half Circuit Breakers Substation

5.3.1 Substation Configuration

The substation configuration of a one-and-a-half circuit breakers substation is very similar to that of a 4/3 circuit breakers substation. The only difference is that there are two fields on one branch for a one-and-a-half circuit breakers substation. As a result, each field shares 3/2 circuit breakers.

The configuration is shown in Fig 5.12.

All the assumptions that applied for the 4/3 circuit breakers substation apply here again.

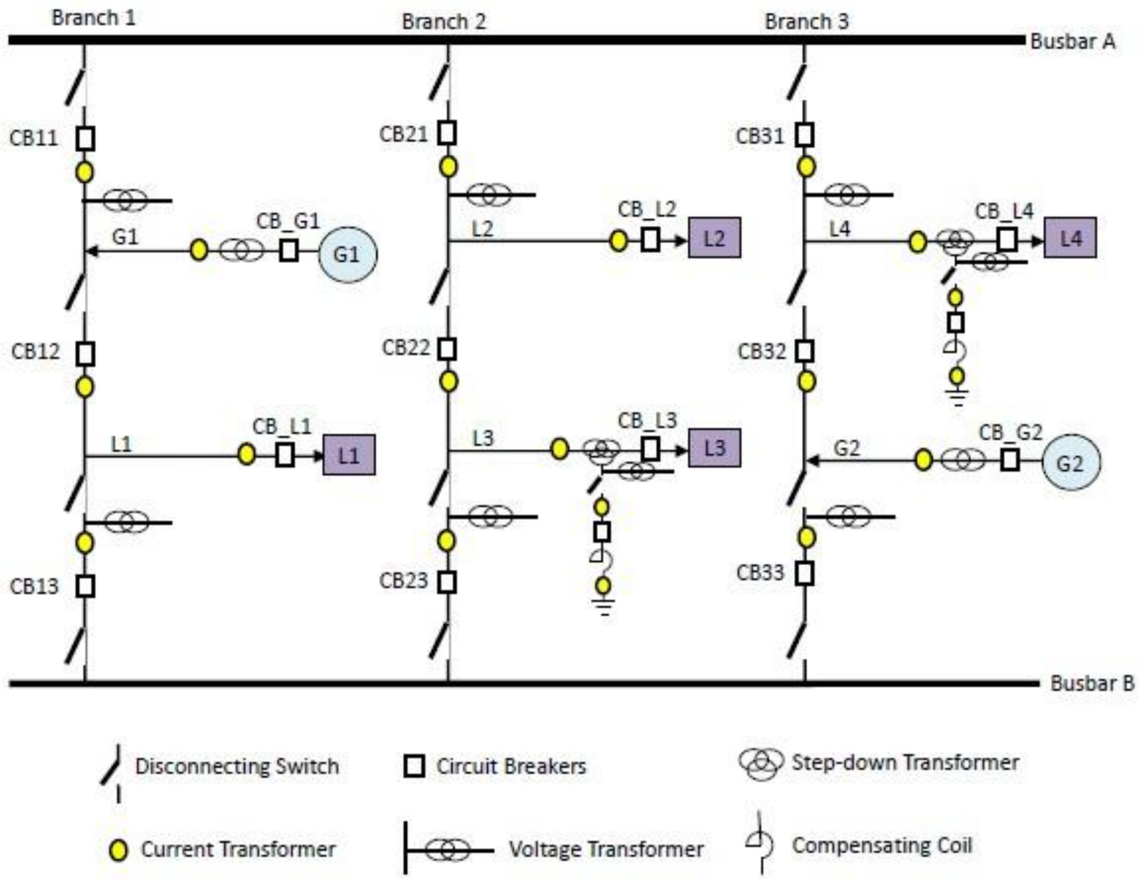


Fig 5. 12 One-and-a-half Circuit Breakers Substation Configuration

5.3.2 Protection Principles and Event Trees

The basic protection principles are the same as for the 4/3 circuit breakers substation, as explained in Chapter 5.2.2.

The protection principles for the substation in Fig 5.12 are shown in Table 5-4.

Table 5 - 4 Protection Principles for a One-and-a-half Circuit Breakers Substation

	Protection System Failures			Circuit Breakers Failures		
Fault Zone	Primary Protection	Back-up Protection	Consequences	Main circuit breakers	CB tripped by Circuit Breaker Failure Function	Consequences
G1	Differential	Distance	Lost G1	CB11	CB21,CB31,CB13,CB_L1	Lost Generation:G1 Lost line:L1
				CB12		
				CB_G1		
G2	Differential	Distance	Lost G2	CB_G2	CB31,CB_L4,CB_L4low,CB 13,CB23	Lost Generation: G2 Lost line:L4
				CB32		
				CB33		

L1	Differential	Distance	Lost L1	CB_L1	CB11,CB_G1,CB23,CB33	Lost Generation: G1 Lost line:L1
				CB12		
				CB13		
L2	Differential	Distance	Lost L2	CB_L2	CB11,CB31,CB23,CB_L3,CB_L3low	Lost line:L2,L3
				CB21		
				CB22		
L3	Differential	Distance	Lost L3	CB_L3	CB21,CB_L2,CB13,CB33	Lost line: L2,L3
				CB_L3low		
				CB22		
				CB23		
L3 50kV Side	Differential	Distance	Lost L3	CB_L3low	CB_L3,CB22,CB23	Lost: L3
L4	Differential	Distance	Lost L4	CB_L4	CB11,CB21,CB33,CB_G2	Lost Generation: G2 Lost line: L4
				CB_L4low		
				CB31		
				CB32		
L4 50kV Side	Differential	Distance	Lost L4	CB_L4low	CB_L4,CB31,CB32	Lost: L4
busbar A	Busbar	Distance	Everything	CB11	CB12,CB_G1,CB22,CB_L2,CB32,CB_L4,CB_L4low	G1,L2,L4
				CB21		
				CB31		
busbar B	Busbar	Distance	Everything	CB13	CB12,CB_L1,CB22,CB_L3,CB_L3low,CB32,CB_G2	L1,L3,G2
				CB23		
				CB33		

The table can be read in the same way of reading Table 5-2. All the corresponding event trees can be found in the Appendix.

To calculate the event trees, the zone data are given in Table 5-5.

Table 5 - 5 Zone Data for One-and-a-half Circuit Breakers Substation

Zone Name	Zone Construction	Zone Data		Components Failure Frequency	Components Unavailability	Zone's Failure Frequency	Zone's Unavailability
		Data	Unit				
G1	disconnecting switch	1	-	0.003	2.74E-06	0.0851	2.30E-03
	current transformer	2	-	0.0002	5.48E-07		
	voltage transformer	1	-	0.0002	5.48E-07		
	G1 Cable	5	km	0.0063	4.32E-04		
	transformer	1	-	0.05	1.37E-04		

G2	current transformer	3	-	0.0002	5.48E-07	0.0853	2.30E-03
	disconnecting switch	1	-	0.003	2.74E-06		
	voltage transformer	1	-	0.0002	5.48E-07		
	transformer	1	-	0.05	1.37E-04		
	G2 Cable	5	km	0.0063	4.32E-04		
L1	disconnecting switch	1	-	0.003	2.74E-06	0.0478	8.64E-03
	voltage transformer	1	-	0.0002	5.48E-07		
	current transformer	3	-	0.0002	5.48E-07		
	L1 line	20	km	0.0022	4.32E-04		
L2	voltage transformer	1	-	0.0002	5.48E-07	0.0478	8.63E-03
	current transformer	2	-	0.0002	5.48E-07		
	L2 line	20	km	0.0022	4.32E-04		
	disconnecting switch	1	-	0.003	2.74E-06		
L3	current transformer	3	-	0.0002	5.48E-07	0.0611	3.62E-04
	voltage transformer	2	-	0.0002	5.48E-07		
	disconnecting switch	2	-	0.003	2.74E-06		
	L3 cable	0.5	km	0.0063	4.32E-04		
	transformer	1	-	0.05	1.37E-04		
	L3 150kV line	0.3	km	0.0031	2.83E-06		
L3 50kV	compensating coil	1	-	0.004	1.37E-06	0.0042	1.92E-06
	current transformer	1	-	0.0002	5.48E-07		
L4	current transformer	2	-	0.0002	5.48E-07	0.0609	3.61E-04
	voltage transformer	2	-	0.0002	5.48E-07		
	L4 cable	0.5	km	0.0063	4.32E-04		
	transformer	1	-	0.05	1.37E-04		
	L4 150kV line	0.3	km	0.0031	2.83E-06		
	disconnecting switch	2	-	0.003	2.74E-06		
L4 50kV	current transformer	1	-	0.0002	5.48E-07	0.0042	1.92E-06
	compensating coil	1	-	0.004	1.37E-06		
Busbar A	disconnecting switch	3	-	0.003	2.74E-06	0.0122	9.45E-06
	busbar	1	-	0.003	6.85E-07		
	voltage transformer	1	-	0.0002	5.48E-07		
Busbar B	busbar	1	-	0.003	6.85E-07	0.0120	8.90E-06
	disconnecting switch	3	-	0.003	2.74E-06		

The data in this table is calculated the same way as the data in Table 5-3.
The final result of the event tree is listed in section 5.5

5.4 Reliability Evaluation for the Typical Double Busbar Substation

5.4.1 Substation Configuration

The substation configuration of a typical double busbar substation is more often used than the 4/3 circuit breakers substation and one-and-a-half circuit breakers substation.

Each line/generator is connected to both busbars with disconnecting switches. Under normal operation, only one disconnecting switch is closed. In the configuration shown in Fig 5.13, half of the lines/generators are connected to busbar A, while the other half is connected to busbar B. Unlike the 4/3 circuit breakers substation, a coupling circuit breaker is added between the two busbars in a typical double busbar substation.

All the assumptions that applied for the 4/3 circuit breakers substation and the one-and-a-half circuit breakers substation apply here again.

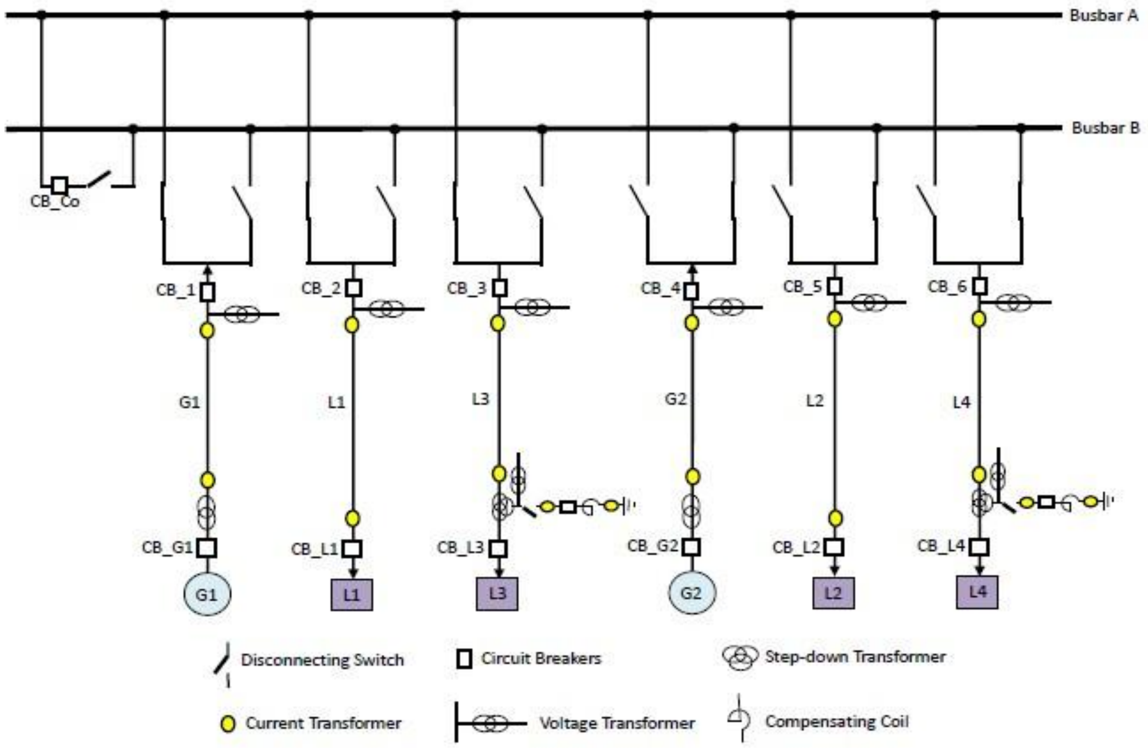


Fig 5. 13 Typical Double Busbar Substation Configuration

5.4.2 Protection Principles and Event Trees

The basic principles of the protection zones are the same as for the 4/3 circuit breakers substation, as explained in Chapter 5.2.2.
The protection principles for the substation in Fig 5.13 are shown in Table 5-6.

Table 5 - 6 Protection Principles for Typical Double Busbar Substation

	Protection System Failures			Circuit Breaker Failures		
Fault Zone	Primary Protection	Back-up Protection	Consequences(Lost Generators/Lines)	Main circuit breakers	CB tripped by Circuit Breaker Failure Function	Consequences(Lost Generators/Lines)
LG1	Differential	Distance	G1	CB1	CB_Co,CB2,CB3	G1,L1,L3
				CB_G1		
LG2	Differential	Distance	G2	CB_G2	CB_Co,CB5,CB6	G2,L2,L4
				CB4		
LL1	Differential	Distance	L1	CB_L1	CB_Co,CB1,CB3	G1,L1,L3
				CB2		
LL2	Differential	Distance	L2	CB_L2	CB_Co,CB4,CB6	G2,L2,L4
				CB5		
LL3	Differential	Distance	L3	CB_L3	CB_Co,CB1,CB2	G1,L1,L3
				CB_L3low		
				CB3		
L3 50kV Side	Differential	Distance	L3	CB_L3low	CB3,CB_L3	L3
LL4	Differential	Distance	L4	CB_L4	CB_Co,CB4,CB5	G2,L2,L4
				CB_L4low		
				CB6		
L4 50kV Side	Differential	Distance	Lost L3	CB_L4low	CB4,CB_L4	L4
busbar A	Busbar	Distance	Everything	CB_Co	CB4,CB5,CB6	G1,L1,L3,G2,L2,L4
				CB1	CB_G1,CB_L1,CB_L3	G1,L1,L3
				CB2		
				CB3		
busbar B	Busbar	Distance	Everything	CB_Co	CB1,CB2,CB3	G1,L1,L3,G2,L2,L4
				CB4	CB_G2,CB_L2,CB_L4	G2,L2,L4
				CB5		
				CB6		

The table can be read in the same way of reading Table 5-2. All the responding event trees can be found in the Appendix.

To calculate the probabilities and failure frequencies in the event trees, the zone data are given in Table 5-7.

Table 5 - 7 Zone Data for Typical Double Busbar Substation

Zone Name	Zone Construction	Zone Data		Components Failure Frequency	Components Unavailability	Zone Failure Frequency	Zone Unavailability
		Data	Unit				
G1	disconnecting switch	2	-	0.003	2.74E-06	0.0881	2.30E-03
	current transformer	2	-	0.0002	5.48E-07		
	voltage transformer	1	-	0.0002	5.48E-07		
	G1 Cable	5	km	0.0063	4.32E-04		
	transformer	1	-	0.05	1.37E-04		
G2	current transformer	2	-	0.0002	5.48E-07	0.0881	2.30E-03
	disconnecting switch	2	-	0.003	2.74E-06		
	voltage transformer	1	-	0.0002	5.48E-07		
	transformer	1	-	0.05	1.37E-04		
	G2 Cable	5	km	0.0063	4.32E-04		
L1	disconnecting switch	2	-	0.003	2.74E-06	0.0506	8.64E-03
	voltage transformer	1	-	0.0002	5.48E-07		
	current transformer	2	-	0.0002	5.48E-07		
	L1 line	20	km	0.0022	4.32E-04		
L2	voltage transformer	1	-	0.0002	5.48E-07	0.0506	8.64E-03
	current transformer	2	-	0.0002	5.48E-07		
	L2 line	20	km	0.0022	4.32E-04		
	disconnecting switch	2	-	0.003	2.74E-06		
L3	current transformer	2	-	0.0002	5.48E-07	0.0639	3.64E-04
	voltage transformer	2	-	0.0002	5.48E-07		
	disconnecting switch	3	-	0.003	2.74E-06		
	L3 cable	0.5	km	0.0063	4.32E-04		
	transformer	1	-	0.05	1.37E-04		
	L3 150kV line	0.3	km	0.0031	2.83E-06		
L3 50kV	compensating coil	1	-	0.004	1.37E-06	0.0042	1.92E-06
	current transformer	1	-	0.0002	5.48E-07		

L4	current transformer	2	-	0.0002	5.48E-07	0.0639	3.64E-04
	voltage transformer	2	-	0.0002	5.48E-07		
	L4 cable	0.5	km	0.0063	4.32E-04		
	transformer	1	-	0.05	1.37E-04		
	L4 150kV line	0.3	km	0.0031	2.83E-06		
	disconnecting switch	3	-	0.003	2.74E-06		
L4 50kV	current transformer	1	-	0.0002	5.48E-07	0.0042	1.92E-06
	compensating coil	1	-	0.004	1.37E-06		
Busbar A	disconnecting switch	7	-	0.003	2.74E-06	0.0242	2.04E-05
	busbar	1	-	0.003	6.85E-07		
	voltage transformer	1	-	0.0002	5.48E-07		
Busbar B	busbar	1	-	0.003	6.85E-07	0.0210	1.71E-05
	disconnecting switch	6	-	0.003	2.74E-06		

The data in this table is calculated in the same way as the data in Table 5-3.
The final result of the event tree is listed in Chapter 5.5.

5.5 Comparison of the Results

After the calculation of the probabilities and failure frequencies with the event trees, the results are combined in Table 5-8 and Table 5-9.
In Table 5-8, the unavailability and failure frequency of each generator/line for different substation configurations is calculated using the event trees. The table shows the probability/frequency that the specific line/generator is isolated if one component in the substation fails. The protection system failures and circuit breaker failures are considered in the reliability evaluation.

The Mean Time to Failure here represents for a specific generator/line, the average time it takes before fails. It is calculated by equation 2-2, using one divided by the failure frequency.

Table 5 - 8 Comparison of Line/Generator Failure Results

Lost Line/ Generation	Unavailability			Failure Frequency(per year)			Mean Time To Failure(year)		
	3/2 CB	4/3 CB	Typical Double Busbar	3/2 CB	4/3 CB	Typical Double Busbar	3/2 CB	4/3 CB	Typical Double Busbar
G1	2.34E-03	2.34E-03	2.35E-03	0.086	0.086	0.113	12	12	9
G2	2.30E-03	2.34E-03	2.35E-03	0.086	0.086	0.110	12	12	9
L1	8.65E-03	8.65E-03	8.67E-03	0.130	0.134	0.157	8	7	6
L2	8.64E-03	8.65E-03	8.66E-03	0.130	0.134	0.154	8	7	6
L3	4.01E-04	4.00E-04	4.17E-04	0.062	0.062	0.089	16	16	11
L4	3.72E-04	4.00E-04	4.14E-04	0.061	0.062	0.086	16	16	12

To make it more convenient to compare the failure results of the three substation configurations, a bar graph is used as shown in Fig 5.14 and Fig 5.15.

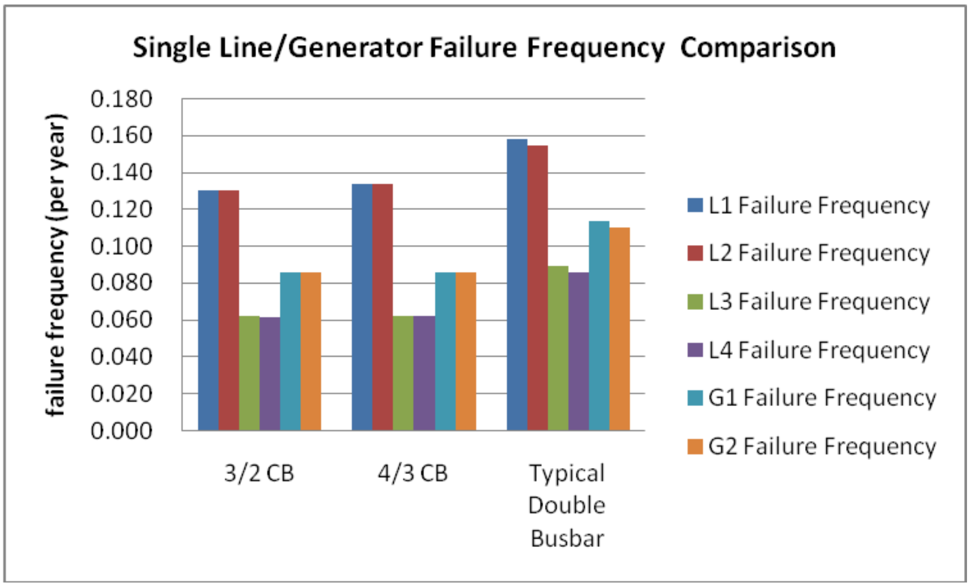


Fig 5. 14 Specific Line/Generator Failure Frequency Comparison

In Fig 5.14, the comparison of the failure frequency for specific lines/generators in different substation configurations is shown.

