Reliability Analysis of Breaker Arrangements in High Voltage Stations: A Fault Tree Approach

Thesis for the Degree of Master of Science

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Abstract

State Enumeration technique for reliability evaluation is the process of selecting and assessing the impact of all possible contingencies in a given system. It starts with first order failure states to higher orders depending on the resolution requirement. In general higher order failure states do not contribute significantly to the results and are usually neglected from an engineering viewpoint.

Fault Tree Analysis (FTA) is a deductive analyzing technique that allows assessing the reliability of complex systems. FTA has been used in the nuclear power, aerospace and railway industries for evaluating the safety and reliability of complex systems. In an FTA analysis, it is postulated that the system has failed in a certain way (top event) and an attempt is made to find out what modes of subsystems behaviours contribute to this failure.

In this thesis the reliability of high voltage breaker arrangements is studied using two alternative techniques implemented in two different simulations tools, namely Subrel and Riskspectrum. Dynamic state enumeration and fault tree analysis are used to perform reliability studies of two breaker arrangements. The breaker-and-a-half and double-breaker-double-bus arrangements are assessed and compared. The thesis introduces a modeling technique for analyzing breaker arrangements via fault tree. The modeling technique and corresponding results from the fault tree analysis are validated against those obtained from Subrel. Uncertainty in reliability data is taken into consideration by randomizing failure rate and time to repair in Riskspectrum. The reliability performance of breaker arrangements is compared and discrepancies are explained. It is concluded that the reliability of a breaker and half arrangement is in principle equal to that of a double breaker double bus.

Keywords:

Reliability, Unavailability, Breaker arrangement, Breaker and a half arrangement, Double breaker arrangement, Fault tree analysis, Riskspectrum, Subrel

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Chapter 1 Introduction

1.1 Background

The research on reliability study of breaker arrangements in high voltage station is demanding on both theoretical and applied perspective. Breaker and a half arrangement and double breaker arrangement have been commercially available for several decades and mostly used in the areas where high reliability are demanded. Both arrangements are considered highly reliable technically. However, there is no clear comparison which one is outweigh the other except the intuitive calculation of investment cost. Some studies have been carried out using other methods [1], [2], [3]. More effort is being now exerted to use fault tree analysis. First, it offers a new approach to tackle the problem of assessing the reliability of substation arrangements. Second, not only does it verify the results calculated from other methods, but also can do more analyses such as Monte Carlo simulation which cannot be done by other tools. The guideline of fault tree modeling presented in the report can be further applied to the reliability analysis on other complex systems.

In the first part of the study Subrel and Riskspectrum are tested using simple station models. The objective of this part of the study is to understand both software and validate the Subrel results by comparing them with the outcomes from Riskspectrum. In the second part of the study fault tree analysis using Riskspectrum is performed to evaluate the reliability of more complex stations, i.e. breaker and a half arrangement and double breaker arrangement in particular, which have also been assessed using dynamic state enumeration in Subrel.

The results of unavailability and failure frequency of a single outgoing line outage from both tools are the same. However, considering the station failure, represented by the outages both outgoing lines at the same time, the breaker and a half arrangement is about 20% less unavailability than the double breaker arrangement, and the failure intensity of the breaker and a half is 15.6% less than that of the double breaker without considering common cause failure. In this case, the breaker and a half arrangement is more reliable than the double breaker arrangement. However, concerning the presence of common cause failure, the station failures of both arrangements have the same average unavailability and failure frequency. Conclusion is then drawn that the breaker and a half arrangement and the double breaker arrangement offers the same or very close reliability. A few assumptions are made prior to the analysis, and minor discrepancies are explained. Moreover, uncertainty, importance and sensitivity analyses are also performed with results and discussion.

1.2 State of the art

Many studies have concentrated on evaluating reliability of different substation configurations [1], [2], [3]. The methods that have been widely recognized to perform the reliability analysis are state enumeration method [4], minimal cut set method [5], and fault tree method [1], [6].

State enumeration technique is the process of selecting all possible contingencies in a given system for reliability evaluation, and has been carried out mostly by computer software. It starts with first order failure states to higher orders depending on the resolution requirement. A first order failure state refers to the state which only one component fails and the rest succeed. Similarly, a higher order failure state refers to the state which more components failure at the same time and the rest success. In general higher order failure states do not contribute significantly to the results and are usually neglected from an engineering viewpoint.

SUBREL is designed to specify the station arrangement to fulfill the user specification in two main aspects, reliability and economical evaluation. The software uses dynamic state enumeration which simulates all possible contingencies of each component, frequency of each contingency and sums up the impact of all contingencies for overall reliability evaluation. A more complete study of ranking and evaluating substation topologies was carried out using SUBREL and another tool called 'SUBRANK' [7]. The methodology and algorithm implemented in SUBREL have been well accepted, and the software is an effective tool to assess reliability and cost considerations.

Minimal cut set method has been widely accepted in industries for its rapidness of pointing out all weakness of a system. One way of using minimal cut set method is to list all possible causes of the system failure in a table based on the studying the failure modes of each component. The cause may be one failure mode of a component or the combination of different failure modes of different components [5]. The system failure probability can then be calculated based on all minimal cut sets that are listed in the table.

Fault tree method has been used to evaluate most electrical distribution problems including those related to protective systems. Protective systems contain relays, which detect the fault, and then trip breakers to clear the fault. The scenario, so called 'initiating/enabling failure', requires special analysis techniques that are difficult to model using other methods such as Reliability Block Diagram. The initiating event refers to a fault that occurs on one component which may result in a power outage. The enabling event refers to the failure of protective system which fails to detect and isolate the initiating event [6]. Details related to fault tree theories and construction are presented in [6], and Chapter 3 and 4.

1.3 Aims and Scope

Two very specific goals are undertaken in this project. 1) Assessing of the reliability of the breaker and a half arrangement using Fault Tree Analysis via Riskspectrum and state enumeration via SUBREL, and 2) Assess of that of the double breaker arrangement, and compare it with that of breaker and a half. To assess the reliability using Riskspectrum, the fault tree modeling technique is used, and a novel modeling technique is introduced. Guidelines presented in the work for assessing the reliability of a breaker arrangement in substations can be further developed and used for analyzing other breaker arrangements.

Some peripherals of a typical substation are not emphasized in this project. In particular the protection system is assumed to be 100% reliable [8], as well as the auxiliary power supply [9], [10] , and the control system [8], [11]. These peripherals are very important to the reliability of a substation. However, the thesis mainly assesses the reliability of the breaker arrangements, and thus the study on the peripherals is out of the scope of the current project.

1.4 Outline

Chapter 1 is a basic introduction to the project that covers a project description, methods and tools used for reliability assessment.

Chapter 2 presents the station arrangement and breaker technology, which gives a clear illustration of the breaker and a half arrangement and double breaker arrangement. Breaker technology section offers the fundamentals of traditional breakers and modern disconnecting circuit breakers.

Chapter 3 covers an introduction to fault tree analysis and simulation tools, including theories, symbols, and examples.

Chapter 4 gives a detailed evaluation of reliability analysis of the breaker and a half arrangement and double breaker arrangement using Riskspectrum and Subrel.

Chapter 5 explores advanced features Riskspectrum, such as common cause failure, uncertainty analysis, importance analysis and sensitivity analysis of both breaker arrangements.

Chapter 6 reviews the project aims and suggests some relevant aspects for the future work.

Chapter 2 Station Arrangement and Breaker Technology

2.1 Station Arrangement

A substation is an interface in the power system where transmission lines or distribution feeders are marshaled for purposes of controlling load flows and general switching for maintenance purposes, and to which supplies are taken from generating stations and transformed in voltage, if necessary, for distribution [12]. A station secures the power transfer availability under stressful condition such as maintenance or faults of components in the substation by varying the arrangement of circuit breakers. The bus and breaker configuration has a direct impact on the reliability of the system [13]. This section mainly presents the general operation of breaker and a half (shown in fig. 2.1) and double breaker arrangement (shown in fig. 2.2).

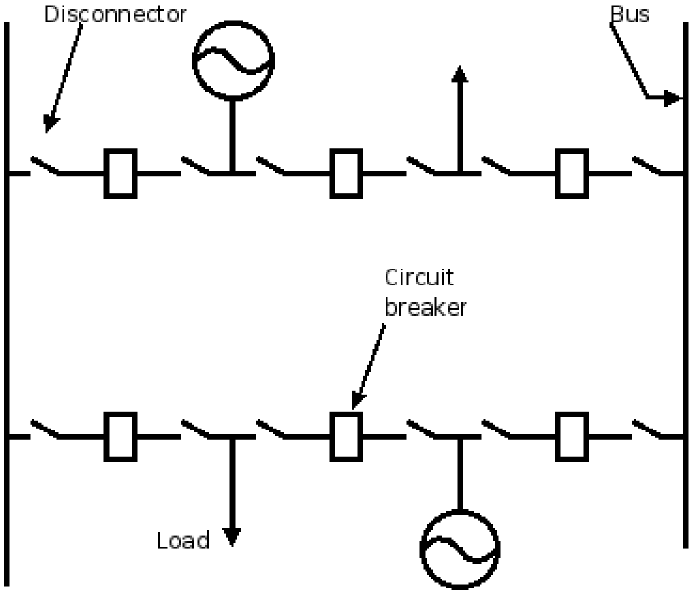


Fig. 2.1 Single line diagram of breaker and a half arrangement

Because of its high flexibility and reliability, the breaker and a half arrangement is frequently used in nuclear power stations to improve the reliability of power flow at the switchyard. During the normal operation, all disconnectors and breakers are closed [13]. Two buses are energized together for redundancy purposes. Two power sources are connected to the arrangement, assuming one generator has the capacity to provide enough power to both loads in case that the other generator or the incoming line experiences a fault. When the breaker experiences a fault, first, two closest breakers trigger to clear the fault. Second, adjacent disconnectors open to isolate the faulted breaker. Third, those two open breakers re-close to restore the power flow. The substation, therefore, reconfigures with faulted component isolated, to transfer power from generators to loads. The standard procedure of clearing a fault [14] is presented as follows:

- Component experiences a fault
- Breakers react to clear the fault
- Disconnectors open to isolate the fault
- Power restores to as many loads as possible

The most salient feature of the breaker and a half arrangement emerges during faulted conditions and maintenance. A single bus fault does not interrupt the service to both loads. Maintenance on a single breaker does not interrupt the service. And in case of a line fault, only the faulted outgoing line is taken out of service without interrupting service on the other healthy outgoing line. The redundancy of such breaker arrangement ensures the continuity of the power flow out of the switchyard. Other merits such as easy expansion and applicable to all voltage levels also make the breaker and a half arrangement a strong candidate for the substation topology where reliability and operational flexibility are of importance. There are, however, some that point out that the relay protection of such arrangement is complicated and the additional cost of introducing more breakers into the system increases [13], [15]. The detailed description of the protection scheme of a breaker and a half arrangement is not included in the report. It is, however, assumed that the arrangement counts with conventional protective schemes all perfectly functioning in case of fault clearance. A simplified breaker and a half arrangement is discussed in the following section.

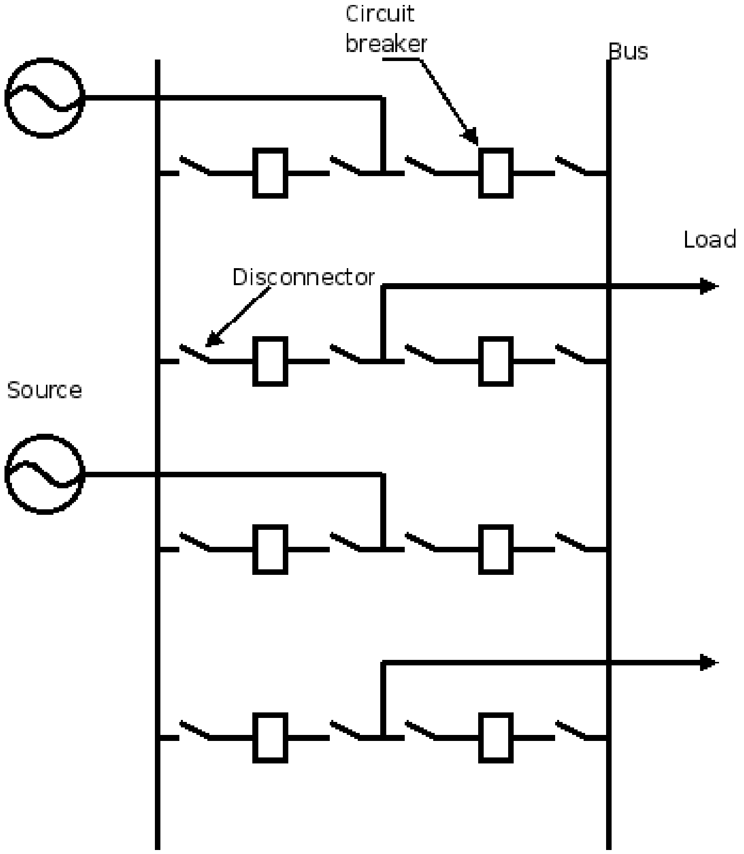


Fig. 2.2 Single line diagram of double breaker arrangement

Double breaker arrangement is yet another solution that offers high reliability of a substation. Similar to the breaker and a half, double breaker arrangement offers high operational flexibility during faulted conditions or maintenance [13], [15]. In the double breaker arrangement, two breakers protect one line between two buses. When there is a line fault, only the faulted line is isolated from the service, and thus the rest of the substation remains functioning. For a bus fault, four side breakers open to clear the fault without interrupting the power flow to both loads. Other merits such as easy expansion and applicable to all voltage levels also make double breaker a strong candidate for substations, especially in nuclear power stations, where reliability and operational flexibility are of importance [13]. Compared to breaker and a half arrangement, double breaker offers similar operational flexibility and maintainability. However, in a simple two-input-two-output substation layout, breaker and a half arrangement requires six breakers, while double breaker arrangement needs eight breakers which requires the investment of two extra breakers. Similarly, the detailed description of the protection scheme of a double breaker arrangement is not included in the report. It is, however, assumed that the arrangement counts with conventional protective schemes all perfectly functioning in case of fault clearance. That is, the evaluation conditions of double breaker arrangement are identical to those in breaker and a half in order to compare the reliability indexes.

2.1.1 Breaker and a half arrangement

The simplest layout of a breaker and a half arrangement contains two diameters connecting two buses, and each diameter consists of three circuit breakers and two lines for the power flowing in and out of the substation, as shown in figure 2.3. In this figure, LA and LB represent incoming lines, while La and Lb represent outgoing lines of the switchyard.

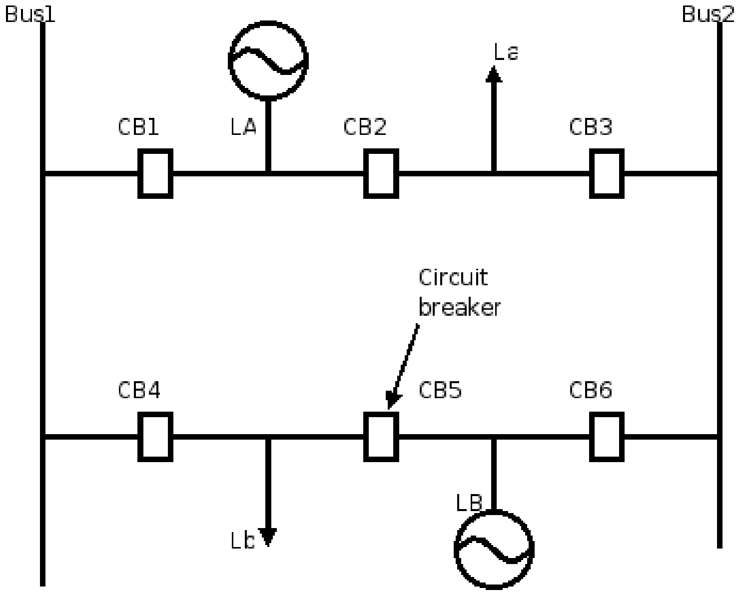


Fig 2.3 Simplified breaker and a half arrangement

In this arrangement, for instance in the upper diameter, the middle breaker 2, (denoted CB2 in Fig. 2.3) is installed to clear the fault on either LA or La, and thus forms a breaker and half arrangement, i.e. each line is protected by one side breaker and half of a middle breaker. During the normal operation, all breakers are closed and both buses are energized, so that the power from the generator side of LA and LB feeds to the loads, La and Lb.

2.1.2 Double breaker arrangement

A simplest layout of a double breaker arrangement contains four diameters connecting two buses, and each diameter consists of two breakers and one line either for power flowing into or out of the arrangement.

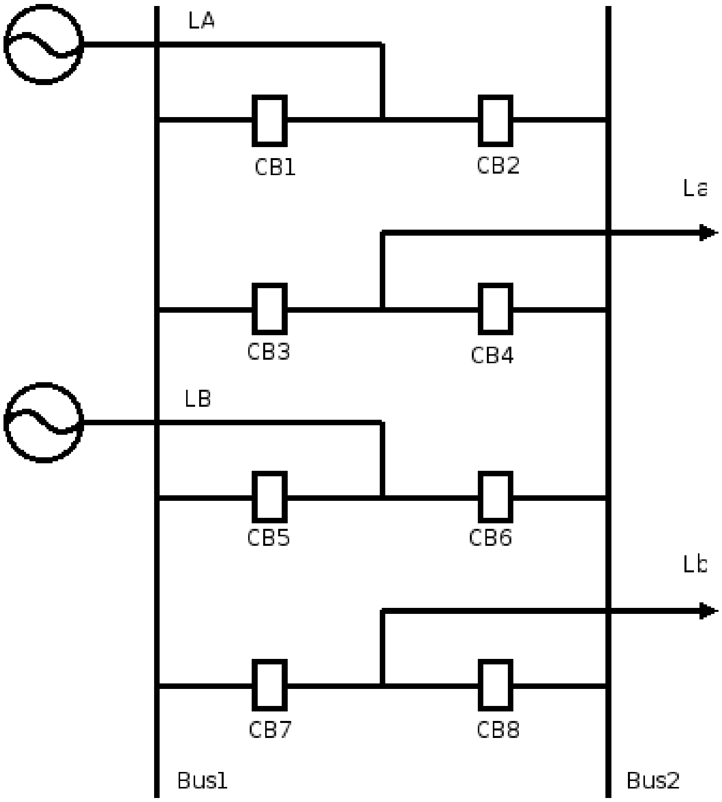


Fig. 2.4 Simplified double breaker arrangements

In this arrangement, each incoming and outgoing line is protected by two dedicated circuit breakers located on both sides of the line, and thus the arrangement is named double breaker arrangement. With the additional breaker per diameter, any circuit breaker can fail, and affect only one diameter. During the normal operation, all breakers are closed and both buses are energized, so that the power from the generator side of LA and LB feeds to the loads, La and Lb.

2.1.3 Other types of arrangement

Single bus arrangement

Fig. 2.5 shows the single-line diagram of a simplified single bus arrangement. It is the simplest arrangement with the worst reliability indexes. In the arrangement shown, the maintenance of breakers has to be undertaken with the outgoing line disconnected, and thus the load experiences a long service interruption [16].

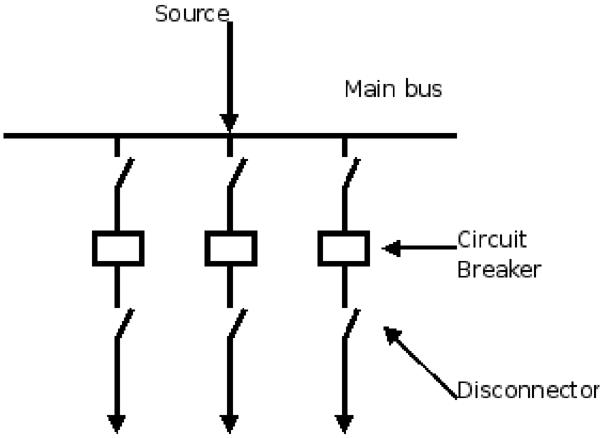


Fig. 2.5 Single bus arrangement

Main-and-transfer bus arrangement

In the main-and-transfer bus arrangement, two buses, a main and a transfer, are installed separately and independently. During the normal operation, all diameters are connected to the main bus. In case of maintenance or fault on the breaker, the load related to the specific breaker will be transferred to the transfer bus, and the original breaker is isolated from the diameter [13], [16].

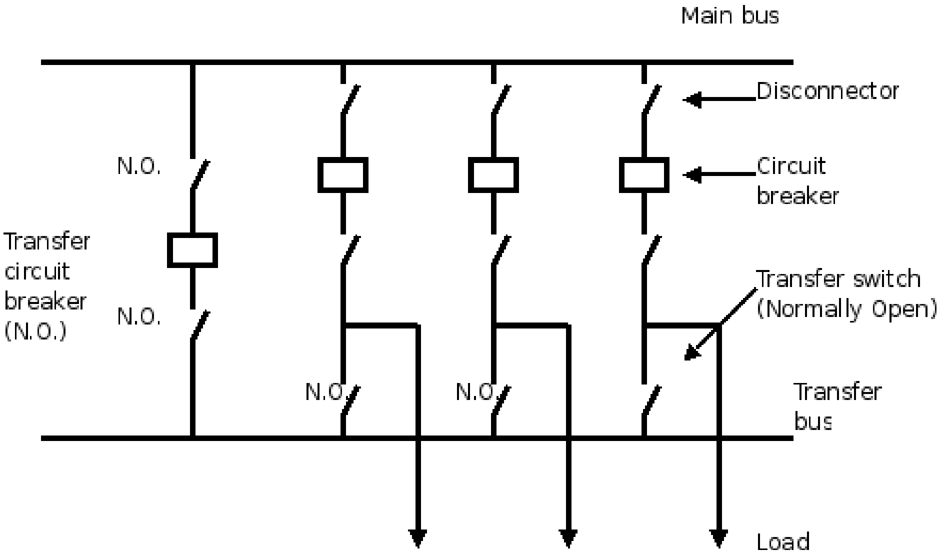


Fig. 2.6 Main-and-transfer bus arrangement

Ring bus arrangement

A ring bus arrangement consists of breakers and disconnectors forming in a ring shape to improve the reliability. Each load is double fed. For a bus and or a load line fault, only the faulted part is removed from the service by the fast reaction of circuit breakers. The rest of the system remains operating without interruption. In case of a breaker failure, two adjacent breakers are tripped to isolate the fault and to further prevent the loss of the entire substation as in single and main-and-transfer bus arrangements [13].

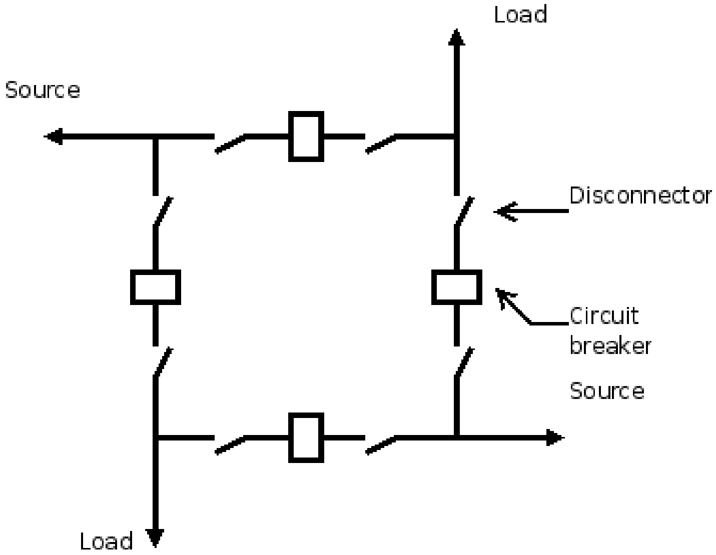


Fig. 2.7 Ring bus arrangement

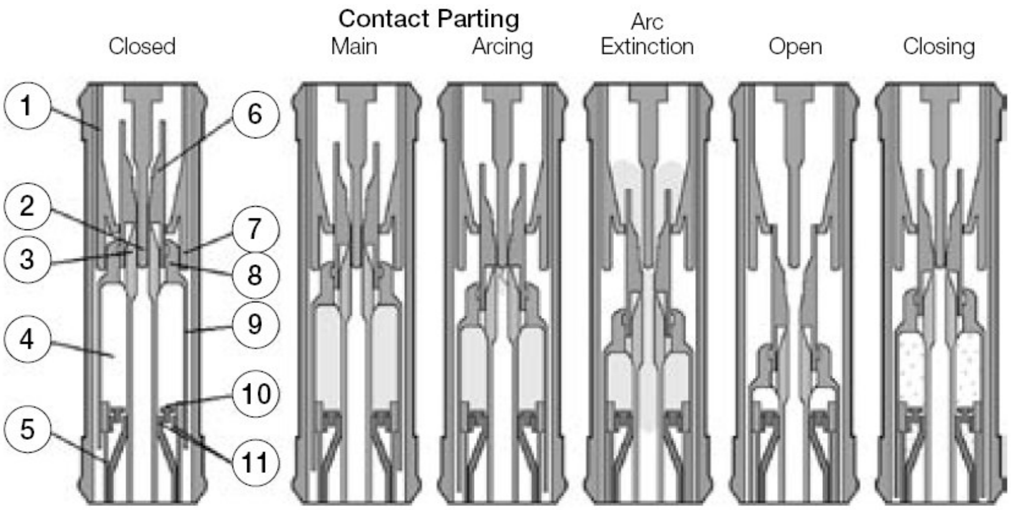
2.2 Breaker Technology

2.2.1 Introduction to breakers

To evaluate the reliability of a particular switchyard, the study of high voltage circuit breakers is necessary to carry out. Circuit breakers, driven by different mechanisms, are placed in the switchyard to perform switching action to complete, maintain and interrupt the current flow under normal or fault conditions. Fast response and complete interruption are essential to protect the rest of power system from the faulted component and maintain the stability of the reconfigured system and its normal operation. SF6 breakers have been widely adopted and replace old oil breakers in power industry in many countries [11], [12], Breakers have to be able to switch from 'no-load' condition to full rated asymmetrical fault current. During the process of interrupting fault current, breakers are under severe thermal and dielectrics withstand stress [17]. Mechanical stress is generally related to high speed opening during the fault and the current rating which also requires larger dimension in size and weight[17], [18].