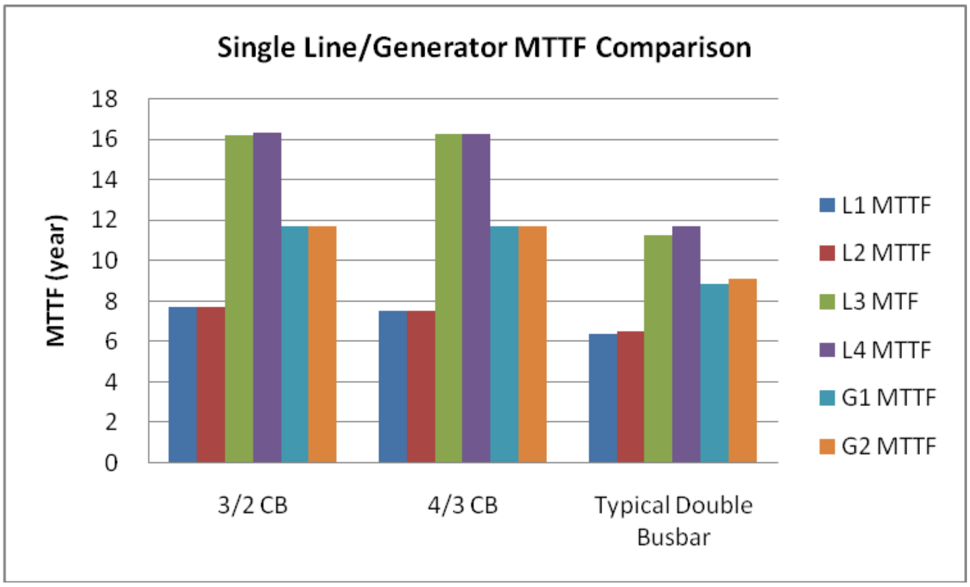


Fig 5. 15 Specific Line/Generator MTTF Comparison

In Fig 5.15, the comparison of Mean Time to Failure for specific lines/generators in different substation configurations is shown.

Take a look at Fig 5.14 and Fig 5.15.
First compare the failure frequency and MTTF of lines and generators within one substation.
For one-and-a-half circuit breakers substation, it is clearly shown that, L1 and L2, L3 and L4, G1 and G2 mutually have equal frequencies to be lost because of components failures within the substation. This is because, L1 and L2, L3 and L4, G1 and G2 share the same parameters with each other.
The failure frequency of L1 and L2 is the highest compared to L3, L4, G1, and G2. Around every eight years, L1 and L2 will be lost because of component failures, which is shorter than the others. This can be explained by the line length of L1 and L2. The dominant component that affects the reliability is the length of line or cable, because the failure frequency increases proportionally with the line length. L1 and L2 are 20km lines, which is much longer than the cables and lines of L3, L4, G1 and G2. Out of the same reason, the failure frequency of G1 and G2 is larger than that of L3 and L4. It takes on average 16 years before L3 or L4 fails, while less than 12 years for G1 and G2.

Considering the 4⁄3 circuit breakers substation and typical double busbar substation, L1 and L2, L3 and L4, G1 and G2 also mutually have more or less the same failure results. The relationship between their failure frequency follows the same rules: L1, L2> G1, G2> L3, L4 as well.

After the comparison of the connections within one substation, a comparison of the

same line/generator failure results of different substation configurations is made.
It is clearly shown in Fig 5.14 and 5.15 that the failure results for the one-and-a-half circuit breakers substation and the 4⁄3 circuit breakers substation is almost the same. The failure frequency of the typical double busbar substation is larger than the other two substations. Consequently, it takes less time for the line/generator in a typical double busbar substation to fail. This can be explained by its protection principle. In a typical double busbar substation, every line/generator is connected directly with one busbar. If one of the lines/generators has a fault occurrence and the circuit breaker fails, all the lines/generators connected to the same busbar will be isolated, which is not the case in the 4⁄3 circuit breakers substation and the one-and-a-half circuit breakers substation. Therefore, the chance of losing lines/generators in a typical double busbar is larger, while the mean time to failure is shorter.

In Table 5-9, the comparison of multiple lines/generators failures is made.

Table 5 - 9 Comparison of Multiple Lines/Generators Failures

number of loss line/generator at the same time	Unavailability			Failure Frequency(per year)			Mean Time To Failure (MTTF) (year)		
	3/2 CB	4/3 CB	Typical Double Busbar	3/2 CB	4/3 CB	Typical Double Busbar	3/2 CB	4/3 CB	Typical Double Busbar
1	2.2E-02	2.2E-02	2.3E-02	0.5491	0.5549	0.5673	2	2	2
2	1.0E-04	2.5E-05	0.0E+00	0.0027	0.0015	0.0000	377	648	-
3	8.2E-08	7.7E-05	1.1E-04	0.0001	0.0012	0.0468	9206	840	21
6	1.8E-08	1.3E-08	2.2E-07	0.0000	0.0000	0.0003	41364	55000	3699
Total	2.3E-02	2.3E-02	2.3E-02	0.5519	0.5576	0.6144	1.81	1.79	1.63

In Table 5-9, the left column shows the number of lines/generators isolated at the same time because of one component failure within the substation. In total, there are six lines/generators that can be lost. Because of the assumed busbar protection principle, the 4⁄3 circuit breakers substation can have two lines/generators isolated at the same time, while the one-and-a-half circuit breakers substation and the typical double busbar substation can have three lines/generators isolated at the same time.
The unavailability and failure frequency here stand for the probability or frequency that multiple lines/generators will be lost at the same time because of component failures inside the substation. These are calculated using the event trees. MTTF stands for the average time it takes before multiple lines/generators loss appears at the same time. It is calculated using equation 2-2.

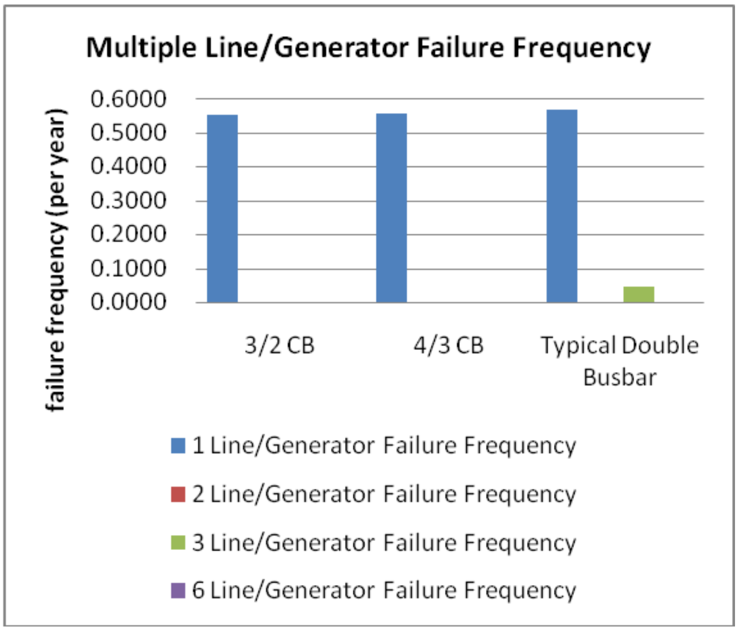


Fig 5. 16 Multiple Lines/Generators Failure Frequency Comparison

To make it more convenient for comparison, in Fig 5.16, the comparison of the failure frequency for multiple lines/generators in different substation configurations is shown.

In Fig 5.17, the comparison of the mean time to failure for multiple lines/generators in different substation configurations is shown.

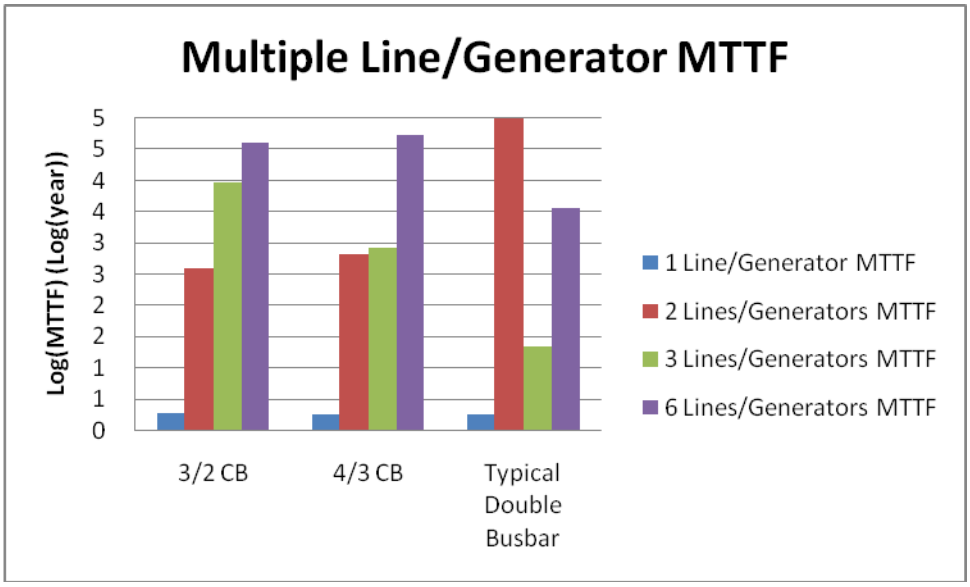


Fig 5. 17 Multiple Lines/Generators MTTF Comparison

Take a look at Fig 5.16 and Fig 5.17.

First analyze the failure statistics within one type of substation. It is clearly shown in Fig 5.16 that the failure frequency of only one loss is much larger than that of multiple losses as could be expected.

Then compare the failure statistics of multiple losses for different substation configurations. The failure frequency of multiple losses is basically the same for the 4/3 circuit breakers substation and the one-and-a-half circuit breakers substation. The failure frequency of multiple losses for the typical double busbar substation is slightly larger than the other two.

In Fig 5.17, the vertical axis is the logarithmic value of the mean time to failure. Within one substation, the MTTF of 1 line/generator is much shorter than multiple lines/generators. Then compare the different substation configurations. The MTTF of 3 lines/generators for the 3/2 circuit breakers substation is larger than the 4/3 circuit breakers substation. This is because in 4/3 circuit breakers substation example, there are two branches, and three lines/generators on each branch. When the fault occurs on the lines/generators in the middle of the branch, and circuit breaker fails, the circuit breaker failure functions will trip the neighboring lines/generators. In this situation, three lines/generators will be lost at the same time. For the 3/2 circuit breakers substation in the example, there are three branches, and each branch has two lines/generators. Therefore, the MTTF for 3 lines/generators of a 4/3 circuit breakers substation is lower than the 3/2 circuit breakers substation, while the MTTF for 2 lines/generators higher. The MTTF for 6 lines/generators of a 4/3 circuit breakers substation and a 3/2 circuit breakers substation are more or less the same.

The MTTF of the typical double busbar substation is much lower than the other two substation configurations.

Compare the total MTTF of the different substation configurations as shown in the following figure.

As can be seen from Fig 5.18, the total MTTF of the 3/2 circuit breakers substation is more or less the same with the 4/3 circuit breakers substation, and much higher than the typical double busbar. This difference is caused by the circuit breaker failure function. For the 4/3 circuit breakers substation and one-and-a-half circuit breakers substation, when an initiating fault occurs and a circuit breaker failure follows, the circuit breaker failure function will only trip the nearby line/generators. However, for the typical double busbar substation, half of the lines/generators are connected to the busbar, and they will all be isolated by circuit breaker failure functions under the same situation.

As a conclusion, the 3/2 circuit breakers substation and the 4/3 circuit breakers substation are of same reliability level. The typical double busbar substation is less reliable than the other two substation configurations.

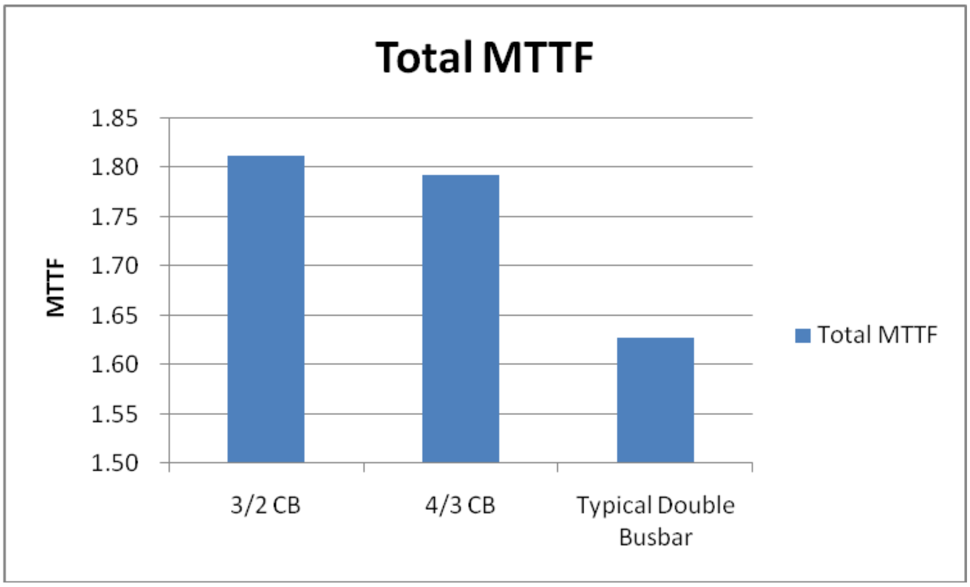


Fig 5. 18 Comparison of Total MTTF of Different Substation Configurations

5.6 Conclusions

In this chapter, it was explained in detail how to build and calculate the reliability results from the event trees for different substation configurations based on protection principles. Then, the failure results of a 4⁄3 circuit breakers substation, a one-and-a-half circuit breakers substation and a typical double busbar substation were compared.

Several conclusions can be made based on the failure principles and the results of comparison.

a. When designing a substation, the generators and important lines must be connected to different busbars, to prevent them from being isolated at the same time because of busbar protection failures.

b. Within one substation, the components that have a dominant effect to the reliability result are the transformers and long lines/cables, because their failure frequency is big. And for line/cable, the failure frequency increases proportional to the line/cable length.

c. A 4⁄3 circuit breakers substation and a 3⁄2 circuit breakers substation are almost of the same reliability level.

d. A 4⁄3 circuit breakers substation and a 3⁄2 circuit breakers substation are more reliable than a typical double busbar substation. This is caused by the circuit breaker failure function.

Chapter 6 Maasvlakte 380kV Substation Reliability Evaluation

6.1 Introduction

Fig 6. 1 High Voltage Electricity Transmission Network of the Netherlands

The high voltage electricity transmission network in the Netherlands is shown in Fig 6.1. The white area indicates the territory of the Netherlands. The red lines are 380kV connections; green lines stand for 220kV connections; blue lines refer to 150kV connections; and the black lines represent 110kV connections. Maasvlakte 380kV substation is located near the harbors of Maasvlakte, Europoort and

Rotterdam. It is marked by a red-dotted-circle in the above figure.

Fig 6. 2 Maasvlakte 380kV Substation Network

If we zoom in on the area marked by the red-dotted-circle, the detailed network of the Maasvlakte 380kV substation is shown in Fig 6.2.

The red dots and blue dots in Fig 6.2 represent 380kV substations and 150kV substations respectively. It can be seen from the figure that Maasvlakte 380kV substation is connected to Simonshaven 380kV substation by two 380kV lines; connected to Westerlee 380kV substation by two 380kV lines; and connected to the the Europoort 150kV substation through Maavslakte 150kV substation by two 150kV lines.

Besides, the purple-dotted arrow in above figure represents the High Voltage Direct Current (HVDC) cable connected between Maasvlakte substation and Great Britain, which is called BritNed. Being a 260km HVDC cable, BritNed can transfer up to 1200MVA power both in and out of Maasvlakte substation.

In total, there are seven output lines connected to Maasvlakte substation. As for the power input, there are already three generation plants connected (EGEN, MV_1 and MV_2), and two more (MV_3 and ElectraBel) will be put into operation around 2013.

In brief, after 2013, there will be five generation plants, six output lines, and one double direction cable connected to Maasvlakte 380kV substation. The huge amount of power flows in this substation makes it one of the most complicated and important substations in the Netherlands. Its reliability with protection failures is studied in this chapter.

6.2 Assumptions and Event trees

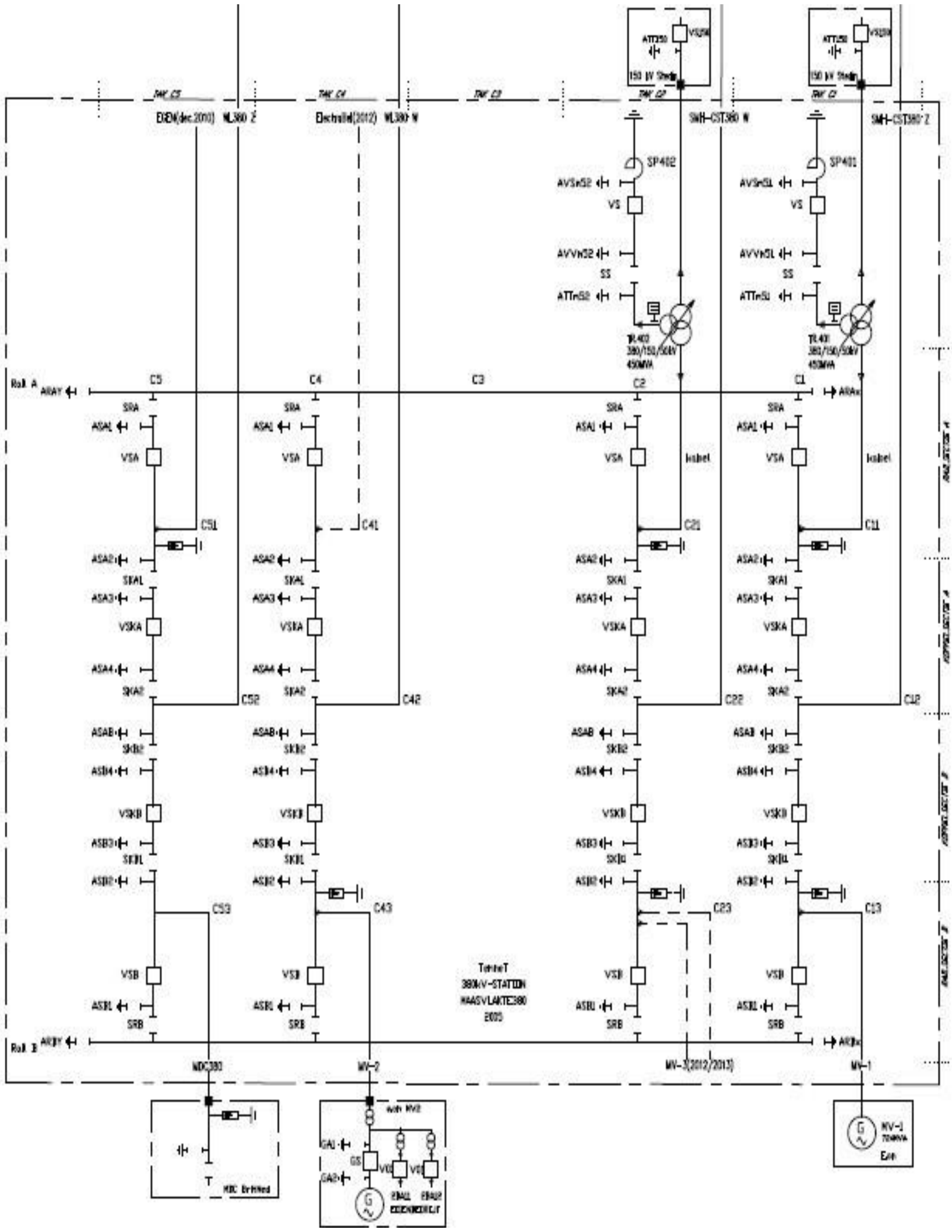


Fig 6. 3 Maasvlakte 380kV Substation Configuration

The configuration of Maasvlakte 380kV substation is shown in the figure above. As can be seen from the figure, Maasvlakte 380kV substation is a 4⁄3 circuit breakers substation.

Before analyzing the reliability of the substation, several assumptions and simplifications are made first.

i. The substation is operating at 380kV.
j. All the parts of this substation are in operation, i.e. maintenance is not considered in this study.
k. The earthing switches within the substation do not have a significant effect on the reliability and are neglected in this chapter.
l. The generators do not belong to the substation. Therefore their failures are not considered in this study.
m. In this chapter, the components that are considered to have a chance to fail are: busbar, circuit breaker, disconnecting switch, current transformer, voltage transformer, surge arrestor, step-up transformer, step-down transformer, line connected to the substation, cable connected to the substation.
n. In this study, the lines and cables connected to the neighboring substations are involved in the reliability model, i.e. the line/ cable fault will lead to a protection reaction.
o. The neighboring substations are assumed to be perfect for modeling convenience. These are assumed to consist of one perfect circuit breaker which will never fail.
p. The back-up protection systems and the back-up circuit breakers are assumed to be perfect in this study.