Circuit breakers, in general, can be categorized differently according to different aspects of characterization, such as types of insulation, types of drives, etc. For instance according to types of insulation, breakers are generally divides into four groups. Air blast circuit breakers offer features such as fast reaction, auto reclosure, simple assembly, and are widely used in railways and arc furnace where repeated operations are essential, and important lines where fast reaction is strongly desired. Unlike air blast breakers extinguishing the arc using air as medium, minimum oil circuit breakers extinguish the arc using transformer oil in insulated housing enclosed in ceramic enclosures. Another type is vacuum circuit breakers, which utilize vacuum to quench the arc when they are open and to insulate the contacts as a dielectric after the arc is interrupted. The last type according to the insulation is SF6 (Sulphur Hexafluoride) circuit breakers. SF6, one of the most controversial materials ever used in electric power technology, offers enormous advantages such as the remarkable combination of high molecule weight (which provides high capacity and high density), high internal binding energy (which makes it highly stable), and high symmetry (which results in low intermolecular force to ensure the SF6 in gaseous form under engineering pressure) [17], [19] non-flammable, electronegative (the breakdown strength is 3 times higher than that of air). Such combination makes SF6 an excellent and highly reliable dielectric medium, and is widely used in breaker construction. However, it is one of the most potent greenhouse gases with 22000 times that of CO2 over 100-year period [20].

Operating mechanism of puffer interrupters



1. Upper current carrier | 2. Stationary arcing contact | 3. Moving arcing contact | 4. Puffer volume | 5. Lower current carrier | 6. Nozzle | 7. Stationary main contact | 8. Moving main contact | 9. Puffer cylinder | 10. Refill valve | 11. Stationary piston

Fig. 2.8 Design features puffer interrupter [21]

During its normal operation, the circuit breaker contacts are closed and current is conducted from the upper current carrier to the lower current carrier via the moving and stationary main contact and the puffer cylinder.

On opening, the moving main and arcing contacts, the puffer cylinder and nozzle are pulled towards the open position. All four parts move instantaneously toward the same position.

As the moving parts are drawn towards the open position, the refill valve is forced closed and SF6 gas begins to be compressed the moving puffer cylinder and the stationary piston. The first contact to part is the main contacts. Parting the main contact well before the arcing contacts ensures that any arc drawn is between the arcing contacts and contained by the nozzle.

When the arcing contacts part, an arc is drawn between the moving and the stationary arcing contacts. As the arc flows, it to some extend blocks the SF6 gas flowing through the nozzle. Thus, the gas pressure in the puffer cylinder continues increasing, until the time when the current waveform crosses zero, where the arc is relatively weak. At this point, the pressured SF6 gas flows from the puffer cylinder through the nozzle extinguishing the arc.

At the open position, there is sufficient distance between the moving and stationary contacts to withstand rated dielectric levels.

On closing, the refill valve opens so that SF6 gas can be drawn into the puffer volume.

Note that the SF6 gas pressure required for interruption is built up by mechanical means. Thus, circuit breakers using puffer interrupter required operating mechanism of sufficient energy to overcome the pressure built up in the puffer cylinder, as well as maintaining the contact speed required to withstand recovery voltage [21].

HPL-B live tank circuit breaker (shown in Fig. 2.9), for example, is one of the latest achievements that ABB Group developed. The breaker is SF6 insulated, and driven by motor charged spring operated mechanism [21]. To understand the possible failure of the breaker, it is necessary to understand its essential parts whose failure or malfunction will lead to a failure of the breaker.

- Material: aluminum and galvanic steel
- Insulator
- Operating mechanism
- Sealing system for SF6 volume
- SF6 density monitor
- Support structure
- High voltage terminals
- Reinsertion resistors
- Controlled switching devices
- Condition monitor

Fig. 2.9 HPL B for outdoor installation (courtesy to ABB)

2.2.2 Modern Breakers (Disconnecting Circuit Breakers)

A new trend of designing circuit breakers is to combine the disconnectors and circuit breakers into one component, named disconnecting circuit breakers (DCBs). The idea of such new device is to decrease the maintenance frequency of the disconnectors, especially the air insolated system (AIS), so that the unavailability of the system due to maintenance operation of disconnectors can be significantly reduced. Moreover, DCBs offers advantages such as less space required, less environmental impact, less cost [22], etc.

Fig. 2.10 HPL Combined Disconnecting Circuit Breaker (courtesy to ABB)

Disconnectors, traditionally, are designed to isolate the breaker during its maintenance state. In the early years of circuit breaker invention, due to the technological constraints, maintenance operation of circuit breaker has been quite demanding, and disconnectors have been thus introduced to isolate the breaker in case of maintenance. However, according to the maintenance specification from modern circuit breaker manufacturers, the maintenance operation required for a circuit breaker is less than once per 15 years. In contrast to the rapid development of circuit breakers, essential maintenance frequency of disconnectors does not significantly reduce. Typical maintenance operation for a disconnector working in a ‘fairly good’ environment is about once in 5 years; other harsh environment such as sandy or salty requires more intensive maintenance operation about once per year. Apparently, those disconnectors around circuit breakers and along the lines are jeopardizing the availability of the power delivery. DCBs, on the other hand, have the similar failure rate as traditional CBs, improve the availability by integrating disconnectors into CBs. On both sides of a DCB, two disconnecting clamps are used to physically disconnect the DCB from the service, and most importantly, these clamps do not need maintenance or the maintenance frequency is extremely low. Comparing traditional CBS with DCBs in a typical breaker and a half arrangement, the substation layout with DCBs reduces 50%

of the land, 90% of unavailability due to maintenance and 50% of unavailability due to component failure [22], [23].

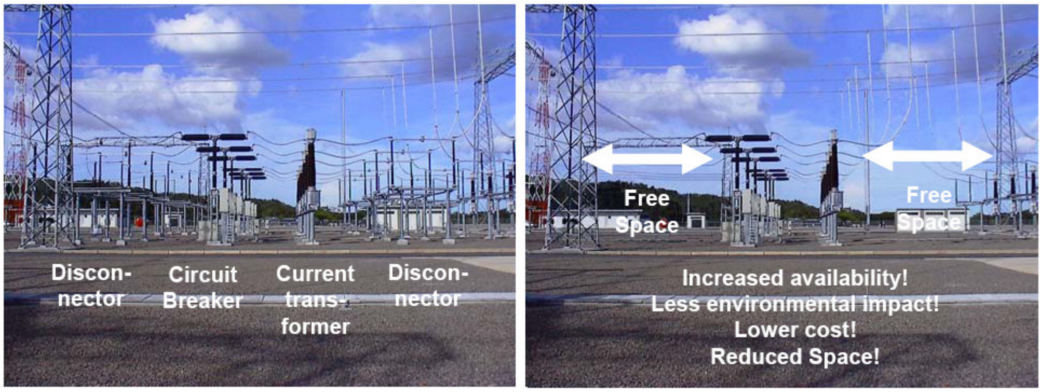


Fig. 2.11 Visual impact of substation layout with CBs and DCBs (courtesy to ABB)

2.1.3 Failure modes

According to CIGRE report Working Group 06 of Studying Committee 13, 13 different failure modes are identified as major failure modes, in which some of them are characterized as 'failure required immediate interruption and repair' ones and the rest can stay for a while without breaker isolation and repair.

Characteristics of the major failures [24]:

- Does not close on command
- Does not open on command
- Closes without command
- Opens without command
- Does not make the current
- Does not break the current
- Fails to carry the current
- Breakdown to earth
- Breakdown between poles
- Breakdown across open pole (internal)
- Breakdown across open pole (external)
- Locking in open or closed position
- Others

According to CIGRE report, many failure modes have the similar impact on the system which require immediate interruption and repair. These failure modes are characterized into group one, and the rest are grouped into maintenance or similar effects that do not require immediate attention as group two. The other reason to characterize failure modes into two groups is that Subrel only considers a component in either group one failure mode or normal operating mode, and one part of the project aim is to validate the mechanism of Subrel, and thus it is reasonable to consider only group one, which fits the group of failures that require immediate interruption and repair, and treat the group two failure and maintenance as the extension of the current project.

It is also worth noticing that some breaker failures are caused by other adjacent components failure. For instance, in breaker and a half arrangement, if a short circuit fault occurs on the incoming line A and circuit breaker 2 fails to clear the fault, circuit breaker 3 must open as a backup protection. In this case, the breaker failure results the whole diameter out of service. More detailed scenarios will be discussed in section 4.2.3.

2.2.4 Reliability data

The input data for basic events of fault tree are taken from an ABB/STRI project. As the evaluation of breaker arrangements mainly focuses on developing a prototype of modeling technique, simplified arrangements without disconnectors are considered as follows.

Table 2.1 Reliability data

Component	Failure Rate in Riskspectrum (λ)	Failure Rate in SUBREL (λ)	Mean Time to Repair (MTTR)
HV circuit breaker	1E-6 #/hr	0.0088 #/year	12 hr
Bus	2.05E-7 #/hr	0.0018 #/year	12 hr
Incoming line (10km)	9.13E-6 #/hr	0.008 #/year/km	8 hr
Outgoing line (0.1km)	9.13E-8 #/hr	0.008 #/year/km	8 hr

Since the incoming lines are directly connected to the generation plant, the length is assumed approximately 10 km. The outgoing lines are connected to the cable near the switchyard, and thus the length is assumed approximately 100 m. The length of the line contributes to its failure rate in both Riskspectrum and Subrel. Also it is worth mentioning that the failure rate λ in Riskspectrum is in a hourly base, while that in Subrel is in a yearly base. The unit convention is

Hourly base = Yearly base / 8760 hrs/yr
where 8760 is the number of hours per year

Chapter 3 Fault tree Analysis and Reliability of Complex Structures

3.1 Fault Tree Analysis

FTA was first designed in 1962 by H. A. Watson at Bell Laboratory to fulfill the 'ICBM minuteman' missiles project ordered by the U.S. Air Force. The development of the FT technique has been evolved three stages. In the early 60s, the idea was introduced as a tool to evaluate all possible failures without techniques and algorithms. In the late 60s and early 70s, stochastic process was introduced to complete the design and evaluation of the FTs. In the 80s, the third stage extends the design theories to non-coherent, multi-state and fuzzy fault trees. Many algorithms have been initiated to evaluate larger fault trees by recursive algorithms that do not require prior knowledge of the minimal cut sets and/or the truncation algorithms of minimal cut sets [25].

Fault tree construction [25].
The general approach of constructing a fault tree consists of three phases: preliminary analysis, specifications and the construction.

Preliminary analysis:

- Decomposition of the system
- Identification of the components
- Definition of failure modes of the components
- Reconstitution of the system through the components

Specifications:

- Phases
- Boundary conditions
- Specific hypotheses
- Initial conditions

Construction

- Defining the undesirable event
- Resolution of the events
- End of construction

Fault tree symbols
In Riskspectrum some standard symbols of constructing fault trees are shown in Fig. 3.1. More information about other symbols can be found in [26]. The following symbols are commonly used to construct fault trees of breaker arrangement in Chapter 4.

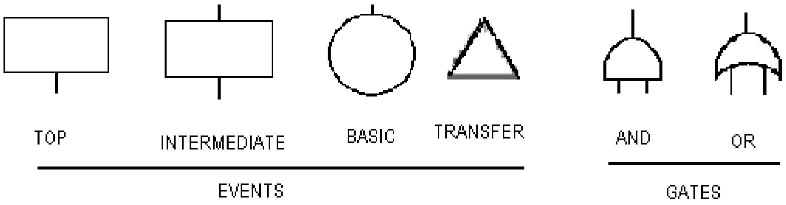


Fig. 3.1 Fault tree symbols

Top event Top event is carefully defined which represents the ultimate undesirable event that needs reliability evaluation. It defines the risk severity of the system.

Intermediate event Intermediate events describe a system state produced by antecedent events.

Basic event Basic events are basic causes of the top and all intermediate events, and need no further development, and therefore, they determines the resolution of the fault tree analysis.

Transfers indicate that the event is further developed. It is useful to shorten large systems in smaller fault trees without affecting the output. There are two kinds of transfers one is transfer in and the other is transfer out. The difference is that transfer out means that the output of that fault tree is used for others fault trees. Then, transfer in means that some other fault trees outputs are used as input data.

AND/OR gate All events are logically linked with ‘gates’, and the most commonly used are the ‘AND’ gate, which initiates the output event to occur if all input events occur, and the ‘OR’ gate, which initiates the output event if one or many of the input events occur. Note that other gates and events types are also used in fault tree construction for specific purposes, and are not discussed here.

3.1.1 Definition

Reliability

The ability of an item to perform a required function, under given environmental and operational conditions and for a stated period of time

- The term “item” is used here to denote any subsystem, or system that can be considered as an entity.
- A required function may be a single function or a combination of functions that is necessary to provide a specified service.
- All technical items (components, subsystems, system) are designed to perform one or more (required) functions. Some of these functions are active and some functions are passive. Containment of fluid in a pipeline is an example of a passive function. The reliability of the items should be assessed based on the required function under consideration.

- For a hardware item to be reliable, it must do more than meet an initial factory performance or quality specification-it must operate satisfactorily for a specified period of time in the actual application for which it is intended [25].

Failure mode

The effect by which a failure is observed on failed items.

The failures are sometimes classified into three categories: primary failures, secondary failures, or command faults.

A primary failure is a failure that occurs in an environment for which the component is qualified.

A secondary failure is a failure occurs in an environment for which it has not been qualified. In other words, the component fails in a situation that exceeds the conditions for which it was designed.

A command fault is a failure that involved the proper operation of a component but at the wrong time or in the wrong place [25].

Failure rate

The frequency with which an engineered system or component fails, expressed for example in failures per hour.

The Bathtub curve [27] describes the changes of failure rate during an item's lifetime (Fig. *3*.2).

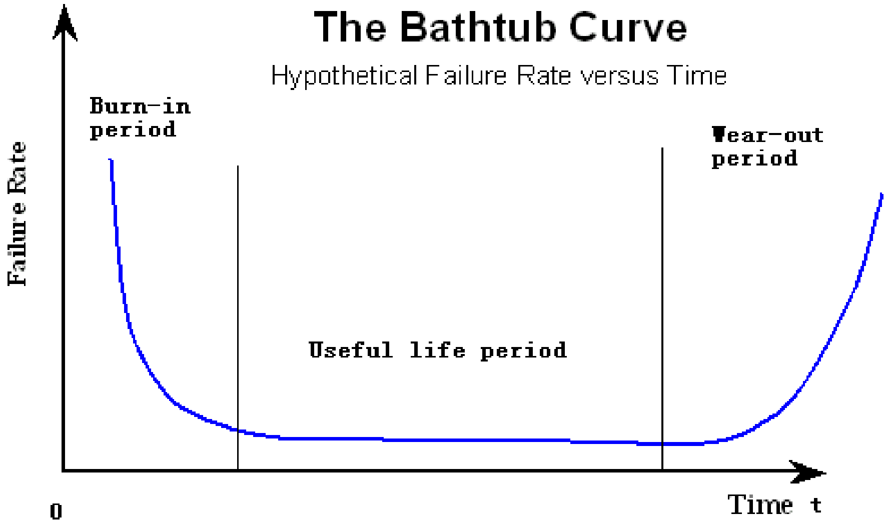


Fig. 3.2 the bathtub curve

The lifetime of a component are described in three intervals: burn-in period, useful life period and wear-out period. In the first interval, the failure rate is high in the initial phase, which explains the fact that the component may fail when it is placed in service due to unexpected defects. After the burn-in period, the failure rate stabilizes at a level where it remains for a certain amount of time, named useful life. The last interval is the wear-out period, which represents the late working stage of the component. The failure rate increases as the working time increases. Reliability analysis is usually done in the middle interval, for the failure rate is nearly constant.

Mean Time to Failure (MTTF)

The average time that a device will take to fail from a functioning state.

Mean Time to Repair (MTTR)

The average time that a device will take to recover from a non-terminal failure.

Common Cause Failure (CCF)

Multiple component faults that occur at the same time or that occur in a relatively small time window and that are due to a common cause. For information can be found in Section 5.1.1.

Redundancy

The provision of more than one means of achieving a function.

Availability

The ability of an item (under combined aspects of its reliability, maintainability, and maintenance support) to perform its required function at a stated instant of time or over a stated period of time

- The average availability A_{AV} denotes the mean proportion of time the item is functioning. If the item is repaired to an "as good as new" condition every time it fails, the average availability is

$$A_{AV} = \frac{MTTF}{MTTF + MTTR} \tag{3.1}$$

where $MTTF$ (mean time to failure) denotes the mean functioning time of the item, and $MTTR$ (mean time to repair) denotes the mean downtime after a failure. Sometimes MDT (mean downtime) is used instead of $MTTR$.

The average unavailability denotes the mean proportion of time the item is not functioning.

$$\overline{A}_{AV} = 1 - A_{AV} = \frac{MTTR}{MTTF + MTTR} \tag{3.2}$$

Difference between reliability and Availability

For availability, repair is considered. That is, if the entity fails often, but is instantly repaired, the availability might be high, but the reliability is low [28].

Cut Set

A sub-set of components whose simultaneous failure leads to the system failure, which is independent of the states of the other components.

Minimal Cut Set

A cut set that does not contain another cut set.

Qualitative assessment

The results from qualitative assessment include:

1. Minimal cut sets
2. Qualitative minimal cut set importance

In a qualitative assessment, minimal cut sets are obtained from Boolean reduction of a fault tree. Minimal cut sets, which contain only one component, are named first order minimal cut sets. Those containing two components are called second order minimal cut sets, which represent two events have to occur at the same time to lead to the TOP event. Similar terminology applies to higher order minimal cut sets. The unavailability associated with minimal cut sets often decreases by orders of magnitude as the size of the minimal cut set increases; the ranking according to their sizes gives a gross indication of the importance of the minimal cut set [26]. The basic events are not necessarily independent, since common cause failure also plays a very important role in the reliability study. A more detailed explanation of CCF is interpreted in Chapter 5.

3.1.2 Probability and Reliability Theories

Fault Tree with a single AND-Gate

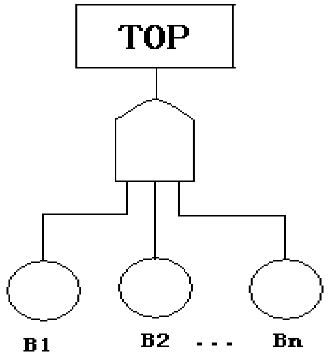


Fig. 3.3 Fault tree of a logic AND gate

In this fault tree, the TOP event occurs if and only if all the basic events B1, B2, …, Bn occur simultaneously.

The basic events are assumed to be independent. The unavailability of the TOP event, $Q_0(t)$, can be determined directly by the algebraic operation. Let $B_i(t)$ denote that basic event B_i fails at time t; i=1, 2, …, n. Pr denotes the probability of an event.

$$Q_0(t) = \Pr(B_1(t) \cap B_2(t) \cap \cdots \cap B_n(t)) = \Pr(B_1(t)) \cdot \Pr(B_2(t)) \cdots \Pr(B_n(t)) \qquad (3.3)$$
$$= q_1(t) \cdot q_2(t) \cdots q_n(t) = \prod_{i=1}^{n} q_i(t)$$

Fault Tree with a Single OR-Gate

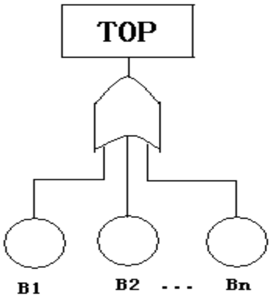


Fig. 3.4 Fault tree of a logic OR-gate

Consider the fault tree in Fig. 3.4, the TOP event occurs if at least one of the basic events B1, B2… Bn occurs.

The basic events are assumed to be independent. Let $B_i(t)$ denotes that the basic event occurs at time t and $B_i^*(t)$ denotes that the basic event does not occur at time t. These above equations can be expressed in Boolean algebra.

$$\Pr(B_i^*(t)) = 1 - \Pr(B_i(t)) = 1 - q_i(t) \text{ for i=1,2,…,n} \qquad (3.4)$$

$$Q_0(t) = \Pr(B_1(t) \cup B_2(t) \cup \cdots \cup B_n(t)) \qquad (3.5)$$
$$= 1 - \Pr(B_1^*(t) \cap B_2^*(t) \cap \cdots \cap B_n^*(t))$$
$$= 1 - \Pr(B_1^*(t)) \cdot \Pr(B_2^*(t)) \cdots \Pr(B_n^*(t))$$
$$= 1 - \prod_{i=1}^{n} (1 - q_i(t))$$

The relationship between failure rate and mean values of up time and down time are Failure rate [6]:

$$\lambda = \frac{1}{MTTF} \qquad (3.6)$$

Repair rate [6]:

$$\mu = \frac{1}{MTTR} \qquad (3.7)$$

3.2 *Simulation Tools*

3.2.1 Riskspectrum [29]

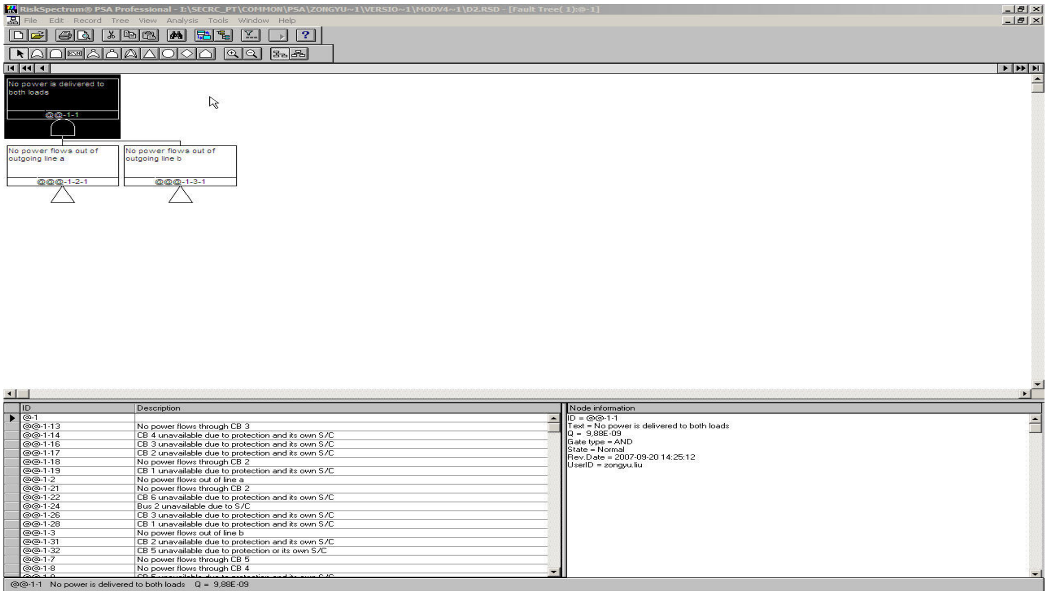
Riskspectrum, which is developed by RELCON AN, is a professional and powerful software for reliability analysis. It can perform the calculation based on different reliability indices, for example, failure rate (failure frequency) and repair time, or unavailability.

The basic events in Riskspectrum Professional do not hold any reliability data. Instead, references to reliability parameters are used. Depending on which reliability model you choose for the basic events. There are several reliability models to choose for a basic event:

- Repairable (monitored repairable component)
- Tested (periodically tested component)
- Probability (component with fixed unavailability)
- Mission time (component with limited mission time)
- Frequency (initiator, fixed frequency event)
- Non-repairable

When creating basic events, template events are used as templates and assigning data to groups of basic events. The template can include data such as reliability model, reliability parameters, description etc.

The fault tree is created in fault tree editor, a dialog window with a fault tree page. The fault tree will be built in the fault tree page by choosing the relevant events and logic gates. Quantitative analysis involves minimal cut set analysis, importance and sensitivity analysis, and Monte Carlo simulation. One should keep in mind that Riskspectrum is to some degree a calculation tool that solves fault trees with additional features. It can be applied not only to reliability analysis of power systems but also other objects of interests.