After those assumptions and simplifications, the simplified model of Maasvlakte 380kV substation is shown below.

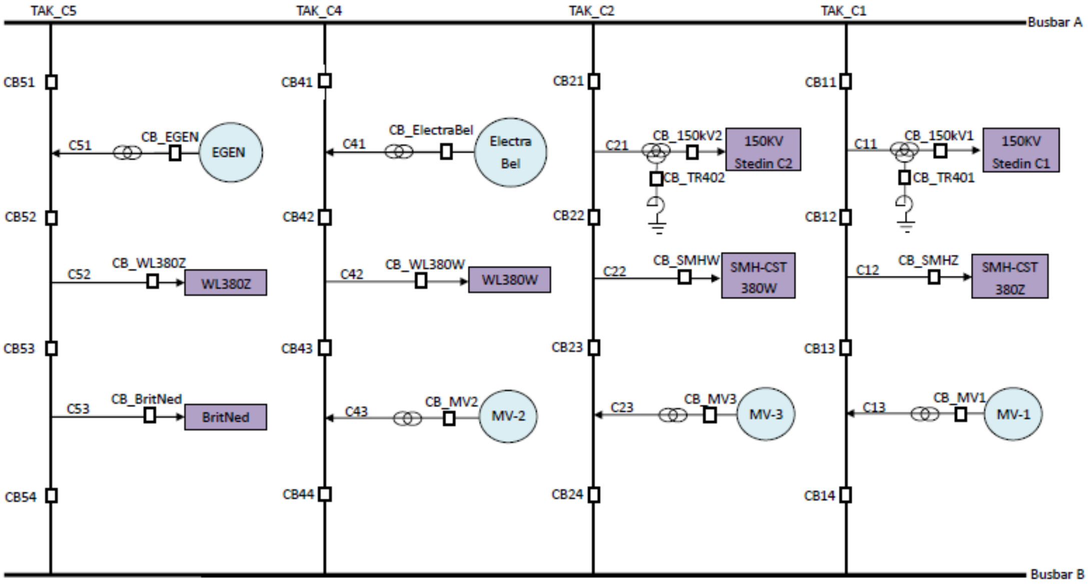


Fig 6. 4 Maasvlakte 380kV Substation Simplified Model

The protection zone principles of Maasvlakte 380kV substation are the same as those of the 4/3 circuit breakers substation, which have been explained in detail in Section 5.2.2.

The current transformers, voltage transformers, disconnecting switches and surge arrestors within one zone are not shown in the simplified model above. The location zone of these components can be found in Table 6-1.

The components failure statistics are given in Table 2-1. The unavailability of the zone can be calculated by equations 4-1 and 4-3. The failure frequency of the zones can be calculated by equation 5-1.

Table 6 - 1 Zone Data of Maasvlakte 380kV Substation

Zone Name	Zone Construction	Zone Data		Components Failure Frequency	Components Unavailability	Zone Failure Frequency	Zone Unavailability
		Data	Unit				
C51	disconnecting switch	1	-	0.003	2.74E-06	0.1239	4.89E-03
	current transformer	2	-	0.0002	5.48E-07		
	voltage transformer	1	-	0.0002	5.48E-07		
	surge arrestor	1	-	0.001	2.28E-07		
	C51 Cable	11	km	0.0063	4.32E-04		
	transformer	1	-	0.05	1.37E-04		
C52	current transformer	2	-	0.0002	5.48E-07	0.0506	4.73E-05
	disconnecting switch	2	-	0.003	2.74E-06		
	voltage transformer	1	-	0.0002	5.48E-07		
	C52 Line	20	km	0.0022	2.01E-06		
C53	disconnecting switch	1	-	0.003	2.74E-06	0.0041	4.44E-06
	voltage transformer	1	-	0.0002	5.48E-07		
	current transformer	1	-	0.0002	5.48E-07		
	C53 line	0.3	km	0.0022	2.01E-06		
C41	voltage transformer	1	-	0.0002	5.48E-07	0.0854	2.23E-03
	current transformer	2	-	0.0002	5.48E-07		
	transformer	1	-	0.05	1.37E-04		
	C41 cable	5.05	km	0.0063	4.32E-04		
	disconnecting switch	1	-	0.003	2.74E-06		
C42	current transformer	2	-	0.0002	5.48E-07	0.0506	4.73E-05
	disconnecting switch	2	-	0.003	2.74E-06		
	voltage transformer	1	-	0.0002	5.48E-07		
	C42 line	20	km	0.0022	2.01E-06		
C43	disconnecting switch	1	-	0.003	2.74E-06	0.0587	4.22E-04
	surge arrestor	1	-	0.001	2.28E-07		
	voltage transformer	1	-	0.0002	5.48E-07		
	current transformer	2	-	0.0002	5.48E-07		
	transformer	1	-	0.05	1.37E-04		
	C43 cable	0.65	km	0.0063	4.32E-04		
C21	current transformer	2	-	0.0002	5.48E-07	0.0620	3.72E-04

	voltage transformer	2	-	0.0002	5.48E-07		
	surge arrestor	1	-	0.001	2.28E-07		
	disconnecting switch	2	-	0.003	2.74E-06		
	C21 cable	0.525	km	0.0063	4.32E-04		
	transformer	1	-	0.05	1.37E-04		
	C21 150kV line	0.295	km	0.0031	2.83E-06		
C21 50kV	compensating coil	1	-	0.004	1.37E-06	0.0042	1.92E-06
	current transformer	1	-	0.0002	5.48E-07		
C22	current transformer	2	-	0.0002	5.48E-07	0.0792	7.34E-05
	disconnecting switch	2	-	0.003	2.74E-06		
	C22 line	33	km	0.0022	2.01E-06		
	voltage transformer	1	-	0.0002	5.48E-07		
C23	disconnecting switch	1	-	0.003	2.74E-06	0.0894	2.52E-03
	surge arrestor	1	-	0.001	2.28E-07		
	C23 cable	5.52	km	0.0063	4.32E-04		
	voltage transformer	1	-	0.0002	5.48E-07		
	current transformer	2	-	0.0002	5.48E-07		
	transformer	1	-	0.05	1.37E-04		
C11	current transformer	2	-	0.0002	5.48E-07	0.0626	3.98E-04
	voltage transformer	2	-	0.0002	5.48E-07		
	C11 cable	0.585	km	0.0063	4.32E-04		
	transformer	1	-	0.05	1.37E-04		
	C11 150kV line	0.36	km	0.0031	2.83E-06		
	surge arrestor	1	-	0.001	2.28E-07		
	disconnecting switch	2	-	0.003	2.74E-06		
C11 50kV	current transformer	1	-	0.0002	5.48E-07	0.0042	1.92E-06
	compensating coil	1	-	0.004	1.37E-06		
C12	current transformer	2	-	0.0002	5.48E-07	0.0792	7.34E-05
	disconnecting switch	2	-	0.003	2.74E-06		
	C12 line	33	km	0.0022	2.01E-06		
	voltage transformer	1	-	0.0002	5.48E-07		
C13	disconnecting switch	1	-	0.003	2.74E-06	0.0578	3.57E-04
	surge arrestor	1	-	0.001	2.28E-07		
	voltage transformer	1	-	0.0002	5.48E-07		
	current transformer	2	-	0.0002	5.48E-07		
	transformer	1	-	0.05	1.37E-04		
	C13 cable	0.5	km	0.0063	4.32E-04		
Busbar A	disconnecting switch	4	-	0.003	2.74E-06	0.0152	1.22E-05
	busbar	1	-	0.003	6.85E-07		
	voltage transformer	1	-	0.0002	5.48E-07		
Busbar	busbar	1	-	0.003	6.85E-07	0.0150	1.16E-05

B	disconnecting switch	4	-	0.003	2.74E-06		

According to the explanation in Chapter 5.2.2, the protection principles of Maasvlakte substation are listed in Table 6-2.

The event trees responding to this table can be found in the Appendix.
The Results are shown in section 6.3.

Table 6 - 2 Protection Principle of the Maasvlakte 380kV Substation

	Protection System Failures			Circuit Breakers Failures		
Fault Zone	Primary Protection	Back-up Protection	Consequences	Main Circuit Breakers	Back-up Circuit Breakers	Consequences
C51	Differential	Distance	Lost Generation: EGEN	CB51 CB52 CB_EGEN	CB41,CB21,CB11,CB53,CB_WL380Z	Lost Generation:EGEN Lost Line: WL380Z
C52	Differential	Distance	Lost Load:WL380Z	CB_WL380Z CB52 CB53	CB51,CB_EGEN,CB54,CB_BritNed	Lost Generation: EGEN Lost line:WL380Z,BritNed
C53	Differential	Distance	Lost Load: BritNed	CB_BritNed CB53 CB54	CB52,CB_WL380Z,CB44,CB24,CB14	Lost line:BritNed,WL380Z
C41	Differential	Distance	Lost Generation: ElectraBel	CB_ElectraBel CB41 CB42	CB51,CB21,CB11,CB43,CB_WL380W	Lost Generation: ElectraBel Lost line:WL380W
C42	Differential	Distance	Lost Load: WL380W	CB_WL380W CB42 CB43	CB41,CB_ElectraBel,CB44,CB_MV2	Lost Generation:MV_2,ElectraBel Lost line:WL380W
C43	Differential	Distance	Lost Generation: MV-2	CB_MV2 CB43 CB44	CB42,CB_WL380W,CB54,CB24,CB14	Lost Generation:MV_2 Lost line:WL380W

C21	Differential	Distance	Lost Load: 150kV Stedin C2	CB_TR402	CB51,CB41,CB11,CB23,CB_SMHW	Lost line:SMH380W,150kV2
				CB_150kV2		
				CB21		
				CB22		
C21 50kV side	Differential	Distance	No	CB_TR402	CB_150kV2,CB21,CB22	Lost line:150kV2
C22	Differential	Distance	Lost Load: SMH-CST 380W	CB_SMHW	CB21,CB_TR402,CB_150kV2,CB24,CB_MV3	Lost Generation:MV_3 Lost line:SMH380W,150kV2
				CB22		
				CB23		
C23	Differential	Distance	Lost Generation: MV-3	CB_MV3	CB22,CB_SMHW,CB54,CB44,CB14	Lost Generation:MV_3 Lost line:SMH380W
				CB23		
				CB24		
C11	Differential	Distance	Lost Load: 150kV Stedin C1	CB_TR401	CB51,CB41,CB21,CB13,CB_SMHZ	Lost line:SMH380Z,150kV1
				CB_150kV1		
				CB11		
				CB12		
C11 50kV side	Differential	Distance	No	CB_TR401	CB_150kV1,CB11,CB12	Lost line:150kV1
C12	Differential	Distance	Lost Load: SMH-CST 380Z	CB_SMHZ	CB11,CB_TR401,CB_150kV1,CB14,CB_MV1	Lost Generation:MV_1 Lost line:SMH380Z,150kV1
				CB12		
				CB13		
C13	Differential	Distance	Lost Generation: MV-1	CB_MV1	CB12,CB_SMHZ,CB54,CB44,CB24	Lost Generation:MV_1 Lost line:SMH380Z
				CB13		
				CB14		

busbar A	Busbar	Distance	Everything	CB51	CB52,CB_EGEN,CB42,CB_ElectraBel,CB22,CB_TR402,CB_150kV2,CB12,CB_TR401,CB_150kV1	Lost Generation:EGEN,ElectraBel Lost line:150kV2,150kV1
				CB41		
				CB21		
				CB11		
busbar B	Busbar	Distance	Everything	CB54	CB53,CB_BritNed,CB43,CB_MV2,CB23, CB_MV3,CB13,CB_MV1	Lost Line:BritNed Lost Generation: MV_2,MV_3,MV_1
				CB44		
				CB24		
				CB14		

6.3 Failure Results

Table 6 - 3 Specific Line/Generator Failure Results

Lost Line/Generation	Unavailability	Failure Frequency	Mean Time To Failure(year)	MTTR(repair time)(hours)
EGEN	4.89E-03	0.1242	8.0	345
ElectraBel	2.32E-03	0.0858	11.7	237
MV-1	3.58E-04	0.0582	17.2	54
MV-2	4.22E-04	0.0590	16.9	63
MV-3	2.52E-03	0.0899	11.1	246
WL380Z	6.98E-05	0.0514	19.5	12
WL380W	6.02E-05	0.0515	19.4	10
SMH380Z	7.80E-05	0.0801	12.5	9
SMH380W	8.75E-05	0.0802	12.5	10
BritNed	5.29E-06	0.0046	217.0	10
150kV1	3.99E-04	0.0631	15.9	55
150kV2	3.73E-04	0.0625	16.0	52

In Table 6-3, the failure statistics of specific lines/generators are shown.
The unavailability and failure frequency of a line/generator represents the probability/frequency that this line/generator is isolated from the substation due to any component's fault. These are calculated using the event trees.
The mean time to failure has the unit of years, and it represents the average time it takes before the specific line/generator is isolated due to a component's fault. It is calculated using equation 2-2.

The mean time to repair has the unit of hours, and it represents the average time it takes to locate and repair the fault, and then put the specific line/generator back into operation. According to equation 2-5,

$$\mathrm{MTTR} = \frac{U \times 8760}{f} = \frac{Q \times 8760}{f} \qquad 6-1$$

Therefore, an indication of the mean time to repair can be calculated according to the unavailability and failure frequency got from the event trees.
However, the mean time to repair is so dependent on the detailed failure situation that the result can only give a feeling about the system situation instead of giving a precise reference. For example, G1 could be isolated because the disconnecting switch on the branch in G1 zone fails. In this case, the repair time will mainly depend on the repair time or replacement time of the switch. If G1 is isolated because the step-up transformer explodes, then the mean time to repair will be more dependent on the repair time of the transformer, which can have a large range.
Because of the large scatter of mean time to repair, it is only calculated here to give

an indication rather than a precise result.

To make the comparison of the data in Table 6-3 more convenient, two bar graphs are shown below in Fig 6.5 and Fig 6.6.

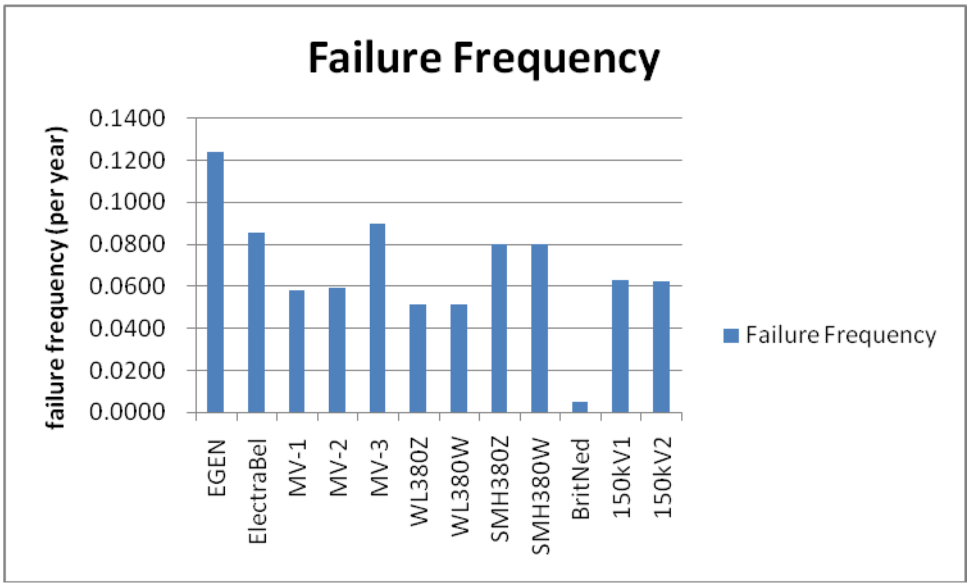


Fig 6. 5 Failure Frequency of Specific Line/Generator

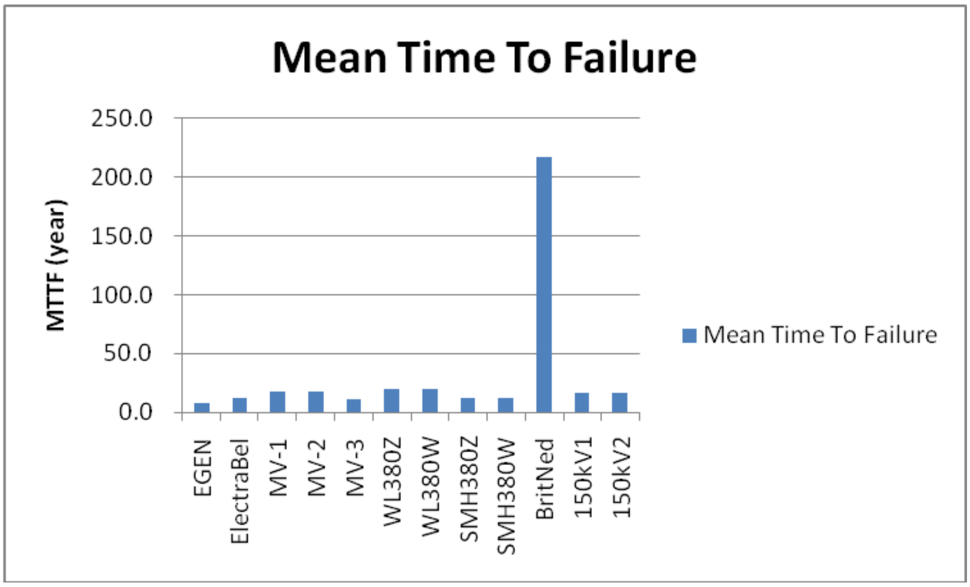


Fig 6. 6 Mean Time to Failure of Specific Line/Generator

As can be seen from the bar graphs above, the lines with similar parameters and positions in the substation share the same failure results. These are WL380Z and WL380W, SMH 380Z and SMH 380W, 150kV1 and 150kV2.

The failure frequency of BritNed is much smaller than that of the other lines. This is caused by the fact that, the dominant component in reliability evaluation is the line or cable. The longer the line, the larger the chance that a line fault occurs. The BritNed line adopted in this model does not include the long HVDC cable over the sea. And the line length of BritNed before reaching the cable is very small. Consequently, BritNed has a much smaller failure frequency than the other connections. Similarly, the indicated mean time to repair only reflects the repair of the connection to BritNed substation, not the repair time of the BritNed cable itself.

For the same reason, the failure frequency of EGEN is much higher than the other generators, because the cable that connected to EGEN is much longer than the others. This explanation applies to the difference of failure frequencies among all the generators.

Table 6 - 4 Multiple Lines/Generators Failure Statistics

number of loss line/generation at the same time	Unavailability	Failure Frequency	Mean Time To Failure (MTTF)	MTTR(repair time)
1	1.15E-02	0.8006	1.2	126
2	5.17E-05	0.0026	381.2	173
3	1.09E-06	0.0012	856.8	8
4	1.43E-07	0.0002	5536.7	7
12	2.38E-08	0.0000	33145.7	7
Total	1.15E-02	0.8046	1.2	126

In Table 6-4, the results of multiple lines/generators losses are listed. These failure results are calculated using the same method as used in Table 6-3. The total failure frequency (or unavailability) refers to the frequency (or probability) that one or more than one of the line/generator is isolated due to component faults.

It can be seen from the table above that, in most of the situations, there is only one line/generator being isolated as could be expected. The chance that two or more than two lines/generators fail at the same time is very small.

Attention has to be paid that the failure statistics of circuit breakers used in the study are based on a historical database. However, as the loading of the substation increases, the circuit breakers will be put into an operational situation that is much more close to the installed capacity than the past.

The short circuit current consists of two parts: a sinusoidal AC current and a DC component. When the loading of the substation increases, the short circuit current after a fault increases, this means that the DC component increases as well. Though the short circuit current in this situation is still smaller than the circuit breaker rated withstand current, the time constant increases significantly as the DC component increases. Then, the time constant is much larger than the circuit breakers rated time constant, which is a severe situation for the circuit breakers besides the high short circuit current. Therefore, the circuit breaker unavailability can become much larger than assumed.

To study whether an increase of the circuit breaker unavailability has a significant effect on the reliability of the whole substation, the circuit breaker unavailability can be increased, and the results from the event trees recalculated.

The circuit breakers unavailability used in the above study is: 0.0015.
Now, increase this by twice, which means that, U (CB) = 0.003.
The new failure results are listed below in Table 6-5 and Table 6-6.

Table 6 - 5 Specific Line/Generator Failure Statistics (U (CB) = 0.003)

Lost Line/Generation	Unavailability	Failure Frequency	Mean Time To Failure(year)	MTTR(repair time)(hours)
EGEN	4.89E-03	0.1246	8.0	344
ElectraBel	2.32E-03	0.0861	11.6	236
MV-1	3.58E-04	0.0587	17.0	53
MV-2	4.23E-04	0.0594	16.8	62
MV-3	2.52E-03	0.0903	11.1	245
WL380Z	9.16E-05	0.0520	19.2	15
WL380W	7.24E-05	0.0521	19.2	12
SMH380Z	8.19E-05	0.0807	12.4	9
SMH380W	1.01E-04	0.0810	12.4	11
BritNed	5.58E-06	0.0049	203.1	10
150kV1	3.99E-04	0.0635	15.7	55
150kV2	3.73E-04	0.0630	15.9	52

Table 6 - 6 Multiple Lines/Generators Failure Statistics (U (CB) = 0.003)

number of loss line/generation at the same time	Unavailability	Failure Frequency	Mean Time To Failure (MTTF)	MTTR(repair time)
1	1.14E-02	0.7969	1.3	126
2	1.03E-04	0.0052	191.2	173
3	2.18E-06	0.0023	429.7	8
4	2.84E-07	0.0004	2774.6	7
12	2.38E-08	0.0000	33145.7	7
Total	1.15E-02	0.8048	1.2	125

Compare Table 6-5 with Table 6-3. The bar graph is shown in Fig 6.7.
Clearly, after doubling the unavailability of the circuit breaker, the frequency of losing lines/generators all increased slightly. This shows that, the increase of failure statistics of the circuit breakers will increase the failure frequency of the lines/generators. However, compared to the total value of the failure frequency, this effect is quite small.

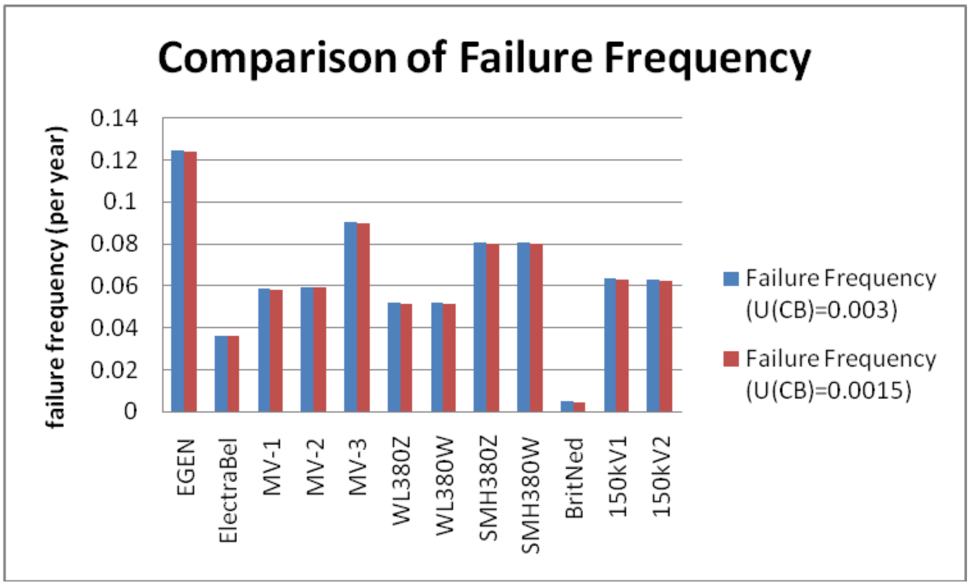


Fig 6. 7 Comparison of Failure Frequency When Changing U(CB)

Compare Table 6-6 with Table 6-4, the result of the failure frequency comparison is listed in Table 6-7 for reading convenience. As shown in Table 6-7, when increasing the unavailability of the circuit breaker, the frequency of losing only 1 line/generator is decreased slightly, while the frequency of losing multiple lines/generators is increased. In total, the frequency of losing line/generator is increased along with the increase of circuit breaker unavailability. This is because when the circuit breaker fails, the circuit breaker failure function will trip the neighboring line/generator. Therefore, there will be more than one line/generator lost at the same time. Consequently, the failure frequency of single line/generator lost is decreased, while the failure frequency of multiple line/generator lost is increased.

Table 6 - 7 Comparison of Failure Frequency When Changing U(CB)

number of loss line/generation at the same time	Failure Frequency (U(CB)=0.003)	MTTF (U(CB)=0.003)	Failure Frequency (U(CB)=0.0015)	MTTF (U(CB)=0.0015)
1	0.7969	1.3	0.8006	1.3
2	0.0052	208.3	0.0026	416.7
3	0.0023	434.8	0.0012	833.3
4	0.0004	2500.0	0.0002	5000.0
12	0		0	
Total	0.8048	1.3	0.8046	1.3

After the effect of unavailability of the circuit breaker is studied, the effect of unavailability of the protection system comes forward. Assume the unavailability of the protection system is doubled and recalculate all the event trees, the results are shown in the following figure and table.

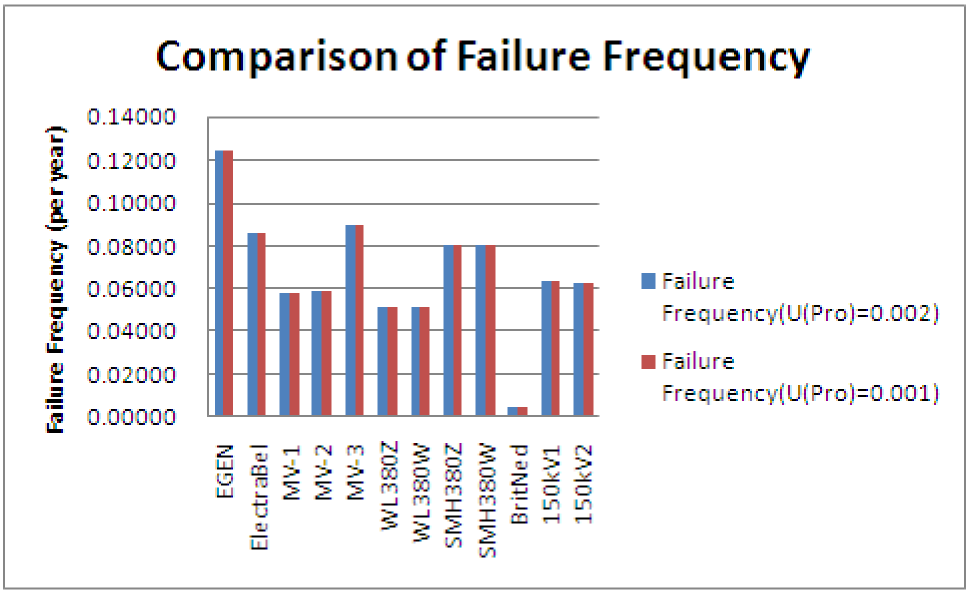


Fig 6. 8 Comparison of Failure Frequency When Changing U(Pro)

In Fig 6.8, the comparison of failure frequency for specific lines/generators when changing U(Pro) are shown. As shown in the figure, the effect of protection system is very small, much smaller than the effect of circuit breakers. When circuit breaker fails, the circuit breaker failure function will be activated and more than one line/generator will be lost at the same time. However, when the primary protection fails, the back-up protection system should react. Normally, the back-up protection and primary protection system cover the same zone and will trip the same circuit breakers. Therefore the effect of protection system failures is quite small.

Table 6 - 8 Comparison of Failure Frequency When Changing U(Pro)

number of loss line/generation at the same time	Failure Frequency (U(Pro)=0.001)	MTTF (U(Pro)=0.001)	Failure Frequency (U(Pro)=0.002)	MTTF (U(Pro)=0.002)
1	0.80063	1.2	0.80064	1.2
2	0.00262	381.2	0.00262	381.7
3	0.00117	856.8	0.00117	854.7
4	0.00018	5536.7	0.00018	5555.6
12	0.00003	33145.7	0.00006	16666.7
Total	0.80464	1.2	0.80466	1.2

The comparison of failure frequency for multiple lines/generators at the same time when changing U(Pro) is shown in the table above. As shown in the table, when double the unavailability of protection system, the total failure frequency of one and more than one of line/generator at the same time is increased slightly. However, the failure frequency of 12 lines/generators is doubled. This is because that, the 12 lines/generators are lost at the same time only when having busbar failures and primary protection fails. According to the event tree, the increase of protection system unavailability will have a big influence on the failure frequency of lines/generators. For the situation where less than 12 lines/generators are lost at the same time, circuit breaker failures are the dominant reason. Hence the effect of protection system unavailability is not obvious.

There are several input parameters for this study. Besides the unavailability of circuit breakers and protection systems, the change of components' failure frequency and mean time to repair also has effect on the final results.

When increase the components' failure frequency by twice, for the lines/generators, the failure frequency is also doubled, mean time to repair will stay the same. The unavailability and total outage time of the lines/generators will also be doubled roughly.

When increase the components' MTTR by twice, for the lines/generators, the failure frequency stays the same while MTTR is doubled. The unavailability and total outage time of the lines/generators will also be doubled roughly.

6.4 Load Flow Combination Analysis

In the power system, the outage of a generator or line will cause a loss of power. This can induce large economic losses. Therefore, not only the failure frequency, unavailability, mean time to failure and mean time to repair should be analyzed in a reliability evaluation, but also the average lost power should be studied.

In this section, the failure results calculated above will be combined with a Maasvlakte substation load flow scenario in 2020. The average lost power will be given as a result.

The load flow for the Maasvlakte substation in 2020 is used in this thesis. An example is given in Fig 6.7.

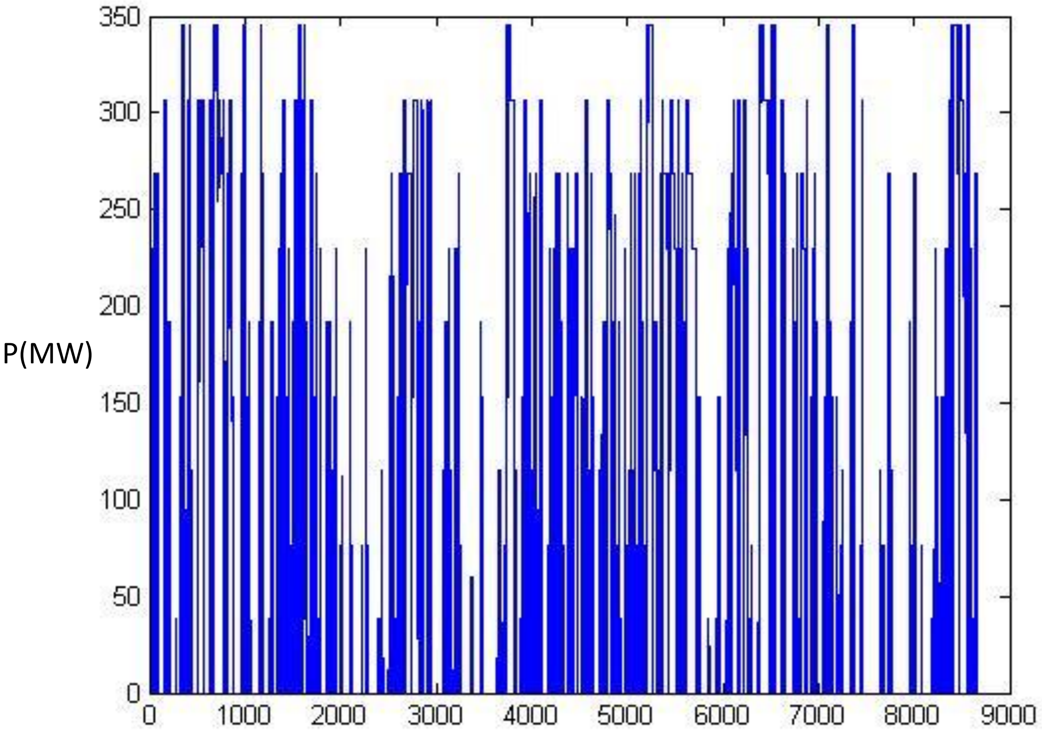


Fig 6. 9 Load Flow Scenario of EGEN in 2020

Fig 6,9 shows the load flow scenario of EGEN in 2020 for a whole year. The horizontal axis is time. The time unit is hours, and 8760 is the total amount of hours for a year. The vertical axis stands for the power, and its unit is MW.

As shown in the figure, the maximum power that EGEN supplies in the scenario is 345.1 MW. The calculated average power that EGEN supplies is 78.25 MW. EGEN's installed capacity is 444.60 MW.

According to Table 6-3, the failure frequency of EGEN is 0.1242 per year, while its mean time to repair is 345 hours.

$$\text{Total Outage Time} = f \times MTTR \tag{6 - 2}$$

$$\text{Average Lost Load} = \text{Total Outage Time} \times \text{Average Load} \tag{6 - 3}$$

$$\text{Maximum Lost Load (in scenario)} = \\ \text{Total Outage Time} \times \text{Maximum Load(in scenario)} \tag{6 - 4}$$

$$\text{Maximum Lost Load (installed Capacity)} = \\ \text{Total Outage Time} \times \text{Load (at Installed Capacity)} \tag{6 - 5}$$

The average lost load, maximum lost load under operation and maximum lost load when operating at the installed capacity can be calculated using equations 6-2 to 6-5.

The load flow scenario in 2020 for the other lines and generators can be found in the Appendix. The results of combining the failure results and the load flow scenario are shown in Table 6-9.

Table 6 - 9 Result of Combining the Failure Results and the Load Flow Scenario for 2020

Lost Line/ Generator	Failure Frequency	MTTR (hour)	Average Load (MW)	Maximum Load on scenario (MW)	Installed Capacity (MW)	Average Lost Load (MWh/year)	Maximum Lost Load in scenario (MWh/year)	Maximum Lost Generation for installed capacity (MWh/year)
EGEN	0.1242	345	78.25	345.10	444.60	3350.36	14776.11	19036.39
ElectraBel	0.0858	237	320.03	684.60	793.65	6505.39	13916.05	16132.73
MV-1	0.0582	54	185.91	219.10	500.00	582.60	686.62	1566.91
MV-2	0.0590	63	185.91	219.10	500.00	687.81	810.61	1849.86
MV-3	0.0899	246	503.79	1018.60	2000.00	11137.15	22517.77	44213.18
WL380Z	0.0514	12	256.45	772.30	-	156.82	472.26	-
WL380W	0.0515	10	263.19	699.10	-	138.72	368.47	-
SMH380Z	0.0801	9	272.36	777.70	-	186.03	531.21	-
SMH380W	0.0802	10	272.36	844.40	-	208.82	647.42	-
BritNed	0.0046	10	698.38	1000.00	-	32.39	46.38	-
150kV1	0.0631	55	159.75	246.80	-	557.99	862.03	-
150kV2	0.0625	52	159.75	254.90	-	521.51	832.11	-

In Table 6-9, the blue columns are the failure results taken from Table 6-3.
The table is to be read from left to right.

The first two purple columns show the load flow information got from the load flow scenario for 2020. The first two pink columns are the calculation results of the average lost load, and maximum lost load in the scenario. For the generators, the installed capacities are also used to calculate the worst case, in which the generators are operating at full capacity constantly. The installed capacity of the generators and the maximum lost load at installed capacity is shown in the third purple column, and third pink column respectively.

Care has to be taken that, WL380W and WL380Z are connected to the nearby substation in such a way that they are actually connected with each other in a loop. Therefore, the lost load calculated in the above form of WL380W and WL380Z is not precise. They can only be taken as an indication rather than precise result. The same rule applies for the SMH380W and SMH380Z.

The data in the above table is drawn as bar graphs Fig 6.10 and Fig 6.11.

The result is related not only to the load flow and failure frequency, but also to the mean time to repair. As has been explained before, the mean time to repair is a parameter that mainly depends on the real situation, and cannot be calculated precisely. Therefore, the data in Fig 6.10 and Fig 6.11 can be only regarded as an indication.

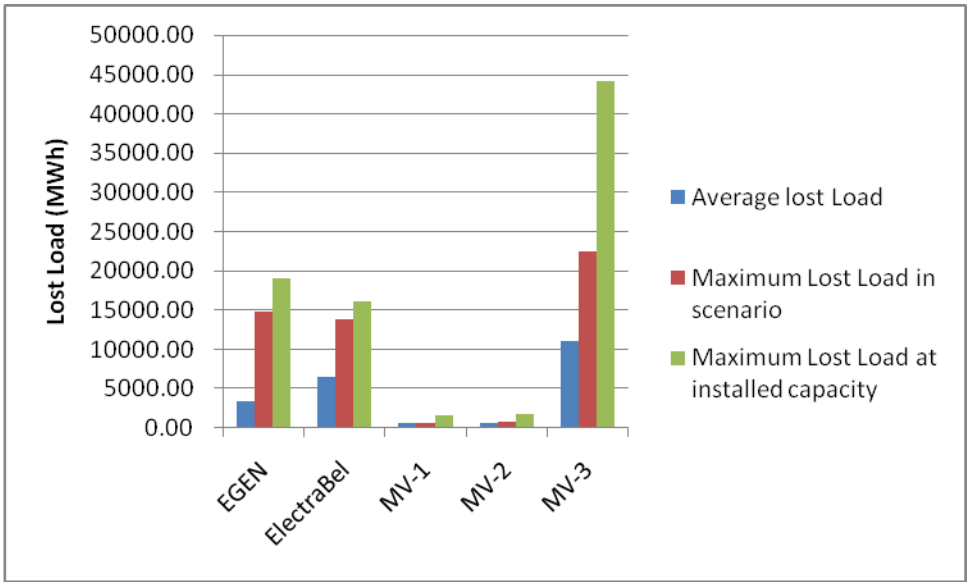


Fig 6. 10 Average and Maximum Lost Load (MWh) for Generators

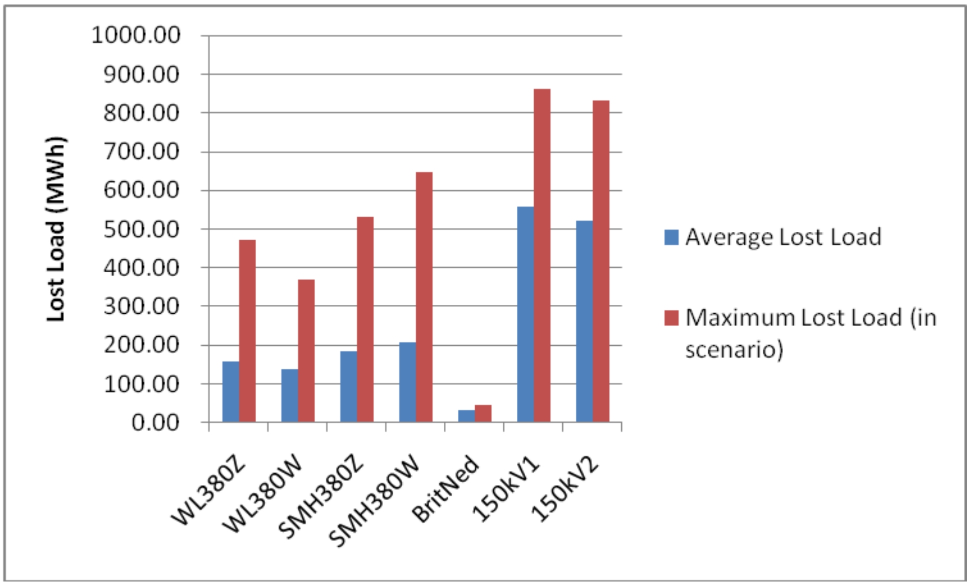


Fig 6. 11 Average and Maximum Lost Load (MWh) for the Lines

Care has to be taken that, WL380Z and WL380W are assumed to be irrelevant in this study, which is not the case in reality. They are actually connected with each other through another substation and can feed each other. Therefore the average lost load for WL380Z and WL380W in Fig 6.11 are not precise enough, and can be only taken as an indication. Same situation stands for SMH380Z and SMH380W.

In the Netherlands, the average sale price of 1 MWh is 50 euros and the cost of producing 1 MWh is around 30 euros. The economic lost caused by the lost of generators is listed in the table below.

Table 6 - 10 Economic Loss Caused by the Generator Loss

Lost Line/ Generator	Average Lost Money (euro/year)	Maximum Lost Money in Scenario (euro/year)	Maximum Lost Money (for installed capacity) (euro/year)
EGEN	100511	443283	571092
ElectraBel	183666	392890	455473
MV-1	17478	20599	47007
MV-2	20634	24318	55496
MV-3	334115	675533	1326396

As can be seen from Table 6-10, the economic loss caused by losing generators due to component failures within the substation is listed. The failures of the cable that is connected between the substation and the generators are included, same for the step-up transformer at the generator side. The data in this table can only be taken as an indication rather than a precise reference for the reason that has been explained above.

In Table 6-10, the losses caused by step-up transformer failures and cable failures are also considered. However, in reality, the step-up transformer, cable connected to generator and the generator side current transformer belong to the generation company and the losses caused by these component failures will not be paid by the electricity transmission system operator (TSO). Ignore theses component failures, and use the event trees to calculate the failure data again. The economic loss for the transmission system operator caused by the generator loss is listed below.