ID	Description
@-1	
@@-1-13	No power flows through CB 3
@@-1-14	CB 4 unavailable due to protection and its own S/C
@@-1-16	CB 3 unavailable due to protection and its own S/C
@@-1-17	CB 2 unavailable due to protection and its own S/C
@@-1-18	No power flows through CB 2
@@-1-19	CB 1 unavailable due to protection and its own S/C
@@-1-2	No power flows out of line a
@@-1-21	No power flows through CB 2
@@-1-22	CB 6 unavailable due to protection and its own S/C
@@-1-24	Bus 2 unavailable due to S/C
@@-1-26	CB 3 unavailable due to protection and its own S/C
@@-1-28	CB 1 unavailable due to protection and its own S/C
@@-1-3	No power flows out of line b
@@-1-31	CB 2 unavailable due to protection and its own S/C
@@-1-32	CB 5 unavailable due to protection or its own S/C
@@-1-7	No power flows through CB 5
@@-1-8	No power flows through CB 4

Node information

ID = @@-1-1
Text = No power is delivered to both loads
Q = 9,88E-09
Gate type = AND
State = Normal
Rev.Date = 2007-09-20 14:25:12
UserID = zongyu.liu

@@-1-1 No power is delivered to both loads Q = 9,88E-09

Fig. 3.5 Workspace of Riskspectrum

3.2.2 SUBREL [14]

Subrel, designed by ABB Electric systems Technology Institute in Raleigh, NC, USA, stands for SUBstation RELiablity. It can compute the reliability of various substation topologies, determine the cost of these topologies, and help to find the most cost-effective design.

Subrel uses a dynamic state enumeration to compute the reliability of each component in the system. Essentially, Subrel models every possible contingency, determines the frequency of each contingency, and sums up the impact of all contingencies for an overall reliability assessment.

The first thing that Subrel does is to determine the amount of time that a substation is in its normal operating state. This is equal to the amount of time during one year minus the time spent in maintenance states:

$$\begin{aligned}&\%\text{Spent in Normal Operating State} = \\ &((8760\text{ hours}) - (\text{Hours spent in maintenance}))/8760*100\end{aligned}$$

The program simulated all faults that occur on components (while the system is in its normal operating state). For each faulted component, Subrel follows the following sequence of events:

1. The component experiences a fault.
2. The nearest protection devices on all energized paths to the faulted component are tripped (the protection system is assumed to be perfect).
3. After a delay (determined by the Mean Time To Switch of sectionalizing points), the fault is isolated and the system is reconfigured to restore power to as many loads as possible.
4. After the faulted components Mean Time To Repair (MTTR) is elapsed, the fault is repaired and the system reverts to its normal operating state.

Each of these faults will impact the reliability of various substation components in various ways. SUBREL keeps track of the contribution of each fault to the outage frequency and outage duration of each component. These values are then weighted based on the failure rate of the faulted component and the probability of the system being in the normal operating state.

After simulating faults in the normal operating state, Subrel simulates all maintenance states and all faults that occur during maintenance states. When a component is maintained, Subrel automatically isolates the component using sectionalizing devices and reconfigures the system to restore power to as many loads as possible. This maintenance state will, of course, cause the component being maintained to experience an outage. It may also cause an outage on nearby components.

After Subrel determines the substation's maintenance state for a particular component, it will simulate faults during this state for all energized complements. This fault simulation is identical to the method used during the normal state except that the system starts off in a different configuration.

3.2.3 Simple model using Riskspectrum

The following example will be analyzed by both Riskspectrum and Subrel for validation purposes.

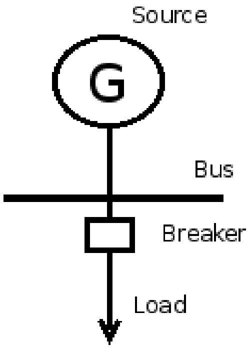


Fig. 3.6 Simple radial bus arrangement

The system consists of four components. The generator and the breaker are connected directly to the bus, and the load is connected in series with the breaker. Assuming the generator is working perfectly. The fault tree is shown as follows.

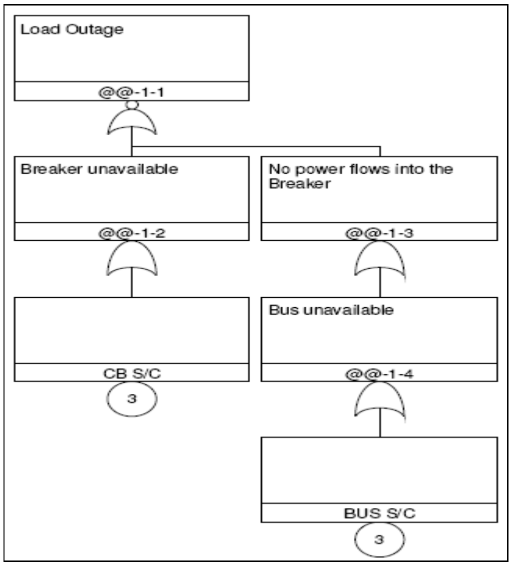
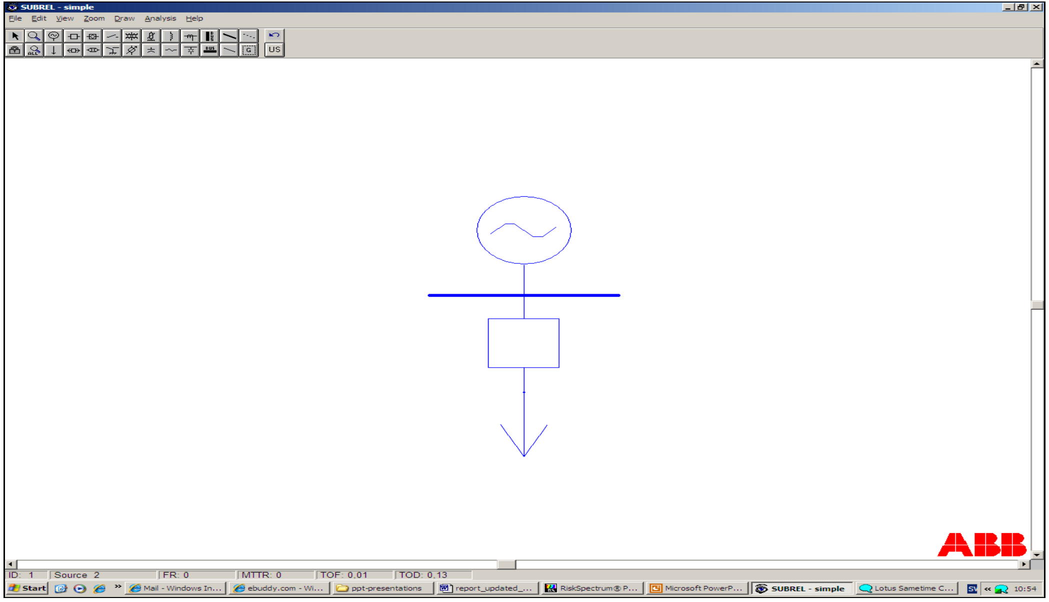


Fig. 3.7 Fault tree of the simple radial bus arrangement

The top event is defined as ‘load outage’, which represents the case when no power flow is delivered to the load. It may occur because either the breaker is unavailable or no power flows into the breaker, which in this case can occur due to the bus failure. The strategy is to track the power flow direction, so that every component in the system can be assessed. Repairable model is used for all components in the arrangement. Two input parameters are essential for the repairable model, namely failure rate and MTTR, and are acquired from ABB/STRI project. In Riskspectrum, average unavailability and unconditional failure intensity are calculated, detailed comparison of results are listed in table 4.2 in the Chapter 4. Maintenance operation is not considered in this case. However, it can be accomplished by adding a basic event representing maintenance with maintenance frequency and maintenance duration accordingly. Maintenance frequency can be represented by failure rate, and maintenance duration can be thus represented by MTTR.

3.2.4 Simple model using SUBREL

In Subrel, the schematic layout is shown in the following,



ID: 1 | Source 2 | FR: 0 | MTTR: 0 | TOF: 0,01 | TOD: 0,13

Fig. 3.8 Workspace of Subrel

Repairable model are assumed in Subrel as stated in the introduction. To assess the reliability of the system, the schematic layout is drawn in the Subrel workspace by clicking on the components icons on the tool bar. Once the layout is completed, the input data are obtained from the Subrel internal library. In Subrel, total outage duration (TOD) and total outage frequency (TOF) are presented by clicking on the component of interests.

3.2.5 Comparison and Discussion

In order to compare the result from both tools, input data are selected from ABB/STRI projects, and are identical in both Riskspectrum and Subrel after unit conversion. One should be aware of the unit difference between input parameters of Riskspectrum and Subrel. In Riskspectrum, the failure rate is in times per hour, while in Subrel, the unit of failure rate is in times per year. Assuming 365 days in one calendar year, and thus gives the conversion equation.

TABLE 3.1 Input parameters

Input Parameters	Riskspectrum		Subrel	
	Breaker	Bus	Breaker	Bus
Failure Rate	1E-6 (# / hr)	2.05E-7 (# / hr)	0.0088 (# / yr)	0.0018 (# / yr)
MTTR (hr)	12	12	12	12

Table 3.2 Simulation Outputs

Scenario Evaluation	Riskspectrum Average	Subrel Total Outage	Riskspectrum Unconditional	Subrel Total Outage

	Unavailability	Duration	Failure Intensity	Frequency
Load Outage	1,45E-05 (hr/hr)	0,1272 (hr/yr)	1,20E-06 (#/hr)	0,0106 (# / yr)

$$Q_{average} = {}^{TOD}\!\big/_{8760hr/yr} \quad (3.8)$$

$$W = {}^{TOF}\!\big/_{8760hr/yr} \quad (3.9)$$

Applying two simulation tools to one system, similar outcomes are expected. That is to say, two different methods adopted in these tools may have discrepancies due to algorithm differences, equation simplification differences, etc. However, in this simple arrangement, the results are identical after the unit conversion. The modeling technique is then validated, and ready for evaluating a much complex system using both fault tree method and state enumeration method by Riskspectrum and Subrel.

One should also pay special attention to data selected from various sources. The idea of the simulation is to predict the future outage based on the knowledge and data gathered from the past. However, it is difficult to validate the recorded data from different sources, and hence it is users' responsibility for selecting the validated data and evaluating the precision of the outcome from the simulation based on these data inputs under discretion. Orders of magnitude in the results are more informative than the significant digits of results.

Chapter 4 Modeling and Simulation

4.1 Breaker and a Half Arrangement

Fault tree analysis is carried out using Riskspectrum to evaluate the simplest breaker and a half arrangement. Major failure modes of lines and buses are grouped to short circuit fault, which contributes most of their major failures, based on the percentage data provided by IEEE Goldbook **[9]**. Also, usually engineers work with so called 'Major Failure Modes' for high voltage breakers, which require immediate isolation and repair. Short circuit fault of a circuit breaker does not contribute to the high percentage of failure types **[24]**. However, due to its severity and impact on the system, only short circuit fault is considered throughout the fault tree analysis. Similarly, only short circuit fault is also considered in bus and line faults for similar reasons.

It is also worth noticing that in the simplified arrangement, the breaker does not have reclosing function, which means that the breakers have both protection and isolation functions when a fault occurs nearby. In a more complex breaker and a half arrangement, the fault isolation is generally realized by installing two disconnectors on both sides of a breaker, which are not shown in the simplest model (Fig. 4.5).

4.1.1 Modeling Technique

The modeling technique of designing the fault tree is tracking all components in the arrangement according to the power flow direction. Each component can be either in its working state or unavailable state. Two examples are presented to illustrate the basic modeling technique.

Example 1:

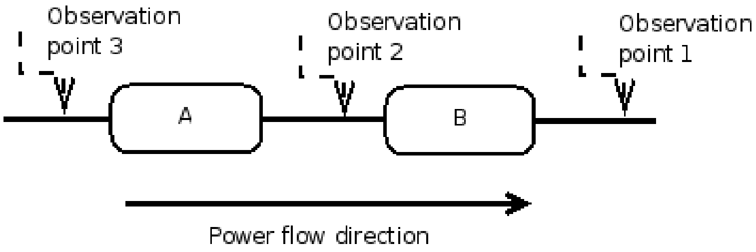


Fig. 4.1 Illustration of modeling technique

In Fig. 4.1, Component A and B are placed in series, and three observation points are illustrated along the power flow direction. The fault tree assesses the average unavailability using fault tree (shown in Fig 4.2), which is the failure probability of a system. So in this case, the top event is to evaluate no power at observation point 1. The possible reason is either 'component B is not functioning', which blocks the power flow through it, or 'there is no power flowing into component B', which in the layout is represented by the fact that no power flows at observation point 2. 'No power flows at observation point 2' can be further split into two causes. One is component A unavailable, and the other is that no power at the observation point 3.

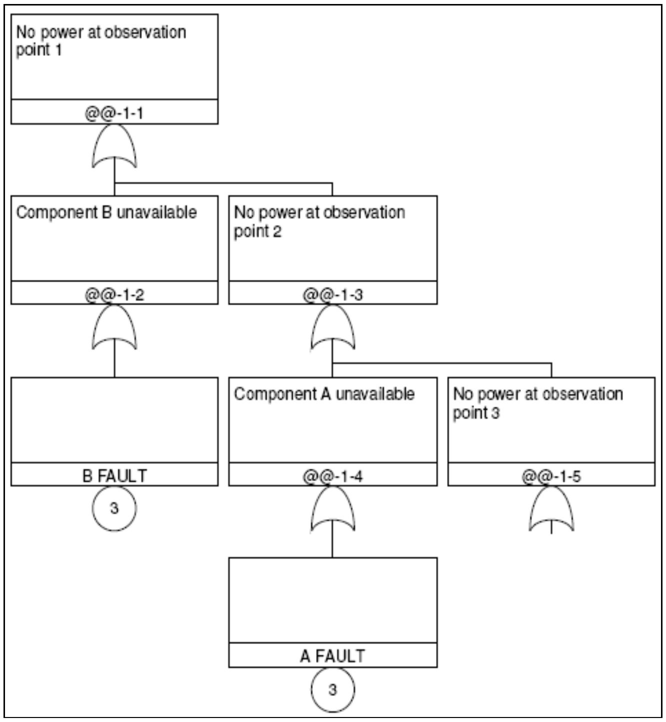


Fig. 4.2 Fault tree analysis of example 1

Example 2:

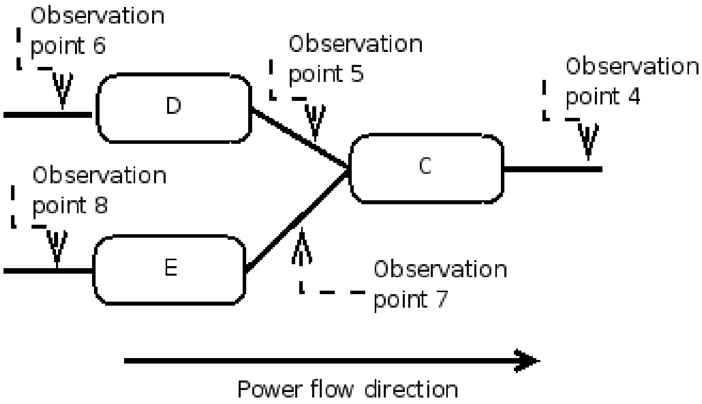


Fig. 4.3 Illustration of modeling technique continued

In example 2 shown in Fig. 4.3, component D and E are connected in parallel and together in series with component C. The top event is to assess the event of no power flowing at observation point 4, the occurrence may because either ‘component C is unavailable’ or ‘no power flows at both observation point 5 and 7 at the same time’. This divides the analysis to two branches. One branch traces the power flow through component D from observation point 5, and the other traces the power flow through component E from observation point 8. The fault tree is presented in Fig. 4.4.

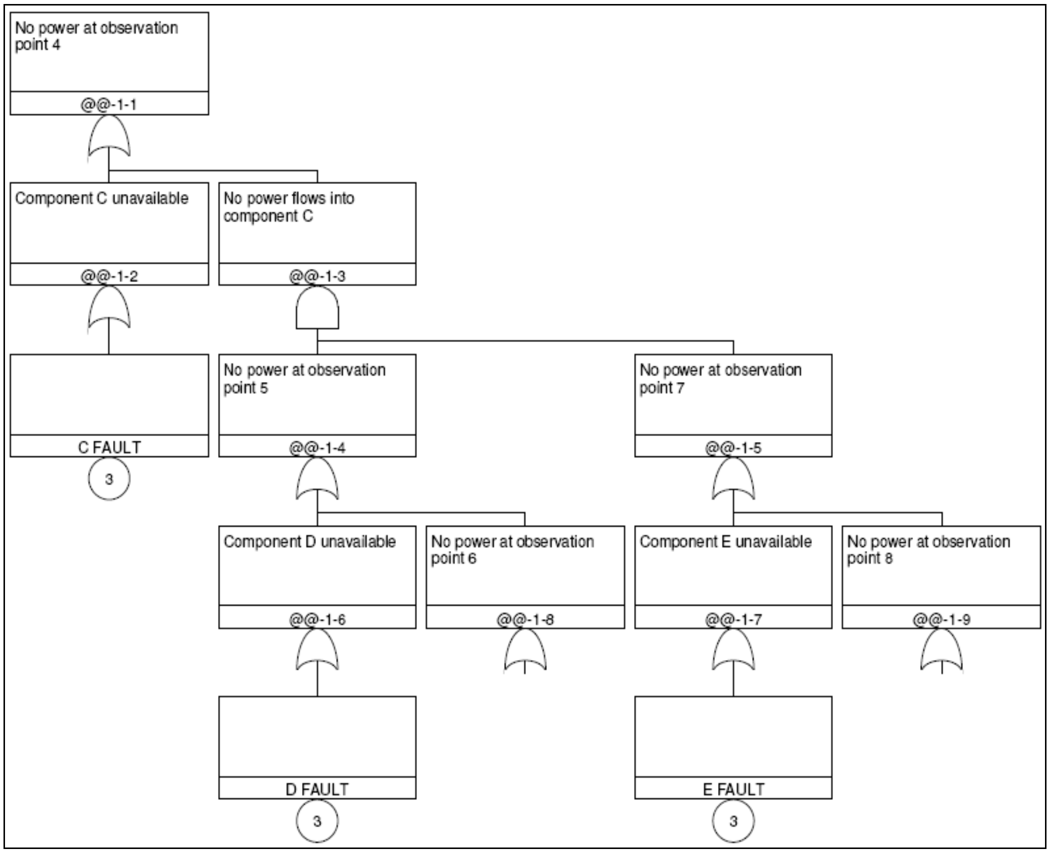


Fig. 4.4 Fault tree of example 2

4.1.2 Fault tree analysis on breaker and a half arrangement

Let us now apply the modeling technique to the simplified breaker and a half arrangement. The single line diagram is shown in Fig. 4.5.

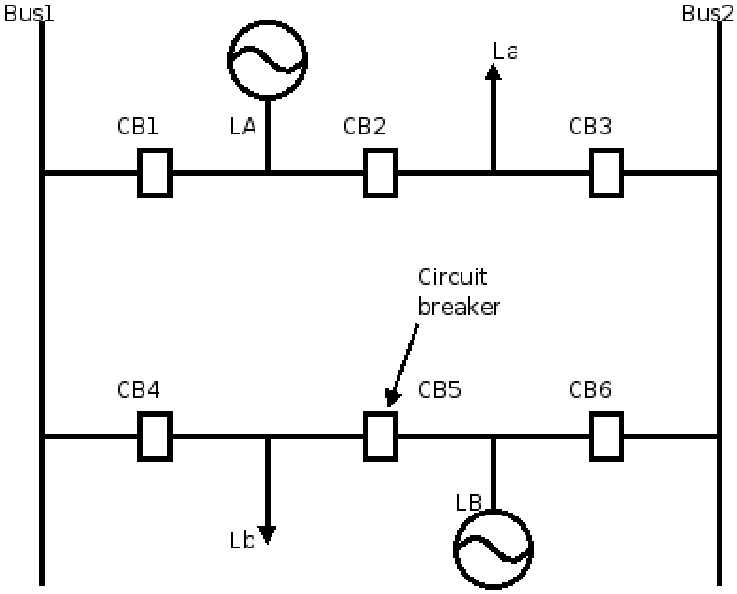


Fig.4.5 Simplified breaker and a half arrangement

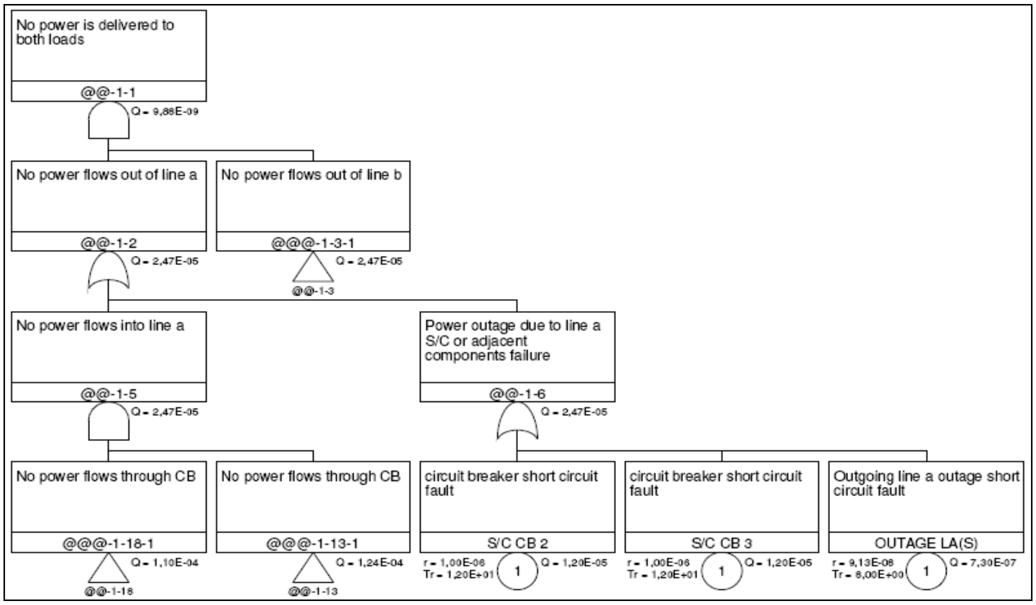


Fig. 4.6 Fault tree of top event

The top event is defined as ‘No power is delivered to both loads’ (Fig. 4.6), resulting in an ‘AND’ gate to split two causes, ‘No power flows out of line a’ and ‘No power flows out of line b’, which represent the fact that both outgoing lines outage leads to the top event. Since two outgoing lines are symmetrically installed in the arrangement, the fault tree presented in Fig. 4.6 only shows the case of the outgoing line a outage. The modeling technique, as stated in the previous section, is to split the failure into two direct causes, namely either ‘component unavailable’ or ‘no power flows into the component when it is available’, according to the power flow direction. In this case, two contributors directly causes ‘No power flows out of line a’, which is either ‘No power flows into line a’, or ‘Component unavailable’. Component unavailable is specified in either the component itself in a failure state or adjacent components failure that causes its unavailability. ‘No power flows into line a’ states the fact that no power comes into the outgoing line a even it is in a healthy state. Since the power flow into outgoing line a can be traced from both directions through circuit breaker 2 and 3, an ‘AND’ gate is used. This is similar to the example 2 in Section 4.1.1.