Table 6 - 11 Economic Loss Caused by the Generator Loss (Including Step-up Transformer and Cables)

Lost Line/ Generator	Average Lost Money (euro/year)	Maximum Lost Money in Scenario (euro/year)	Maximum Lost Money (for installed capacity) (euro/year)
EGEN	90	397	511
ElectraBel	349	746	865
MV-1	219	258	590
MV-2	214	252	574
MV-3	594	1202	2359

As shown in Table 6-11, the economic loss for TSO caused by the generator is much smaller compared to Table 6-10. This is because that the transformer and transmission cable is the dominant component in reliability evaluation. The economic loss that should be paid by TSO is listed in the table below, which ignores the failure of step-up transformer and cable. As can be seen from the table, the loss for TSO is very small that it is within the risk range that TSO can take.

Table 6 - 12 Economic loss caused by the Generator Loss (For TSO)

Lost Line/ Generator	Average Lost Money (euro/year)	Maximum Lost Money in Scenario (euro/year)	Maximum Lost Money (for installed capacity) (euro/year)
EGEN	90	397	511
ElectraBel	349	746	865
MV-1	219	258	590
MV-2	214	252	574
MV-3	594	1202	2359

6.5 Conclusions

In this chapter, the reliability of Maasvlakte substation was studied by the event tree method. Then, the failure results were combined with a load flow scenario of the

substation for2020. The average lost load and maximum lost load were calculated. According to the result, the dominant component in reliability evaluation of a system is the transformers and line/cable, because their failure frequency is large.
Besides, the lines/generators that share the similar components and positions are of same reliability level. For example, WL380Z & WL380W, SMH 380Z & SMH380W, and 150kV_1 & 150kV_2 are of same reliability level.

The effect of changing input parameters on the final results was also studied.
The failure frequency of line/generator is proportional to the unavailability of the circuit breakers. However, when increasing the unavailability of the circuit breakers, the frequency of losing only one line/generator is decreased because circuit breaker failure function will trip the neighboring lines/generators. The increase of total failure frequency for multiple lines/generators is caused by the circuit breaker failure functions. Therefore, when increasing the unavailability of the circuit breakers by two times, the failure frequency of single line/generator stays the same, while the failure frequency of multiple lines/generators is doubled.
When increasing the unavailability of the protection systems, the failure frequency of lines/generators is only slightly increased. The effect on the final results is much smaller than the effect of circuit breakers.
When increasing the failure frequency of input component, the failure frequency of lines/generators is also increased while the MTTR stays the same.
On the other hand, when increasing the MTTR of input component, the failure frequency of lines/generators stays the same while MTTR is increased proportionally.

By reliability calculation combined with load flow, the economic loss caused by generator loss can be given. The economic loss for TSO is very small and is within risk range.

Chapter 7 Conclusions

In this thesis, the reliability of substations subject to protection failures was studied. Assumed that one of the components inside the substation fails, the probability and frequency that one or more than one of the specific lines/generators becomes isolated were calculated using event tree analysis. The effect of power system protection on the reliability was studied as well.

Two case studies were analyzed in this thesis.
First, the reliability of substations with three different configurations was compared. As a result, the 4/3 circuit breakers substation and the one-and-a-half circuit breakers substation have an equal reliability. Compared to those two configurations, the typical double busbar substation has a lower reliability. Therefore, when designing a new substation, from reliability point of view, it will be a better option for the TSO to choose the 4/3 circuit breakers substation or one-and-a-half circuit breakers substation than the typical double busbar substation. This will offer the system a more reliable substation.

Second, the reliability of Maasvlakte 380kV substation was analyzed. The results show that the lines with similar parameters and locations have similar failure statistics. The lines/cables and transformers are the dominant components in the substation reliability evaluation. According to the results, the lines/generators that share the similar components and positions are of same reliability level. For example, WL380Z & WL380W, SMH 380Z & SMH380W, and 150kV_1 & 150kV_2 are of same reliability level. Besides, the failure frequency of line/generator is proportional to the unavailability of the circuit breakers. Then the failure results calculated using event trees were combined with a Maasvlakte substation load flow scenario for 2020. The average lost load and maximum lost load were calculated to offer an indication for estimating economic losses. As a conclusion, the economic loss for TSO is very small.

In general, being an inductive graphical method, event tree analysis combines the calculation with system principles perfectly. By reading an event tree, the effects of protection failures on the whole system can be seen both qualitatively and quantitatively. Therefore, it is a precise and intuitional method that can be used for power system reliability evaluation subject to protection failures.

In this thesis, all the components within the substation are assumed to be in operation, which means that maintenance is not considered. It will be more precise to include maintenance in the future reliability study.
Besides, the nearby substation in this thesis is considered to be a perfect circuit breaker, which is not the case in reality. By building a model that includes detailed information of the nearby substation, the effect of a fault within one substation to

the others can be analyzed in the future.

Moreover, except for the event tree analysis, Sequential Monte Carlo could also be an option for the reliability evaluation including protection failures. The comparison between different methods can be also interesting for the future studies.

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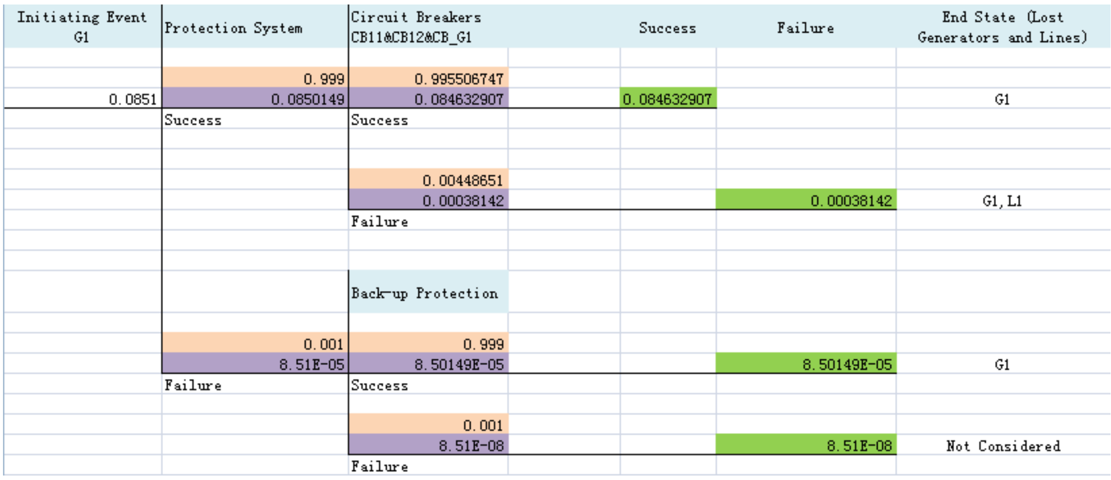
Appendix

A. Event Trees for the 4/3 Circuit Breakers Substation

In the following figures, the event trees for the 4/3 circuit breakers substation in Fig 5.1 are shown. The calculation process is also shown in the figure. The input and output data are failure frequencies.

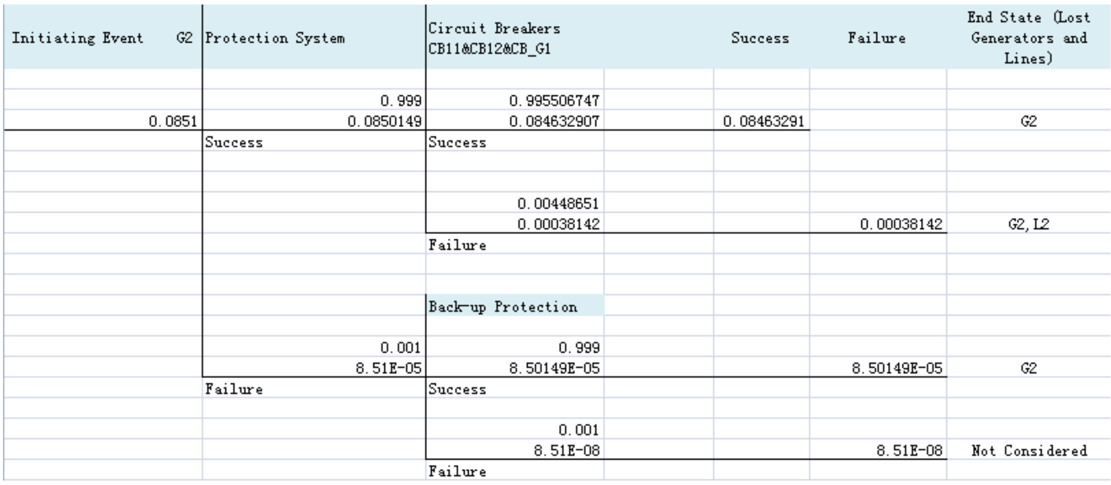


Initiating Event G1	Protection System	Circuit Breakers CB11&CB12&CB_G1	Success	Failure	End State (Lost Generators and Lines)
	0.999	0.995506747			
0.0851	0.0850149	0.084632907	0.084632907		G1
	Success	Success			
		0.00448651			
		0.00038142		0.00038142	G1, L1
		Failure			
		Back-up Protection			
	0.001	0.999			
	8.51E-05	8.50149E-05		8.50149E-05	G1
	Failure	Success			
		0.001			
		8.51E-08		8.51E-08	Not Considered
		Failure			

Fig A. 1 Event Tree for a Fault in G1 Zone

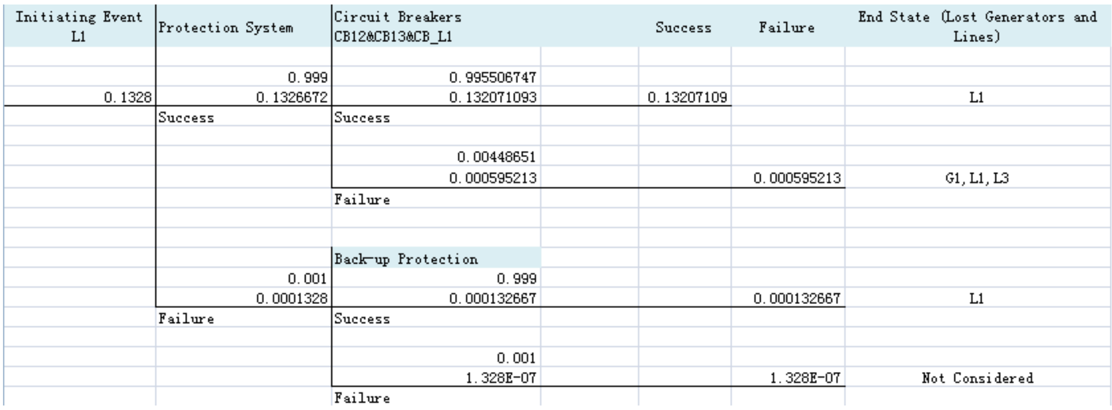
The calculation process is shown in the figure as well. Take Fig A.1 as an example. The data listed in the initiating event column represents for the failure frequency of G1 zone. The data in the pink blocks are failure probabilities of this stage only. The data in the purple blocks are calculated using the equation 4-5. The data in the green blocks are the failure frequencies of each state.

The following figures in the Appendix follows the same rules.



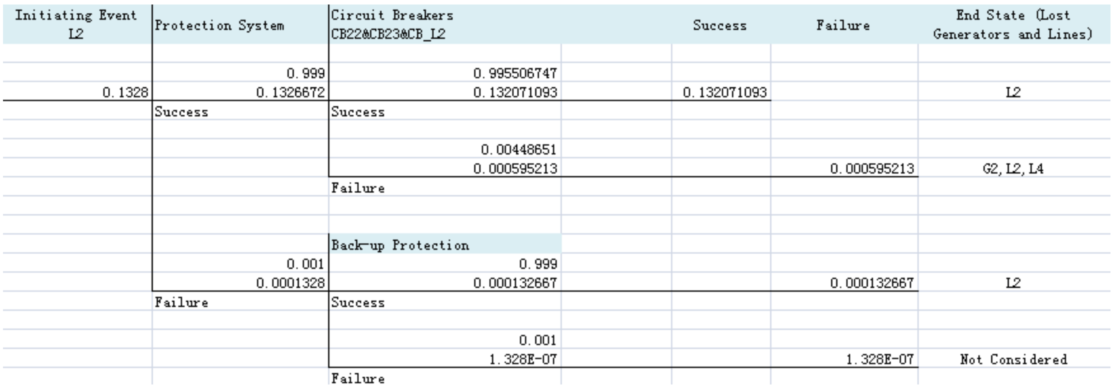
Initiating Event G2	Protection System	Circuit Breakers CB11&CB12&CB_G1	Success	Failure	End State (Lost Generators and Lines)
	0.999	0.995506747			
0.0851	0.0850149	0.084632907	0.08463291		G2
	Success	Success			
		0.00448651			
		0.00038142		0.00038142	G2, L2
		Failure			
		Back-up Protection			
	0.001	0.999			
	8.51E-05	8.50149E-05		8.50149E-05	G2
	Failure	Success			
		0.001			
		8.51E-08		8.51E-08	Not Considered
		Failure			

Fig A. 2 Event Tree for a Fault in G2 Zone



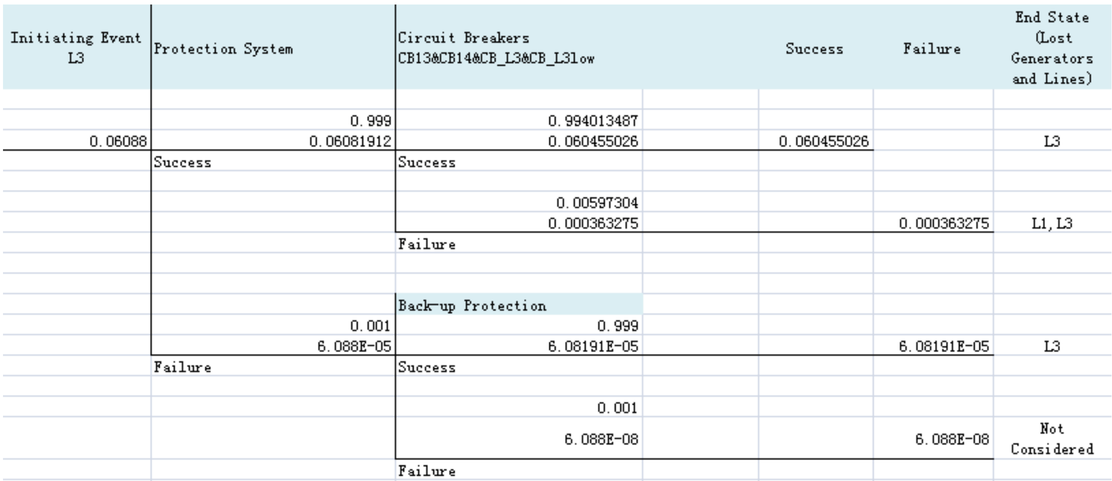
Initiating Event L1	Protection System	Circuit Breakers CB12&CB13&CB_L1	Success	Failure	End State (Lost Generators and Lines)
	0.999	0.995506747			
0.1328	0.1326672	0.132071093	0.13207109		L1
	Success	Success			
		0.00448651			
		0.000595213		0.000595213	G1, L1, L3
		Failure			
		Back-up Protection			
	0.001	0.999			
	0.0001328	0.000132667		0.000132667	L1
	Failure	Success			
		0.001			
		1.328E-07		1.328E-07	Not Considered
		Failure			

Fig A. 3 Event Tree for a Fault in L1 Zone



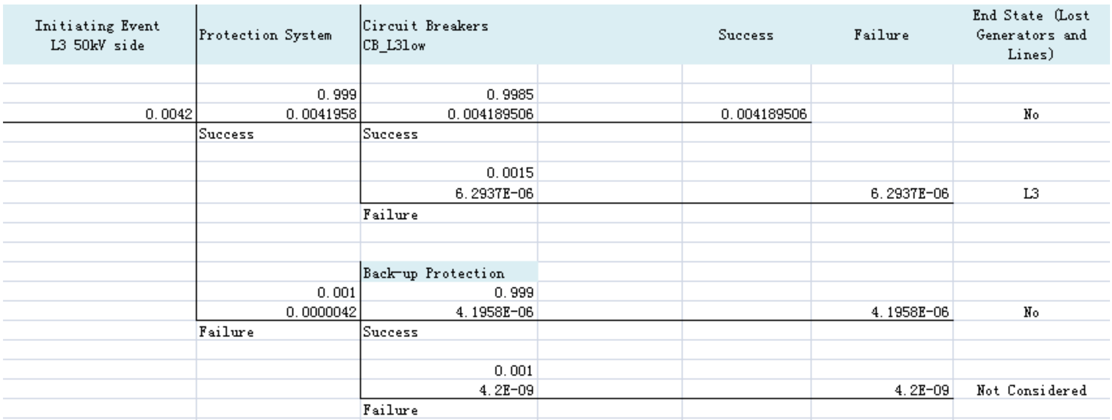
Initiating Event L2	Protection System	Circuit Breakers CB22&CB23&CB_L2	Success	Failure	End State (Lost Generators and Lines)
	0.999	0.995506747			
0.1328	0.1326672	0.132071093	0.132071093		L2
	Success	Success			
		0.00448651			
		0.000595213		0.000595213	G2, L2, L4
		Failure			
		Back-up Protection			
	0.001	0.999			
	0.0001328	0.000132667		0.000132667	L2
	Failure	Success			
		0.001			
		1.328E-07		1.328E-07	Not Considered
		Failure			

Fig A. 4 Event Tree for a Fault in L2 Zone



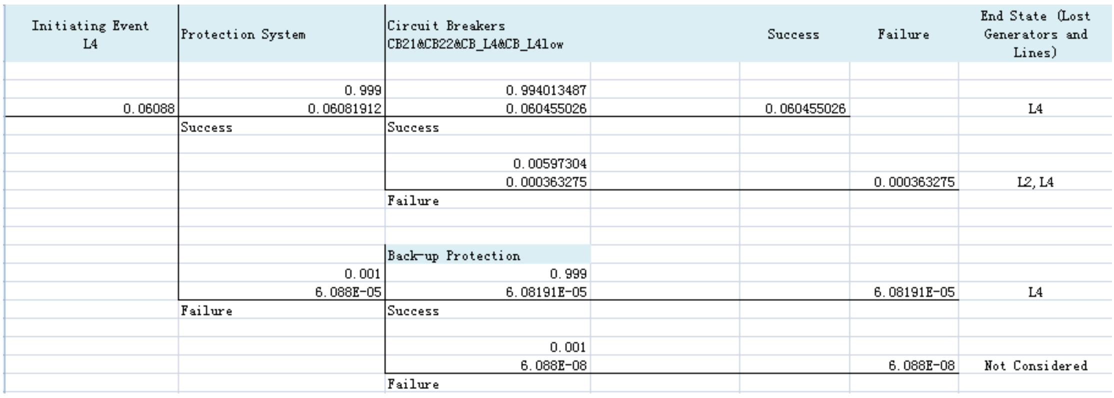
Initiating Event L3	Protection System	Circuit Breakers CB13&CB14&CB_L3&CB_L3low	Success	Failure	End State (Lost Generators and Lines)
	0.999	0.994013487			
0.06088	0.06081912	0.060455026	0.060455026		L3
	Success	Success			
		0.00597304			
		0.000363275		0.000363275	L1, L3
		Failure			
		Back-up Protection			
	0.001	0.999			
	6.088E-05	6.08191E-05		6.08191E-05	L3
	Failure	Success			
		0.001			
		6.088E-08		6.088E-08	Not Considered
		Failure			

Fig A. 5 Event Tree for a Fault in L3 Zone



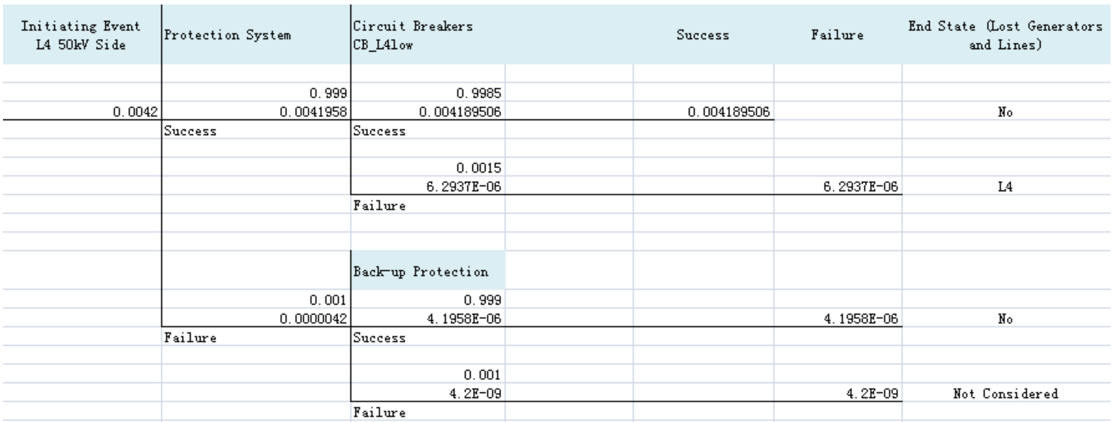
Initiating Event L3 50kV side	Protection System	Circuit Breakers CB_L3low	Success	Failure	End State (Lost Generators and Lines)
	0.999	0.9985			
0.0042	0.0041958	0.004189506	0.004189506		No
	Success	Success			
		0.0015			
		6.2937E-06		6.2937E-06	L3
		Failure			
		Back-up Protection			
	0.001	0.999			
	0.0000042	4.1958E-06		4.1958E-06	No
	Failure	Success			
		0.001			
		4.2E-09		4.2E-09	Not Considered
		Failure			

Fig A. 6 Event Tree for a Fault in L3 50kV Zone



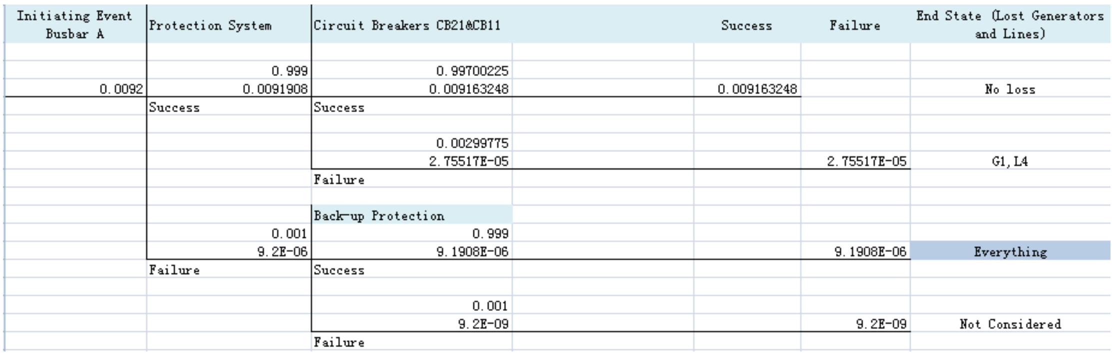
Initiating Event L4	Protection System	Circuit Breakers CB21&CB22&CB_L4&CB_L4low	Success	Failure	End State (Lost Generators and Lines)
	0.999	0.994013487			
0.06088	0.06081912	0.060455026	0.060455026		L4
	Success	Success			
		0.00597304			
		0.000363275		0.000363275	L2, L4
		Failure			
		Back-up Protection			
	0.001	0.999			
	6.088E-05	6.08191E-05		6.08191E-05	L4
	Failure	Success			
		0.001			
		6.088E-08		6.088E-08	Not Considered
		Failure			

Fig A. 7 Event Tree for a Fault in L4 Zone



Initiating Event L4 50kV Side	Protection System	Circuit Breakers CB_L4low	Success	Failure	End State (Lost Generators and Lines)
	0.999	0.9985			
0.0042	0.0041958	0.004189506	0.004189506		No
	Success	Success			
		0.0015			
		6.2937E-06		6.2937E-06	L4
		Failure			
		Back-up Protection			
	0.001	0.999			
	0.0000042	4.1958E-06		4.1958E-06	No
	Failure	Success			
		0.001			
		4.2E-09		4.2E-09	Not Considered
		Failure			

Fig A. 8 Event Tree for a Fault in L4 50kV Zone



Initiating Event Busbar A	Protection System	Circuit Breakers CB21&CB11	Success	Failure	End State (Lost Generators and Lines)
	0.999	0.99700225			
0.0092	0.0091908	0.009163248	0.009163248		No loss
	Success	Success			
		0.00299775			
		2.75517E-05		2.75517E-05	G1, L4
		Failure			
		Back-up Protection			
	0.001	0.999			
	9.2E-06	9.1908E-06		9.1908E-06	Everything
	Failure	Success			
		0.001			
		9.2E-09		9.2E-09	Not Considered
		Failure			

Fig A. 9 Event Tree for a Fault in Busbar A Zone

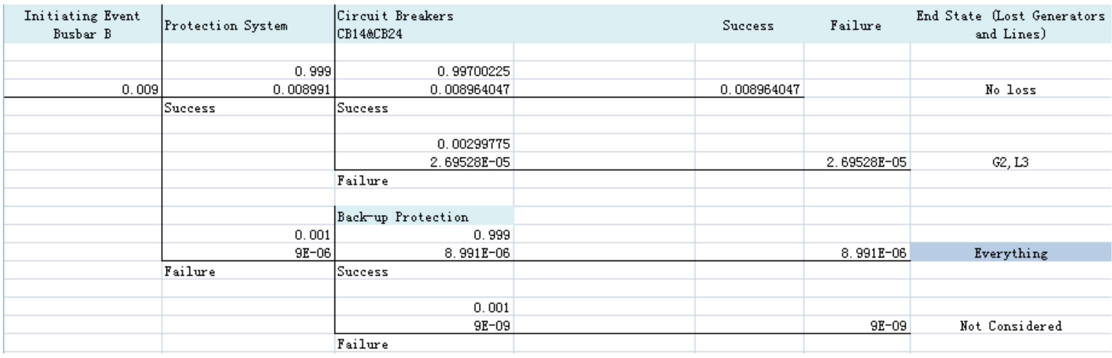


Fig A. 10 Event Tree for a Fault in Busbar B Zone

B. Event Trees for the One-and-a-Half Circuit Breakers Substation

In the following figures, the event trees for the one-and-a-half circuit breakers substation in Fig 5.12 are shown. The calculation process is also shown in the figure. The input and output data are failure frequencies.

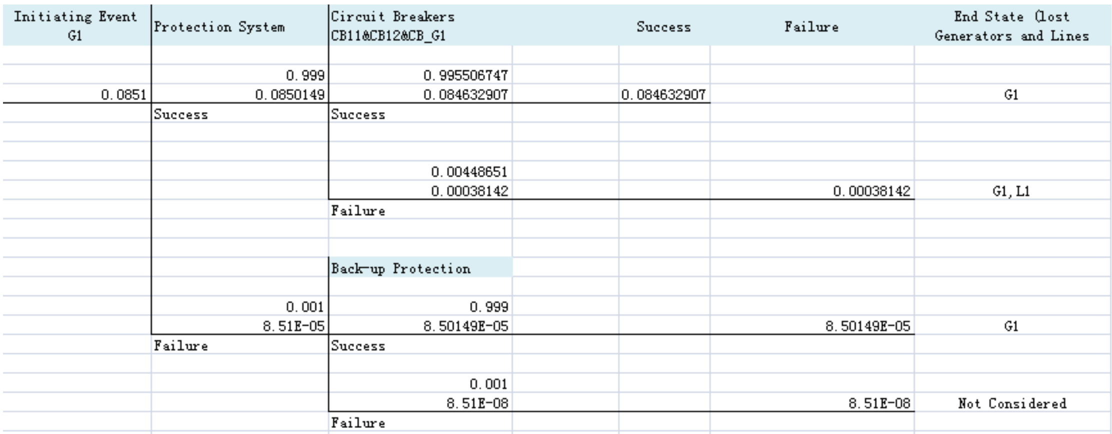


Fig B. 1 Event Tree for a Fault in G1 Zone

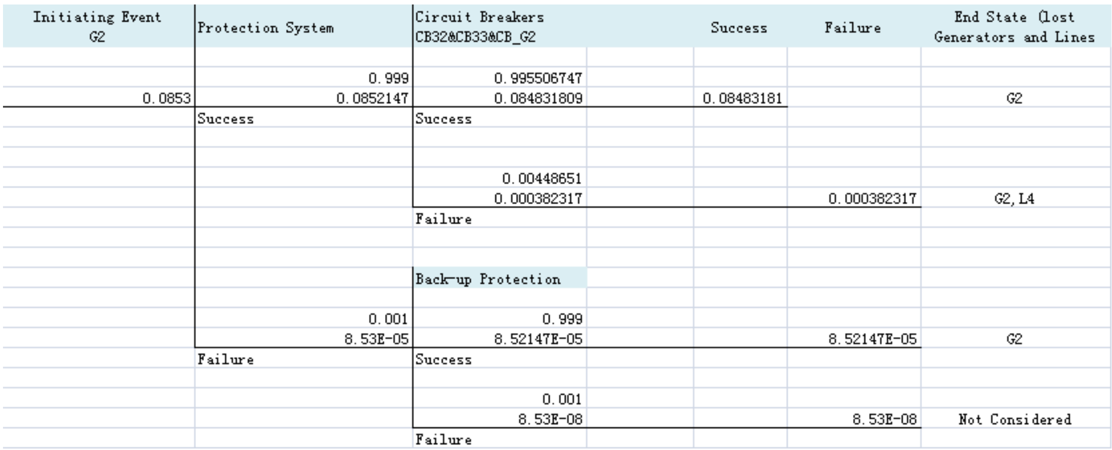


Fig B. 2 Event Tree for a Fault in G2 Zone

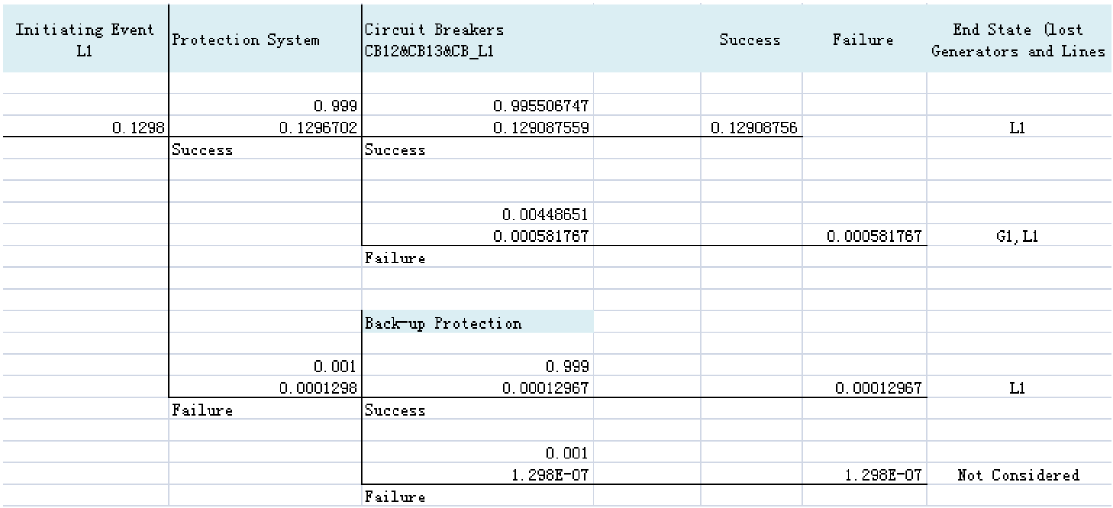


Fig B. 3 Event Tree for a Fault in L1 Zone

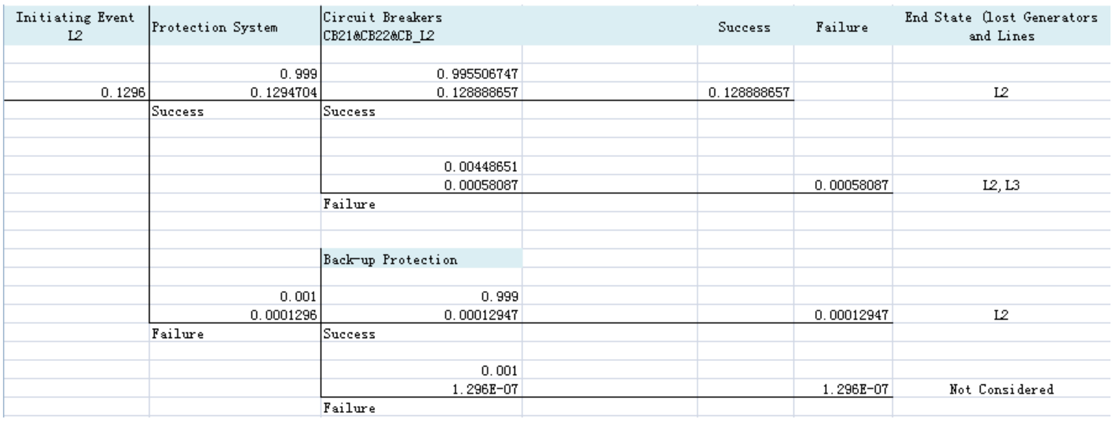


Fig B. 4 Event Tree for a Fault in L2 Zone

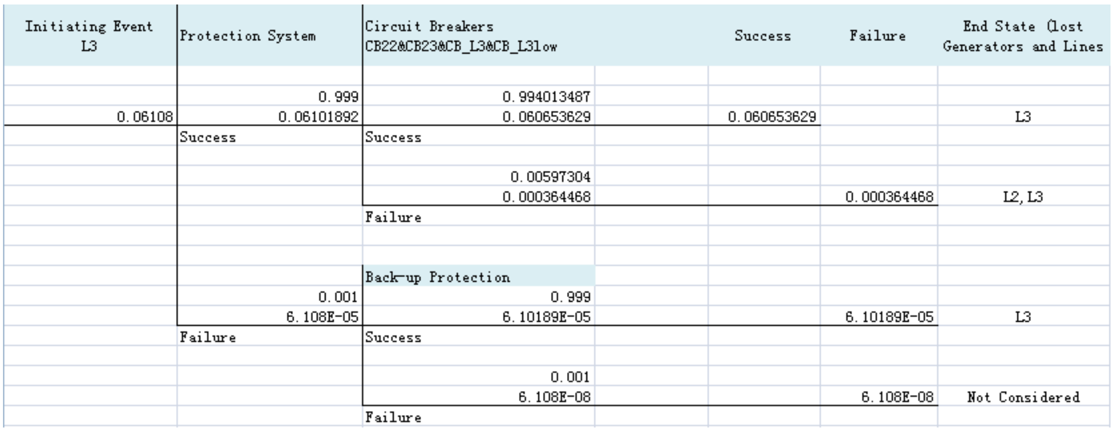


Fig B. 5 Event Tree for a Fault in L3 Zone

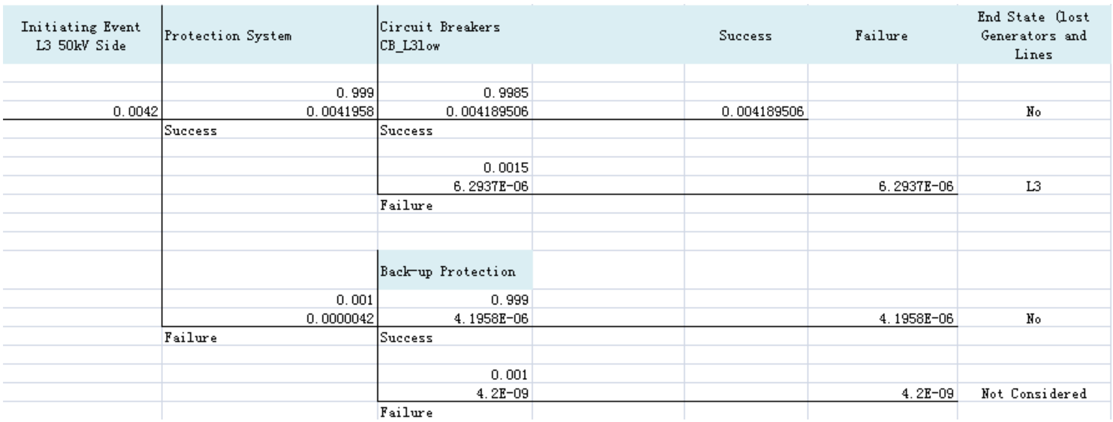


Fig B. 6 Event Tree for a Fault in L3 50kV Zone

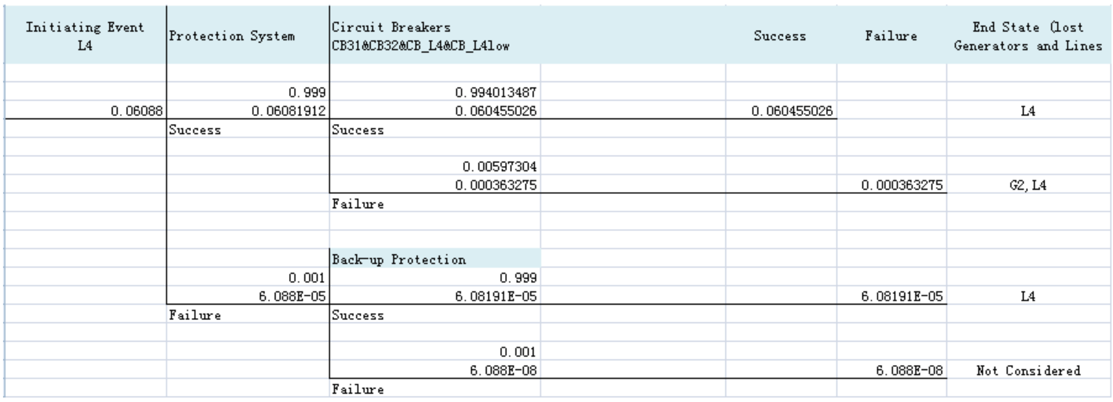


Fig B. 7 Event Tree for a Fault in L4 Zone

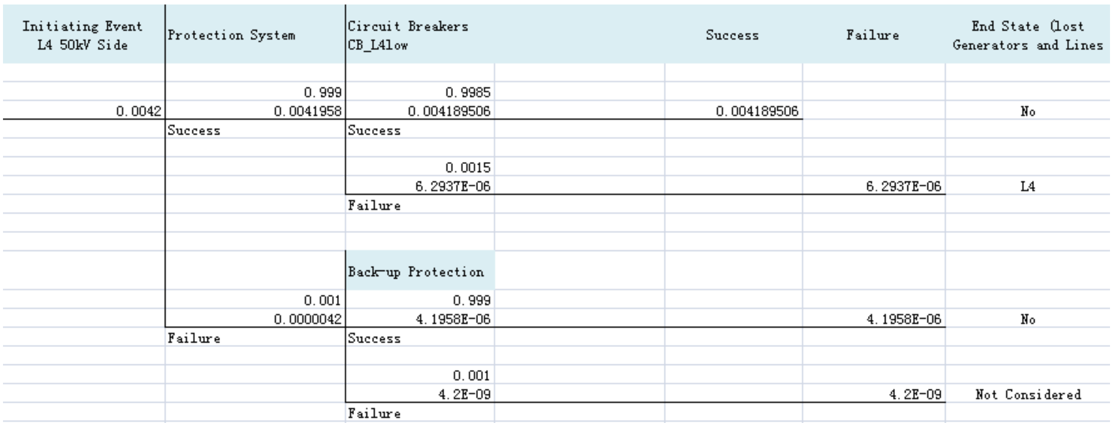


Fig B. 8 Event Tree for a Fault in L4 50kV Zone

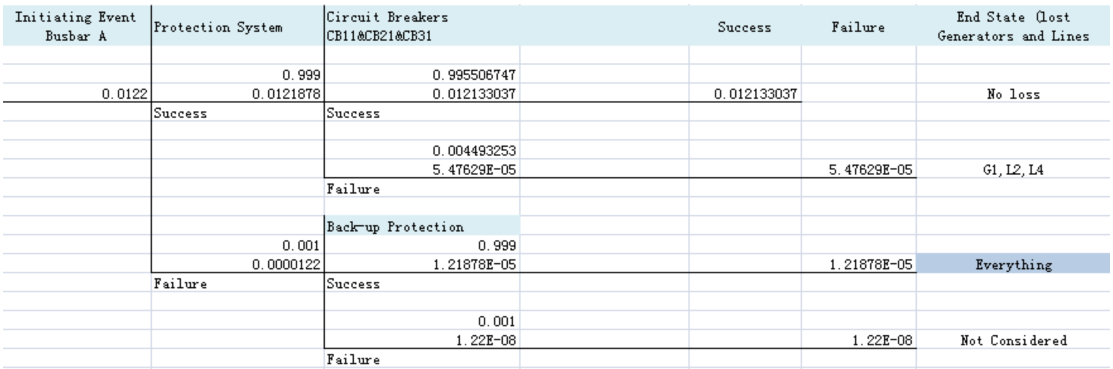
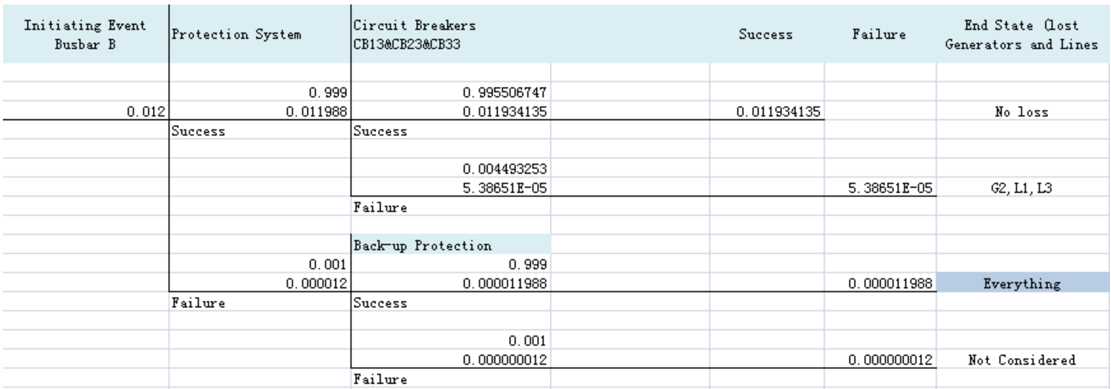