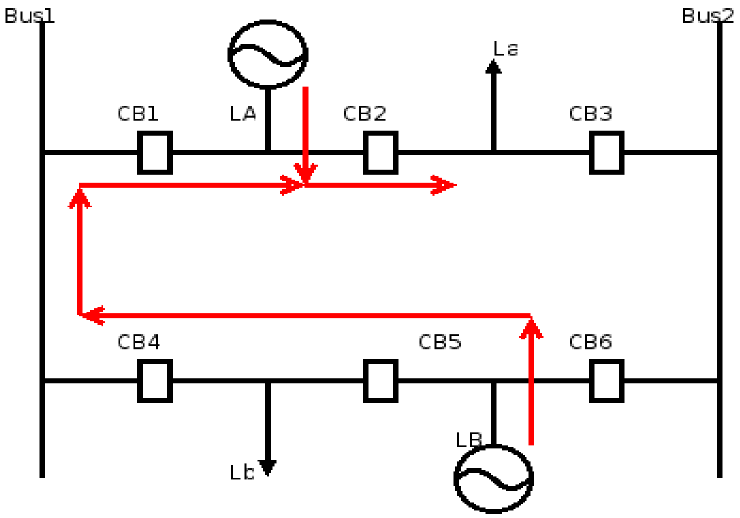


Fig. 4.7 Power flow direction from both incoming lines through CB 2

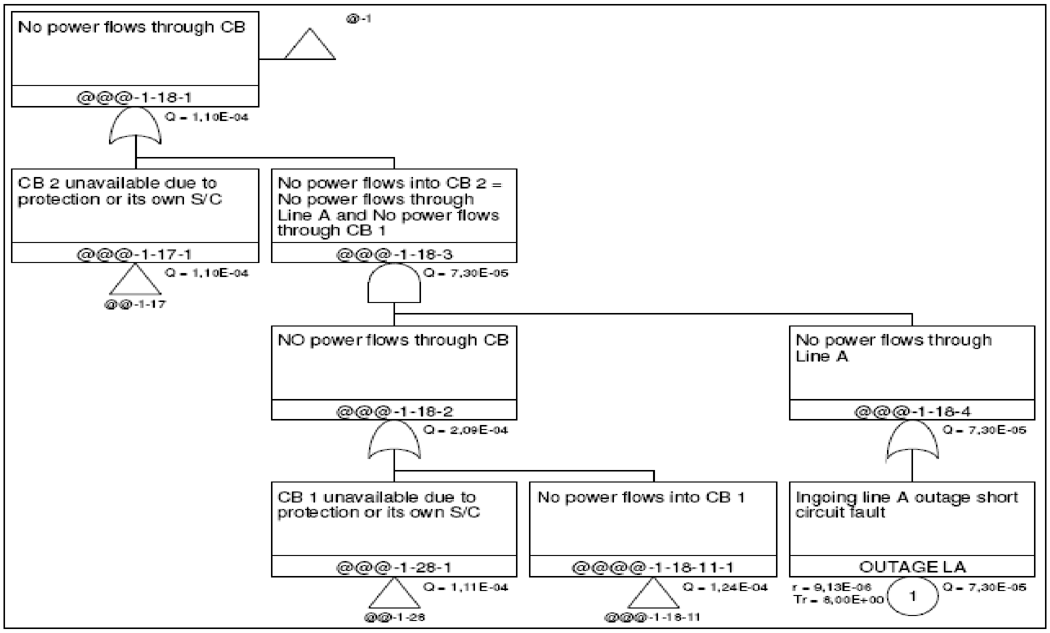


Fig. 4.8 Fault tree of no power flows through CB 2

The power flow direction through CB 2 from both sources is illustrated in Fig. 4.7. Continue the analysis from the previous paragraph, the direct causes of ‘no power flowing through CB 2’ is either ‘CB 2 unavailable’ (Fig. 4.8), which consists of five basic events including both protection actions and CB 2 itself short circuit fault (Fig. 4.9), or ‘No power flows into CB 2’, which refers to the situation where ‘no power coming from both incoming line A’ and ‘no power flowing though CB 1’ at the same time’. Note that under ‘No power flows into CB 2’ gate, only the power flows from incoming line A direction and from CB 1 direction are considered. The short circuit fault of incoming line A, which triggers the protection of both CB 1 and CB 2, is handled in ‘CB 2 unavailable’ intermediate event (Fig. 4.9), which directly leads to the power outage at CB 2.

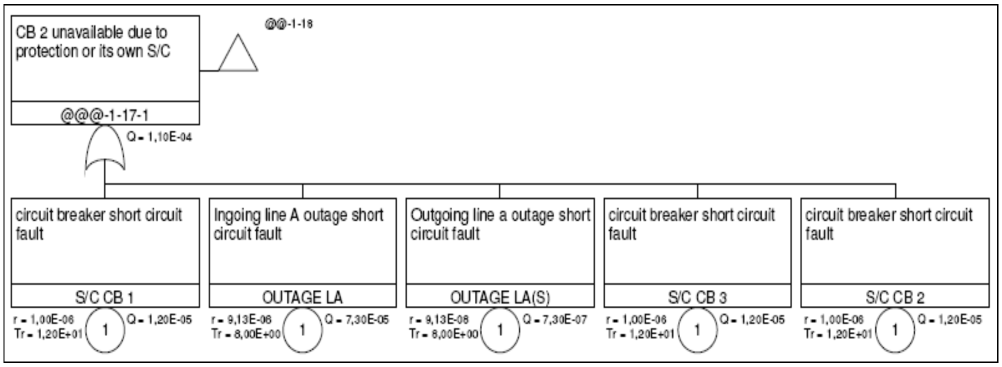


Fig. 4.9 Fault tree of CB 2 unavailable

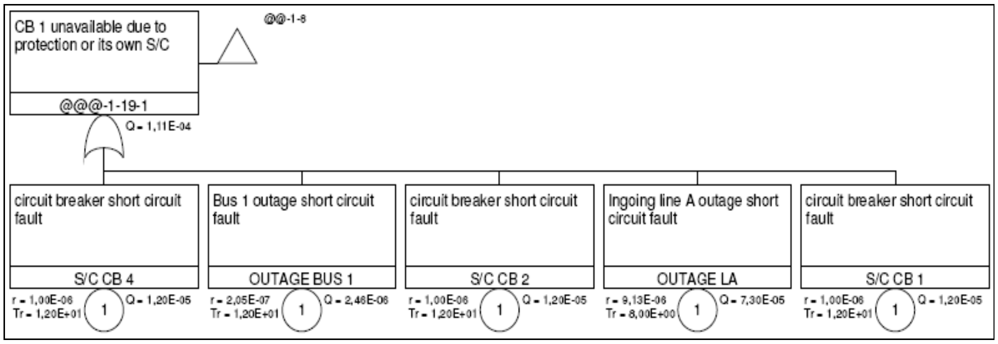


Fig. 4.10 Fault tree of CB 1 unavailable

The intermediate event of ‘CB 2 unavailable’, shown in Fig. 4.9, is specified into five different basic events, the first four are considered as ‘open on demand’ of CB 2 for protection purposes of adjacent components faults, and the last basic event as its own short circuit fault. Similarly, all other breakers are treated in the same way, and will not be further discussed.

Then the fault tree goes one component backward to the analysis of ‘No power flows into CB 1’ (Fig. 4.11). Following the similar approach, the causes of such undesirable intermediate event is either ‘Bus 1 unavailable’, which is the component fault, or ‘no power flows into bus 1’, which is the no power scenario even the component is in the healthy state.

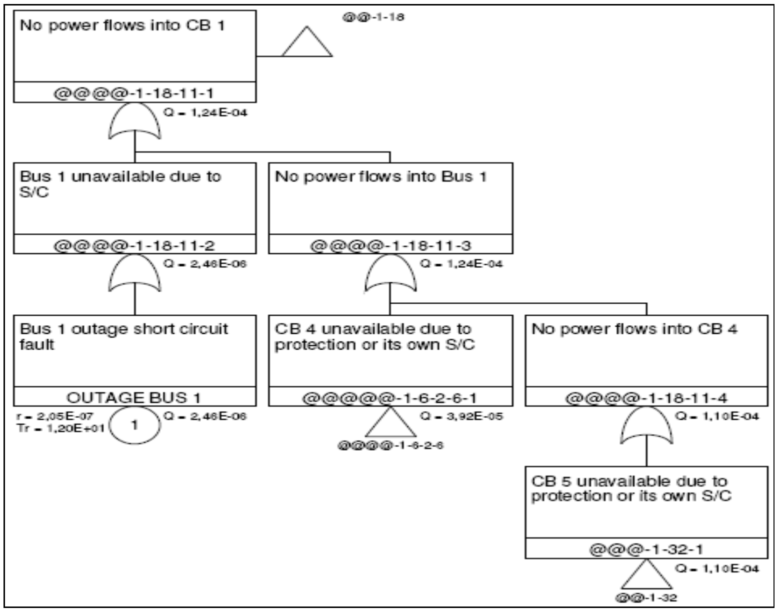


Fig. 4.11 Fault tree of no power flows into CB 1

The analysis continues based on the power flow direction and terminates until it reaches no power coming from the generation side at line B, which is handled in ‘CB 5 unavailable’ gate (Fig. 4.11 and 4.13), The reason that ‘No power flows into CB 5 when it is available’, potentially in parallel with ‘CB 5 unavailable’, can be ignored at the bottom of the fault tree is that all possible reasons that lead to ‘no power flows into CB 5’ are included in the ‘CB 5 unavailable’ intermediate event, and shall not be repeated.

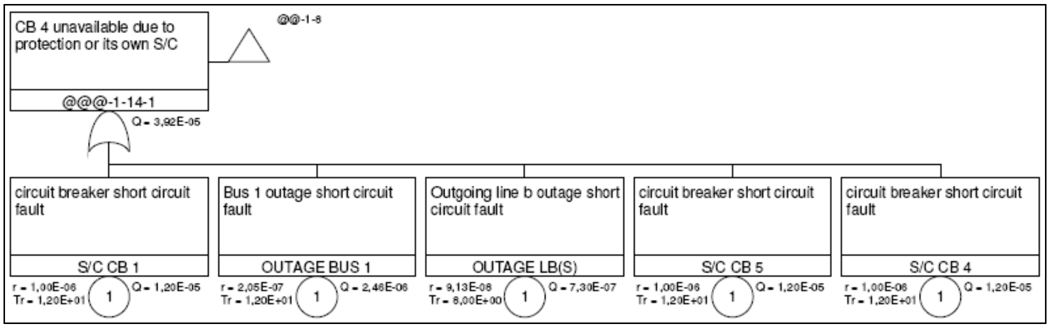


Fig. 4.12 Fault tree of CB 4 unavailable

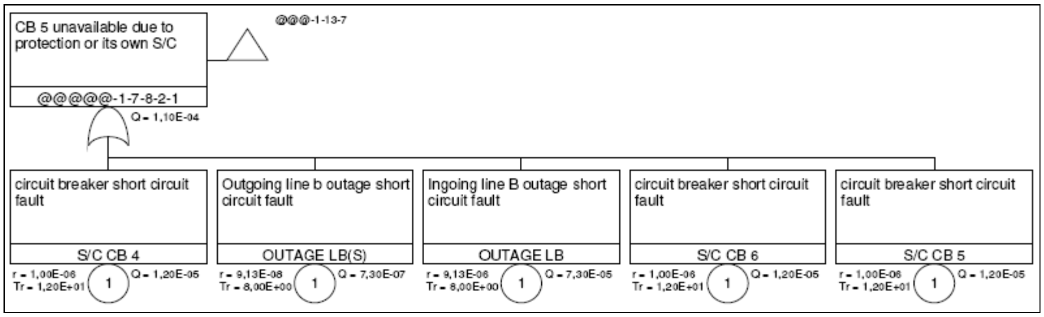


Fig. 4.13 Fault tree of CB 5 unavailable

Remark that under ‘No power flows into line a’, shown in Fig. 4.6, two intermediate events ‘no power flows through CB 2’ and ‘no power flow through CB 3’ are linked by an ‘AND’ gate. Let us analyze the intermediate event of ‘No power flows through CB 3’. It is analyzed in the same pattern as in ‘No power flows through CB 2’, which has been discussed above, with the power flow in the counter-clockwise direction in this case. The fault tree of the CB 3 branch has also been developed and is shown in Fig. 4.14. and Fig. 4.15.