Fig B. 9 Event Tree for a Fault in Busbar A Zone

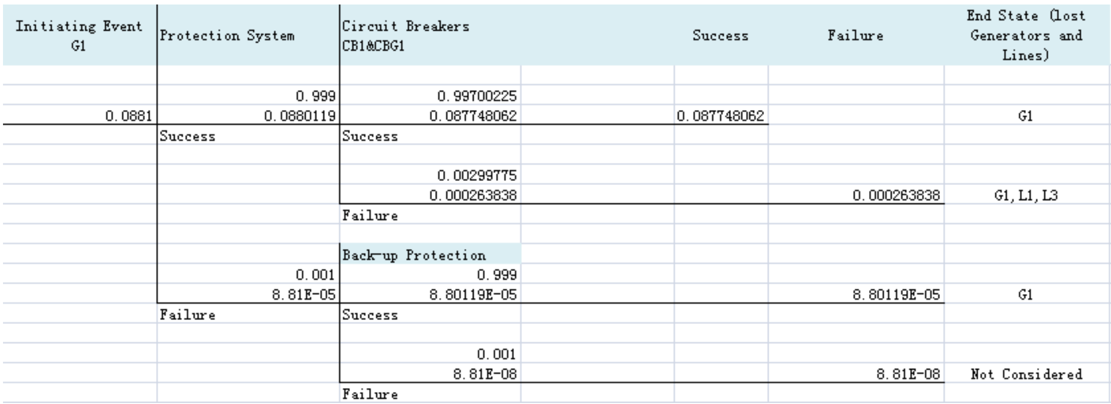


Initiating Event Busbar B	Protection System	Circuit Breakers CB13&CB23&CB33		Success	Failure	End State (Lost Generators and Lines
	0.999	0.995506747				
0.012	0.011988	0.011934135		0.011934135		No loss
	Success	Success				
		0.004493253				
		5.38651E-05			5.38651E-05	G2, L1, L3
		Failure				
		Back-up Protection				
	0.001	0.999				
	0.000012	0.000011988			0.000011988	Everything
	Failure	Success				
		0.001				
		0.000000012			0.000000012	Not Considered
		Failure				

Fig B. 10 Event Tree for a Fault in Busbar B Zone

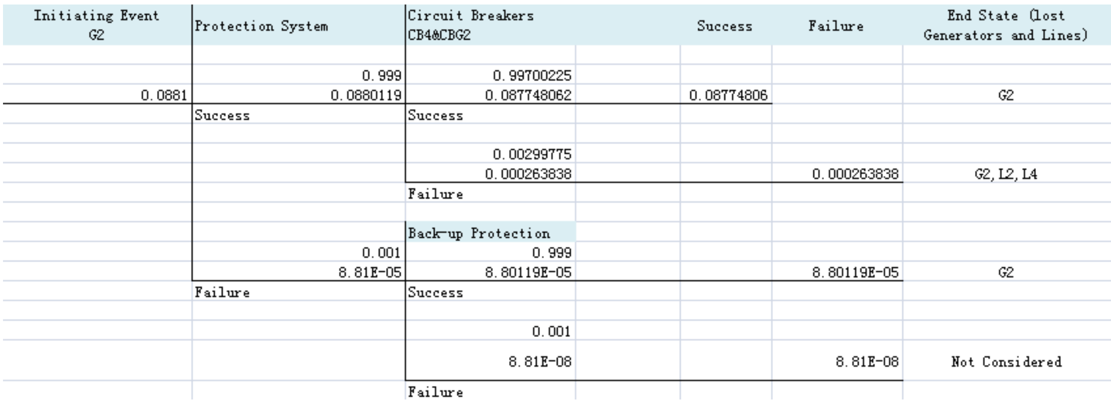
C. Event Trees for the Typical Double Busbar Substation

In the following figures, the event trees for the typical double busbar substation in Fig 5.13 are shown. The calculation process is also shown in the figure. The input and output data are failure frequencies.



Initiating Event G1	Protection System	Circuit Breakers CB1&CBG1		Success	Failure	End State (Lost Generators and Lines)
	0.999	0.99700225				
0.0881	0.0880119	0.087748062		0.087748062		G1
	Success	Success				
		0.00299775				
		0.000263838			0.000263838	G1, L1, L3
		Failure				
		Back-up Protection				
	0.001	0.999				
	8.81E-05	8.80119E-05			8.80119E-05	G1
	Failure	Success				
		0.001				
		8.81E-08			8.81E-08	Not Considered
		Failure				

Fig C. 1 Event Tree for a Fault in G1 Zone



Initiating Event G2	Protection System	Circuit Breakers CB4&CBG2		Success	Failure	End State (Lost Generators and Lines)
	0.999	0.99700225				
0.0881	0.0880119	0.087748062		0.08774806		G2
	Success	Success				
		0.00299775				
		0.000263838			0.000263838	G2, L2, L4
		Failure				
		Back-up Protection				
	0.001	0.999				
	8.81E-05	8.80119E-05			8.80119E-05	G2
	Failure	Success				
		0.001				
		8.81E-08			8.81E-08	Not Considered
		Failure				

Fig C. 2 Event Tree for a Fault in G2 Zone

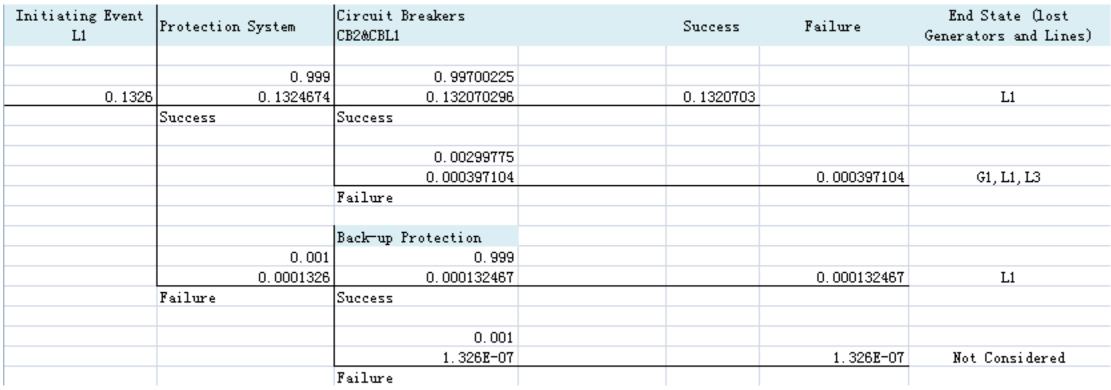


Fig C. 3 Event Tree for a Fault in L1 Zone

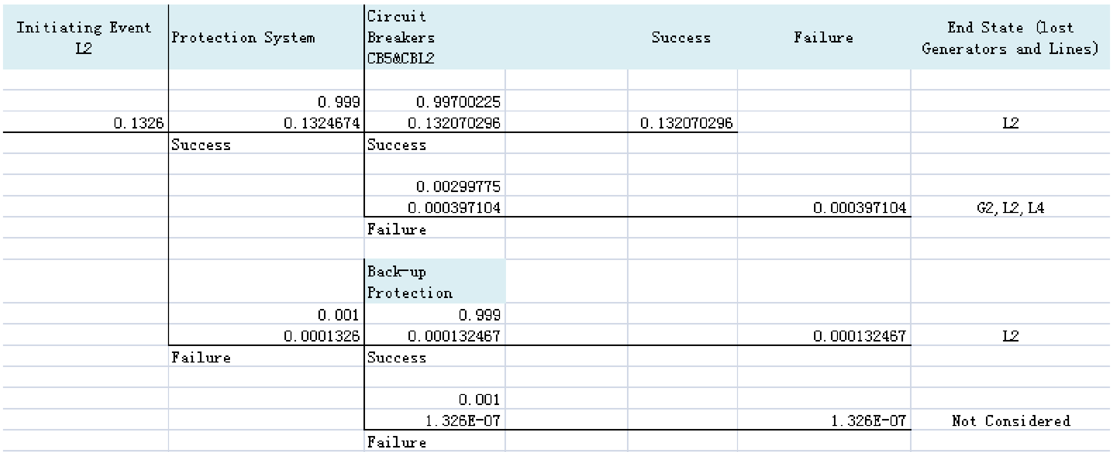


Fig C. 4 Event Tree for a Fault in L2 Zone

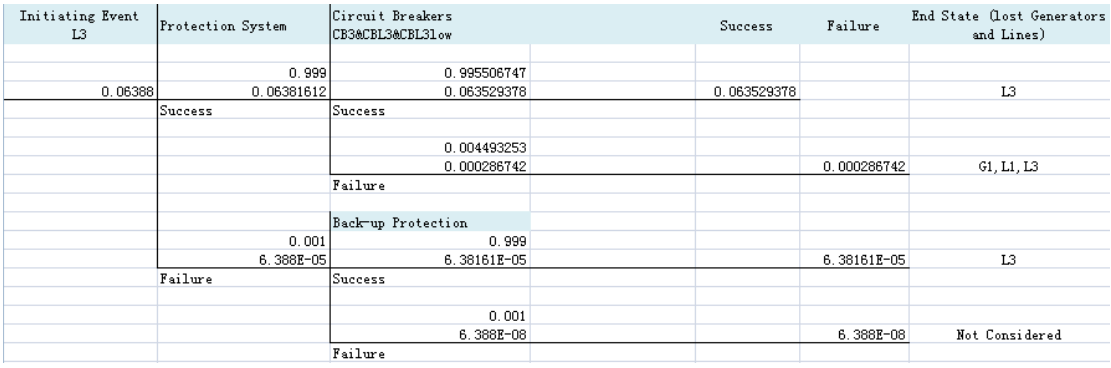
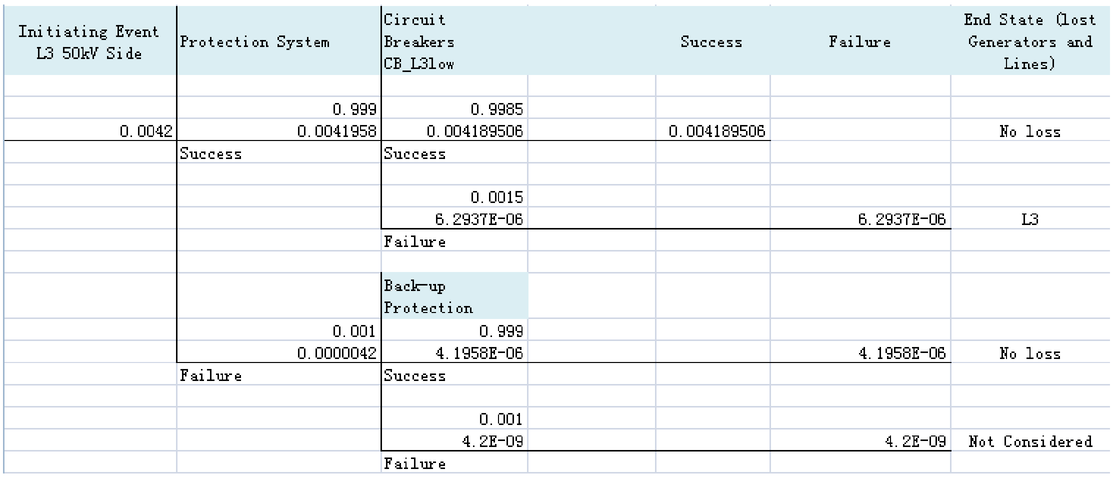
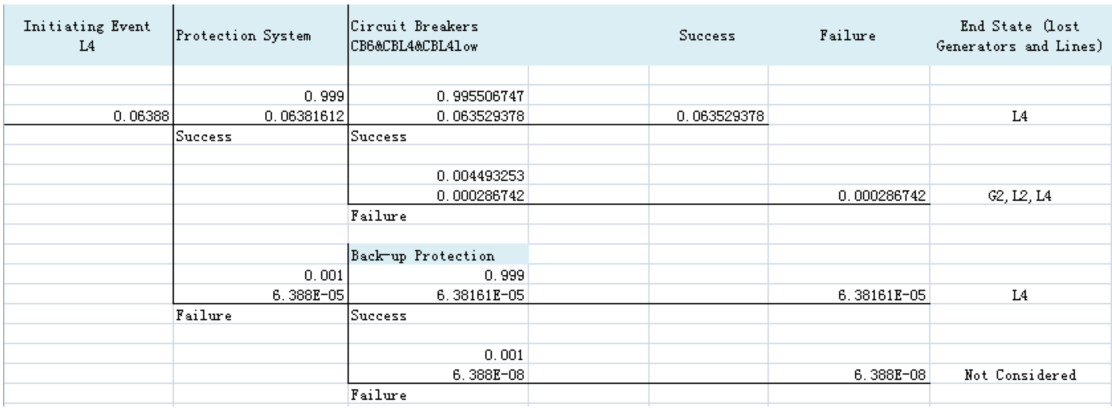


Fig C. 5 Event Tree for a Fault in L3 Zone



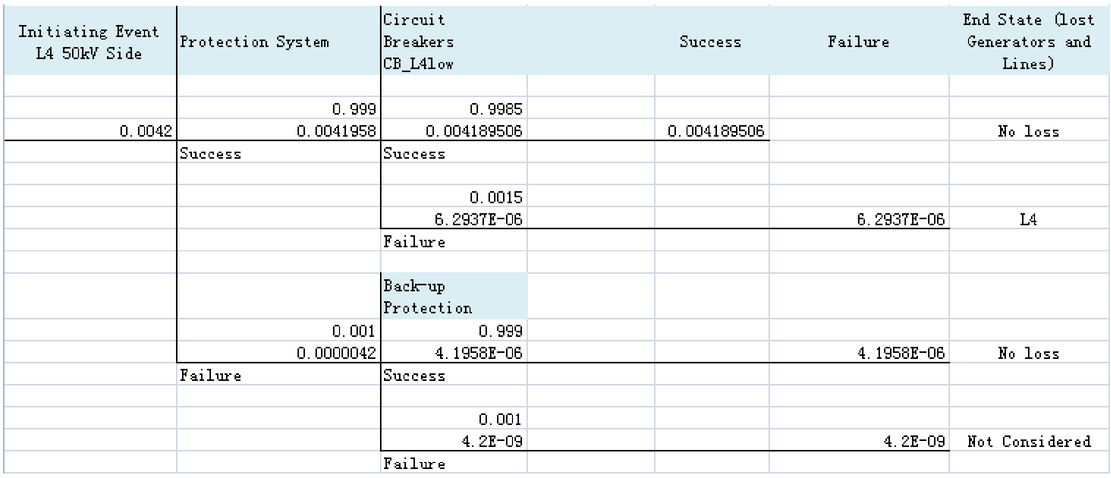
Initiating Event L3 50kV Side	Protection System	Circuit Breakers CB_L3low		Success	Failure	End State (lost Generators and Lines)
	0.999	0.9985				
0.0042	0.0041958	0.004189506		0.004189506		No loss
	Success	Success				
		0.0015				
		6.2937E-06			6.2937E-06	L3
		Failure				
		Back-up Protection				
	0.001	0.999				
	0.0000042	4.1958E-06			4.1958E-06	No loss
	Failure	Success				
		0.001				
		4.2E-09			4.2E-09	Not Considered
		Failure				

Fig C. 6 Event Tree for a Fault in L3 50kV Side Zone



Initiating Event L4	Protection System	Circuit Breakers CB6&CBL4&CBL4low		Success	Failure	End State (lost Generators and Lines)
	0.999	0.995506747				
0.06388	0.06381612	0.063529378		0.063529378		L4
	Success	Success				
		0.004493253				
		0.000286742			0.000286742	G2, L2, L4
		Failure				
		Back-up Protection				
	0.001	0.999				
	6.388E-05	6.38161E-05			6.38161E-05	L4
	Failure	Success				
		0.001				
		6.388E-08			6.388E-08	Not Considered
		Failure				

Fig C. 7 Event Tree for a Fault in L4 Zone



Initiating Event L4 50kV Side	Protection System	Circuit Breakers CB_L4low		Success	Failure	End State (lost Generators and Lines)
	0.999	0.9985				
0.0042	0.0041958	0.004189506		0.004189506		No loss
	Success	Success				
		0.0015				
		6.2937E-06			6.2937E-06	L4
		Failure				
		Back-up Protection				
	0.001	0.999				
	0.0000042	4.1958E-06			4.1958E-06	No loss
	Failure	Success				
		0.001				
		4.2E-09			4.2E-09	Not Considered
		Failure				

Fig C. 8 Event Tree for a Fault in L4 50kV Side Zone

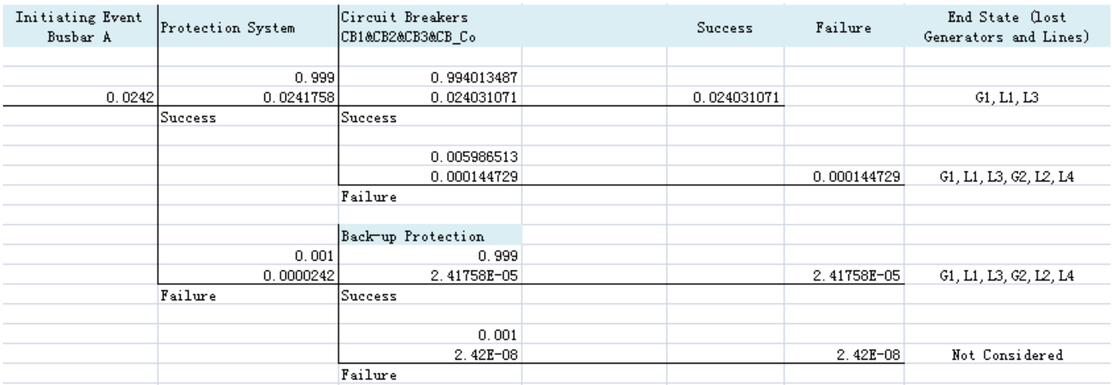


Fig C. 9 Event Tree for a Fault in Busbar A Zone

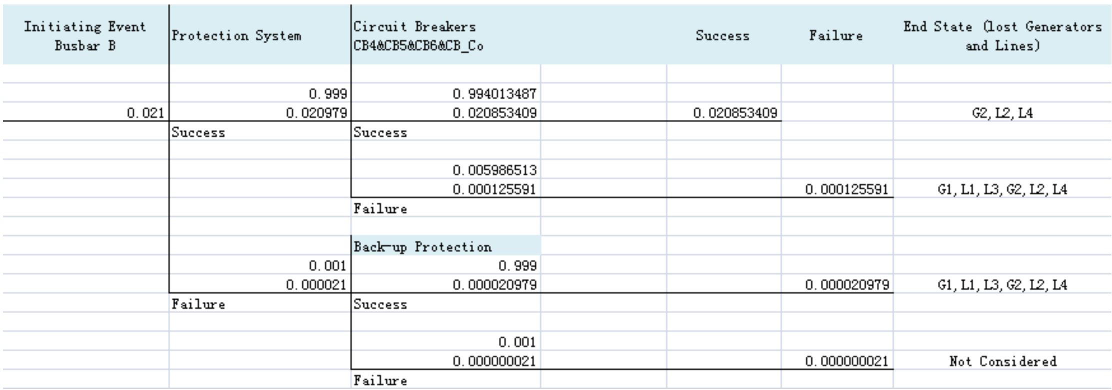


Fig C. 10 Event Tree for a Fault in Busbar B Zone

D. Event Trees for Maasvlakte 380kV Substation

In the following figures, the event trees for Maasvlakte 380kV substation in Fig 6.4 are shown. The calculation process is also shown in the figure. The input and output data are failure frequencies.

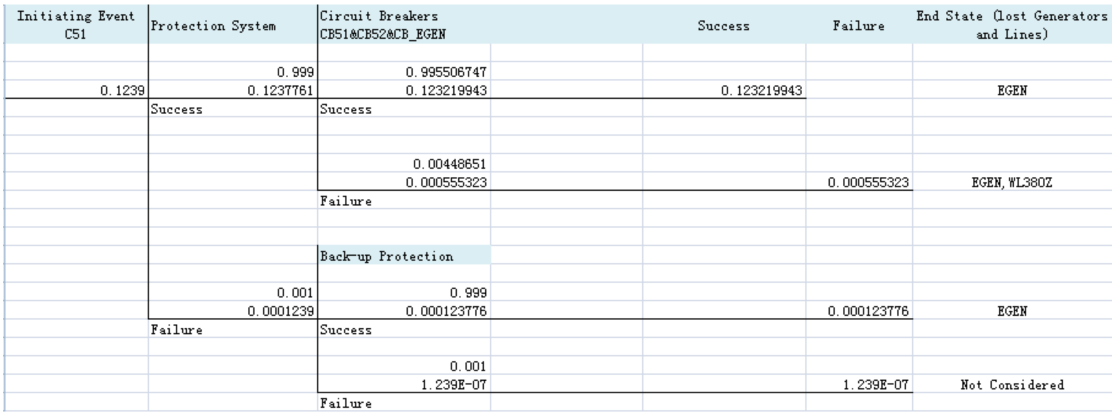


Fig D. 1 Event Tree for a Fault in C51 Zone

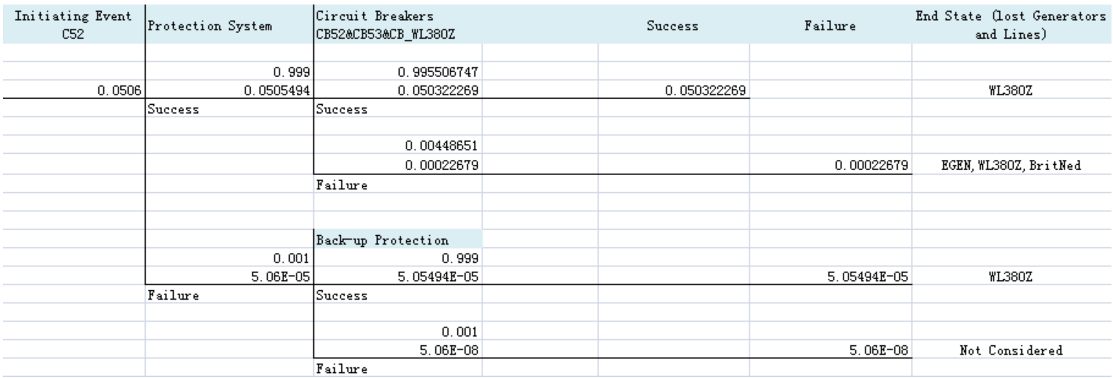


Fig D. 2 Event Tree for a Fault in C52 Zone

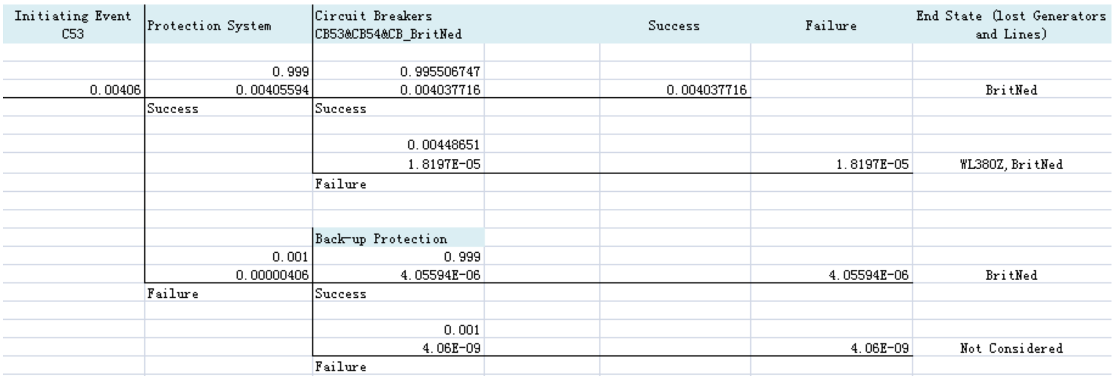


Fig D. 3 Event Tree for a Fault in C53 Zone

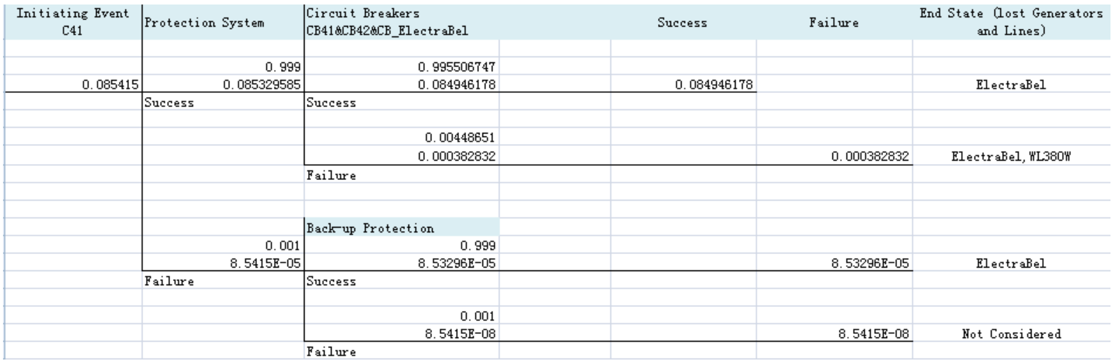


Fig D. 4 Event Tree for a Fault in C41 Zone

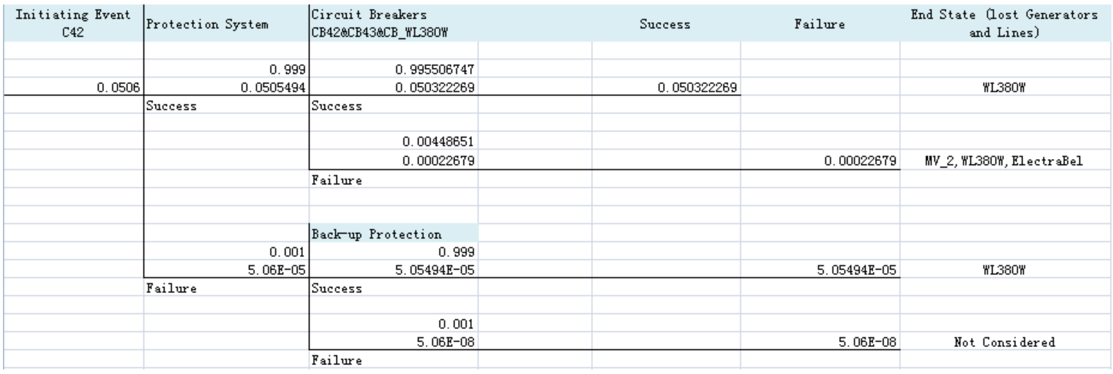


Fig D. 5 Event Tree for a Fault in C42 Zone

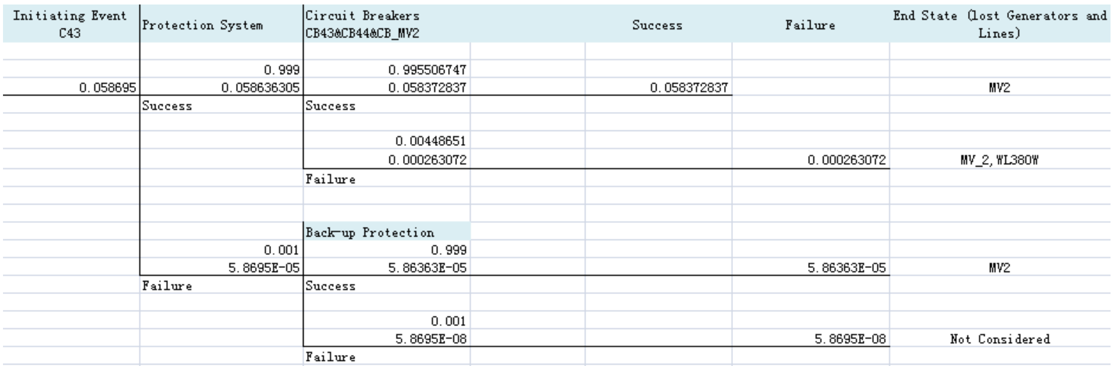


Fig D. 6 Event Tree for a Fault in C43 Zone

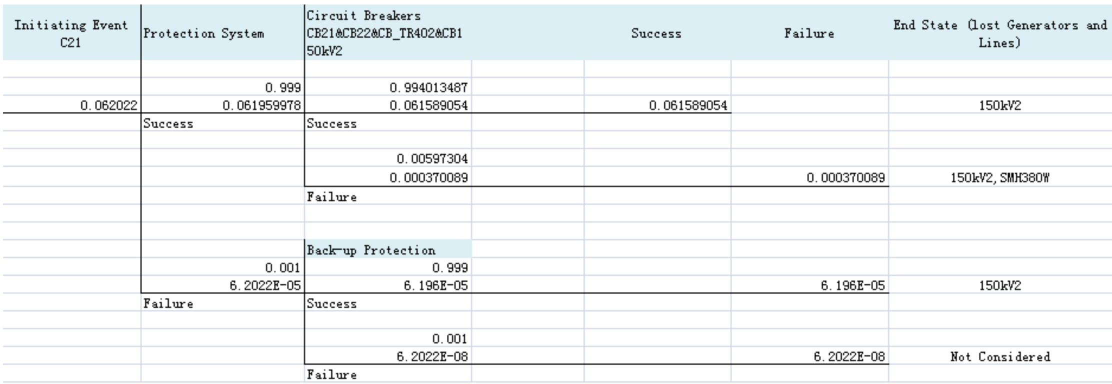


Fig D. 7 Event Tree for a Fault in C21 Zone

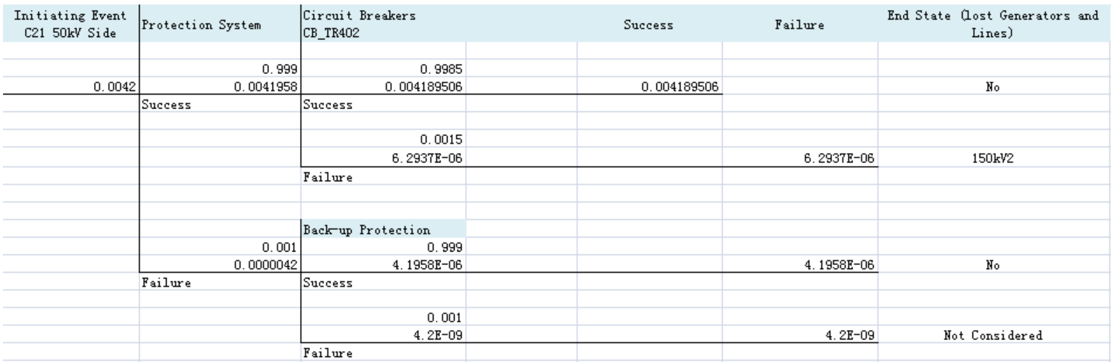


Fig D. 8 Event Tree for a Fault in C21 50kV Side Zone

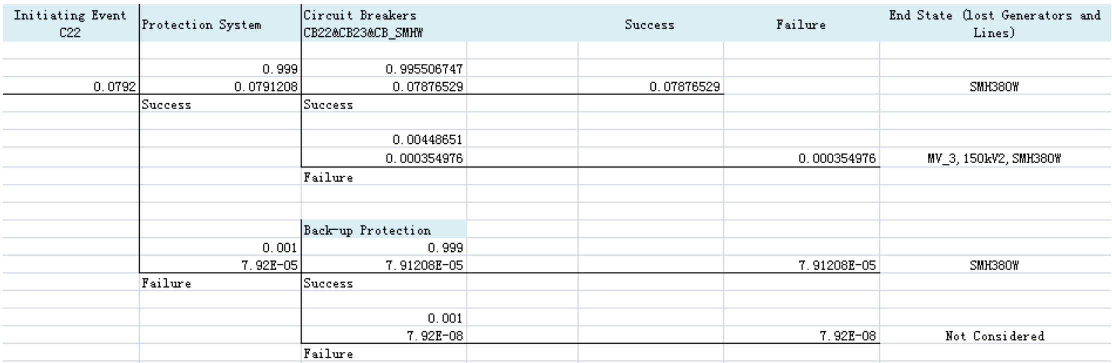


Fig D. 9 Event Tree for a Fault in C22 Zone

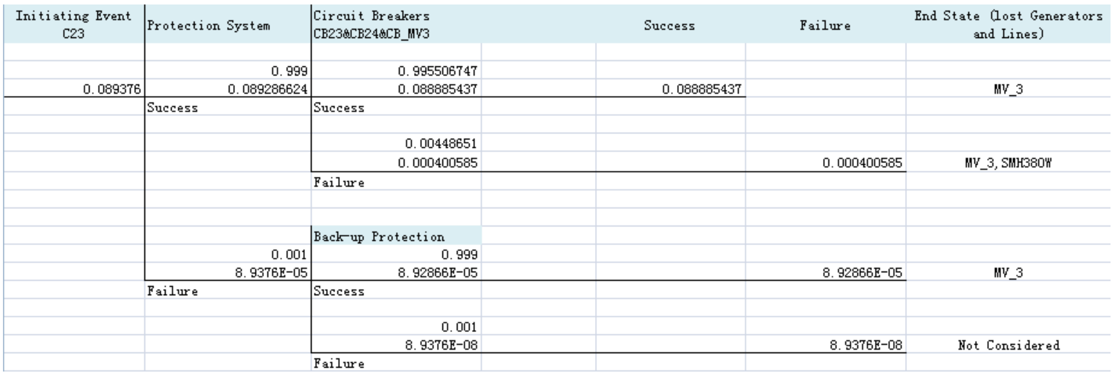


Fig D. 10 Event Tree for a Fault in C23 Zone

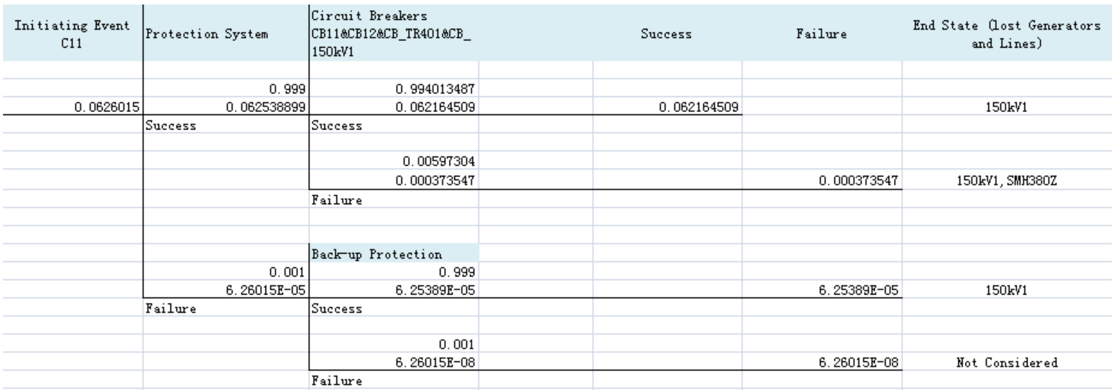


Fig D. 11 Event Tree for a Fault in C11 Zone

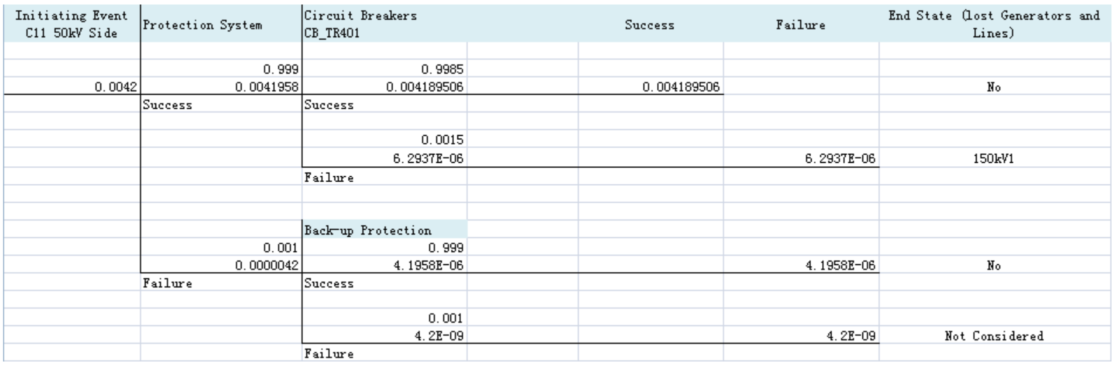


Fig D. 12 Event Tree for a Fault in C11 50kV Side Zone

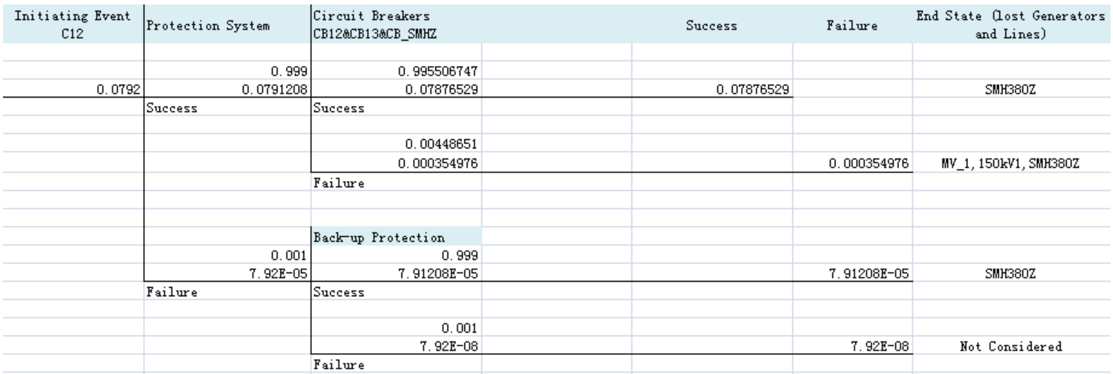


Fig D. 13 Event Tree for a Fault in C12 Zone

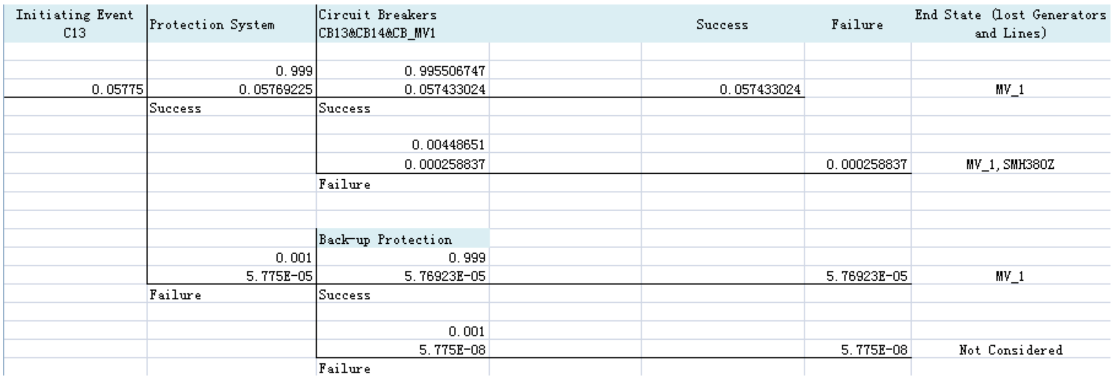


Fig D. 14 Event Tree for a Fault in C13 Zone

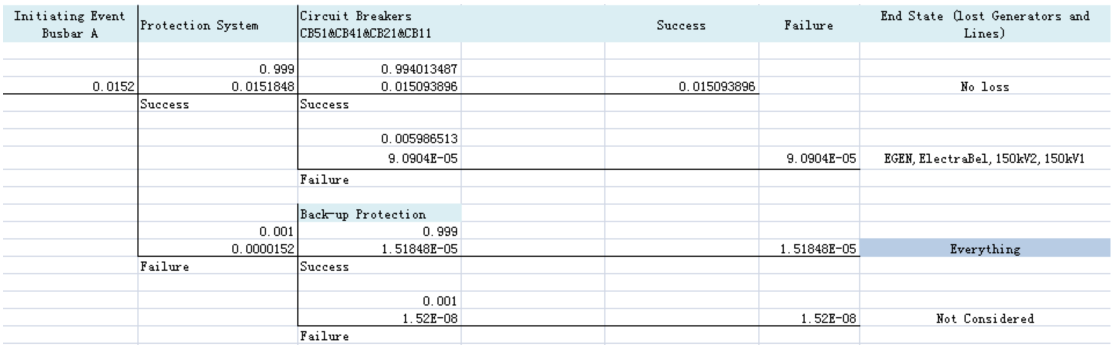


Fig D. 15 Event Tree for a Fault in Busbar A Zone

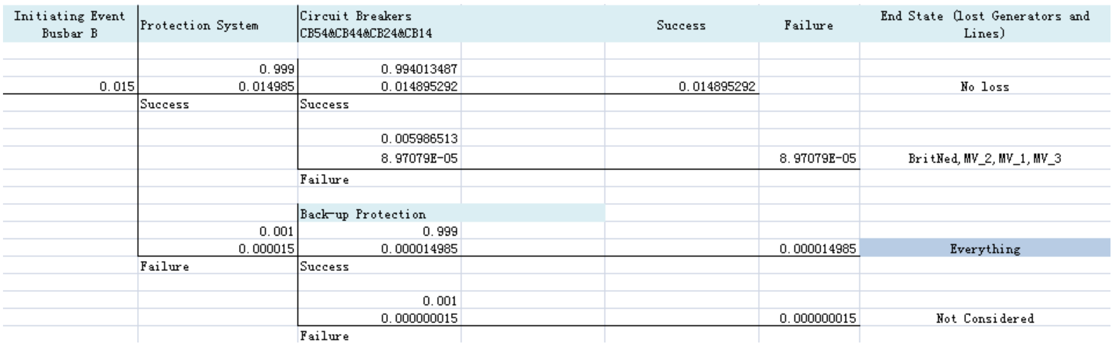


Fig D. 16 Event Tree for a Fault in Busbar B Zone