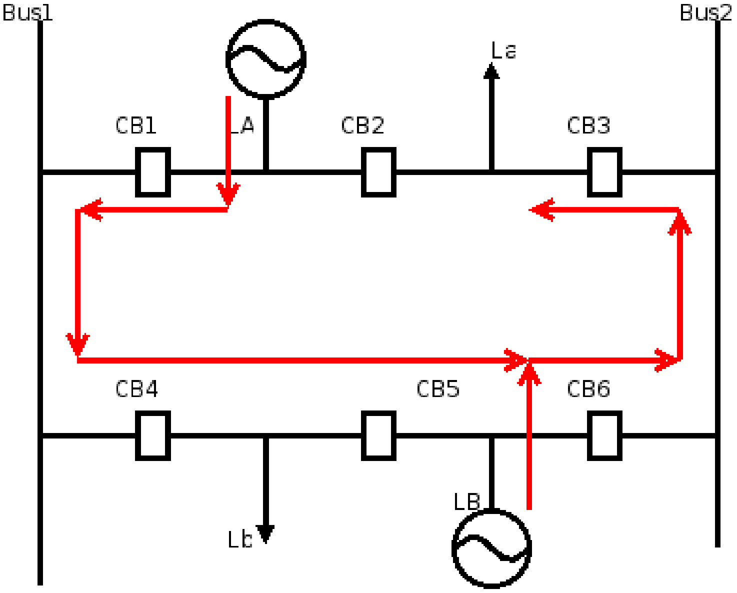


Fig. 4.14 Power flow direction from both incoming lines through CB 3

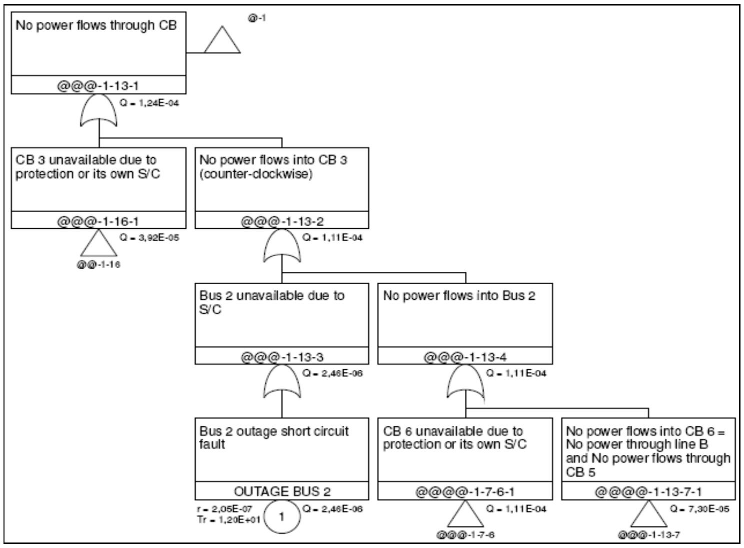


Fig. 4.15 Fault tree of no power flows through CB 3

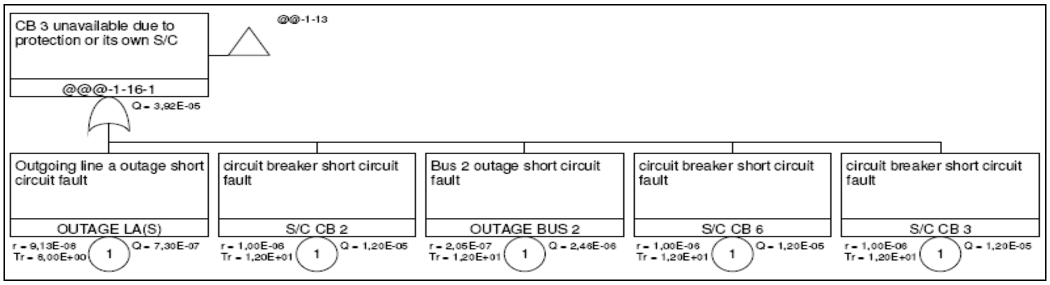


Fig. 4.16 Fault tree of CB 3 unavailable

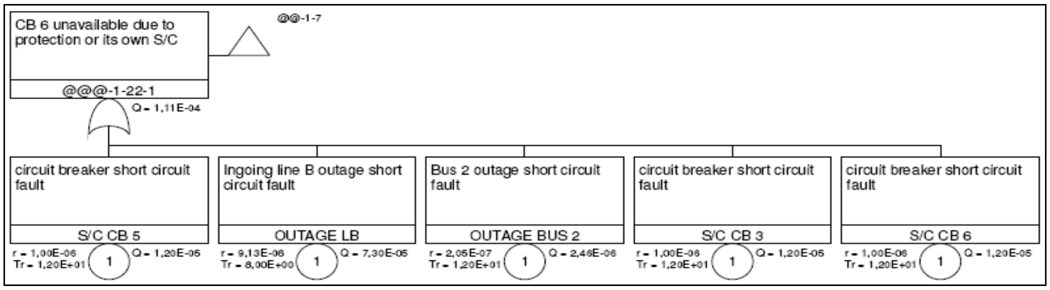


Fig. 4.17 Fault tree of CB 6 unavailable

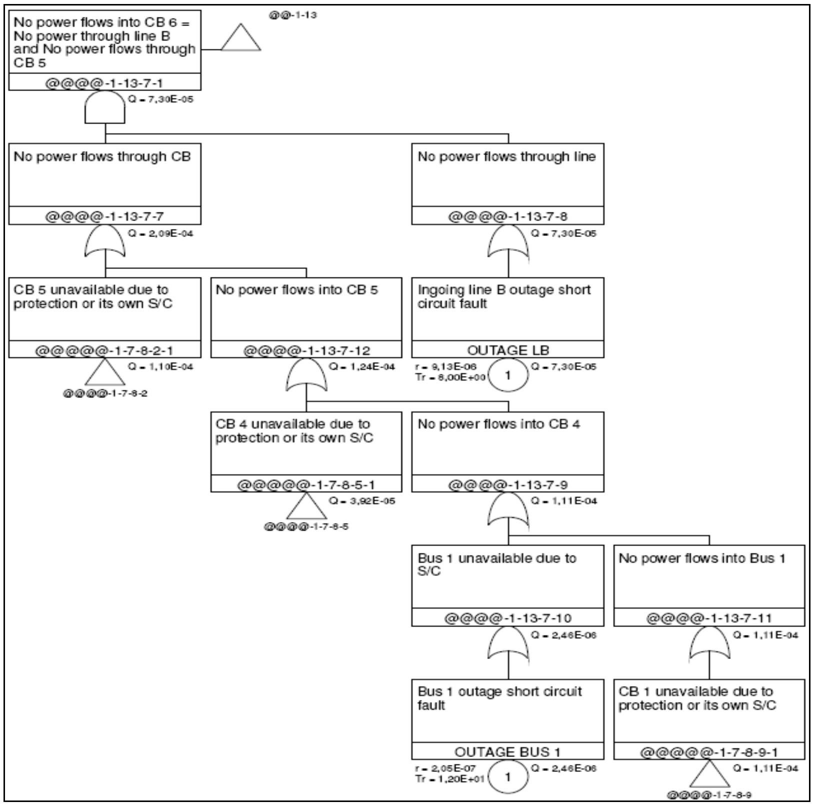


Fig. 4.18 Fault tree of no power flows into CB 6

The same approach has been applied to the other outgoing line b. The main fault tree structure is attached in the appendix section.

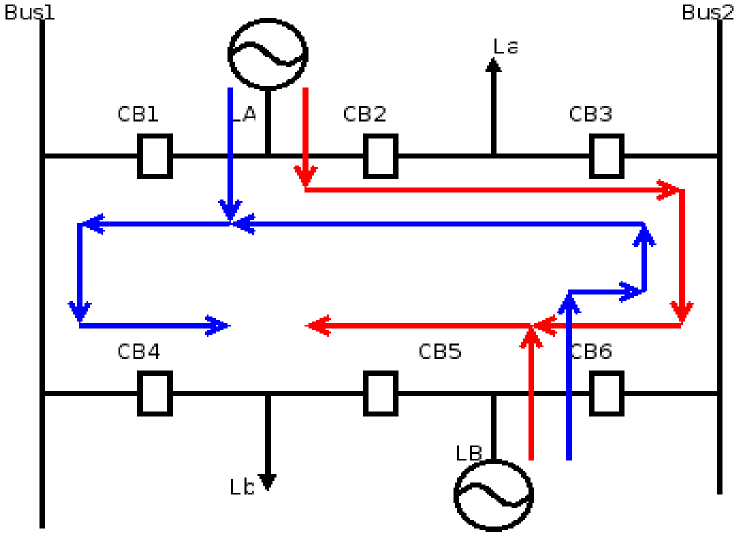
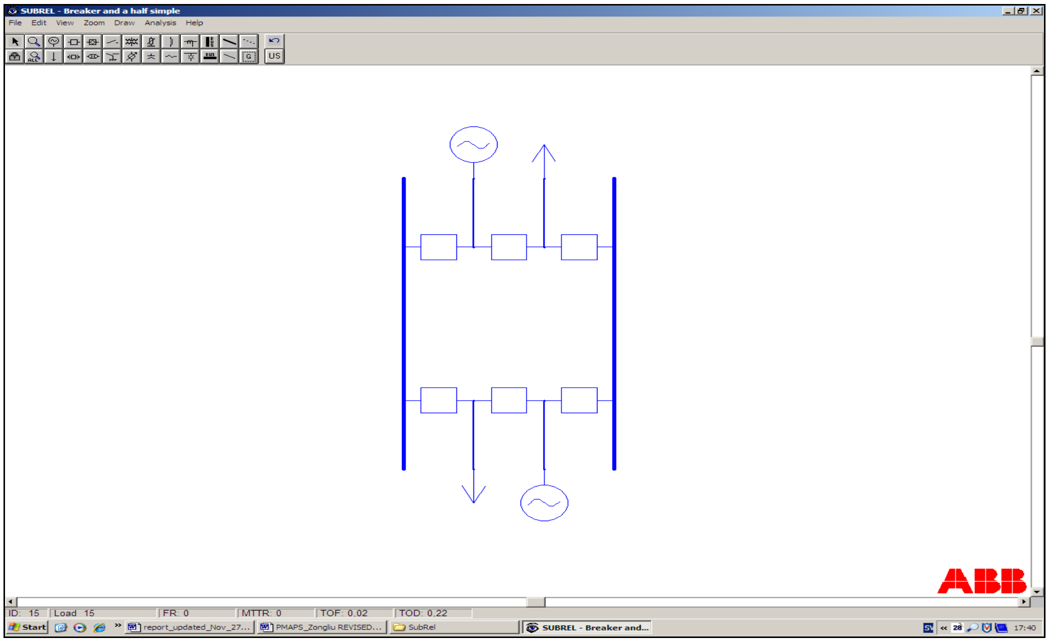


Fig. 4.19 Power flow direction of outgoing line Lb

4.1.3 SUBREL Simulation

To verify the results, Subrel simulation is performed to fulfill the task. Detail description of Subrel software can be found in Section 3.2.2.



ID: 15 | Load 15 | FR: 0 | MTTR: 0 | TOF: 0,02 | TOD: 0,22

Fig. 4.20 SUBREL work space of the simplified breaker and a half arrangement

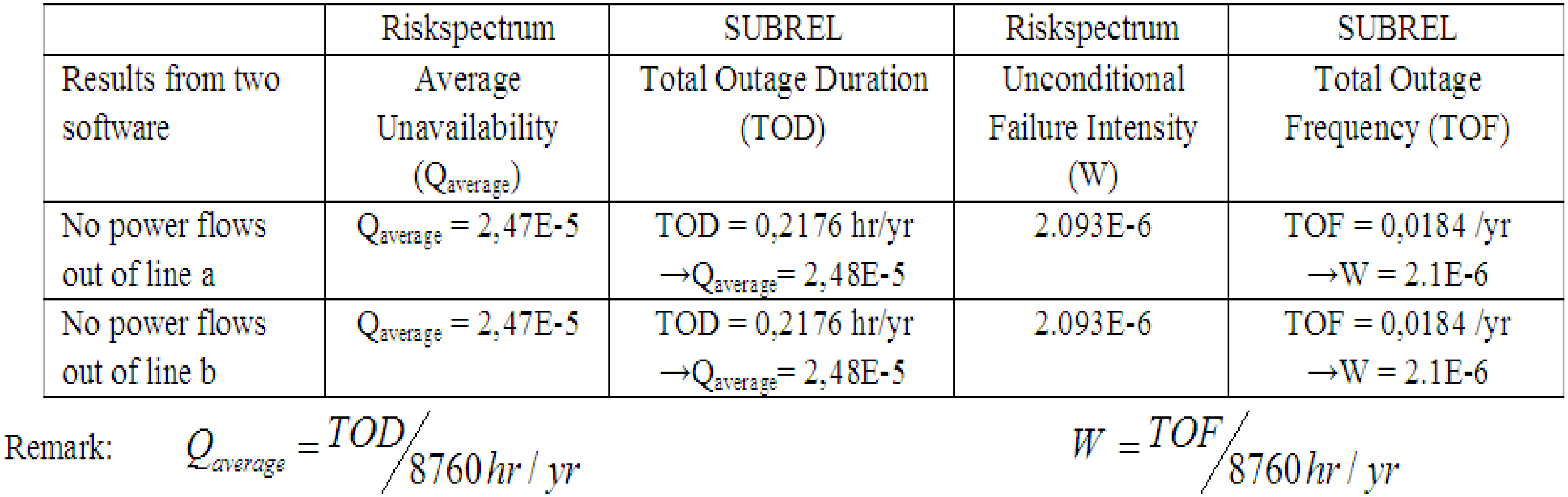
4.1.4 Comparison and Discussion

In this arrangement, each of two incoming lines is assumed to be 10 km long, which is reasonable distance from the power generation plant to the substation. The outgoing lines are assumed to be 100 meter each, which is also a reasonable length from the substation to the underground transmission cables. The reason to specify the length of lines is that the failure rate of lines is proportional to their length. The data are selected from ABB/STRI project. Detailed input parameters are shown in the table below.

Table 4.1 Input parameters

Input Parameters	Riskspectrum		SUBREL	
	Failure Rate	MTTR	Failure Rate	MTTR
Breaker	1E-6 (# / hr)	12 hr	0.0088 (# / yr)	12 hr
Bus	2.05E-7 (# / hr)	12 hr	0.0018 (# / yr)	12 hr
Incoming line	9.13E-6 (# / hr)	8 hr	0.008 (# / yr / km)	8 hr
Outgoing line	9.13E-8 (# / hr)	8 hr	0.008 (# / yr / km)	8 hr

Table 4.2 Simulation Results of Simplified Breaker and a Half Arrangement



	Riskspectrum	SUBREL	Riskspectrum	SUBREL
Results from two software	Average Unavailability ($Q_{average}$)	Total Outage Duration (TOD)	Unconditional Failure Intensity (W)	Total Outage Frequency (TOF)
No power flows out of line a	$Q_{average}$ = 2,47E-5	TOD = 0,2176 hr/yr →$Q_{average}$= 2,48E-5	2.093E-6	TOF = 0,0184 /yr →W = 2.1E-6
No power flows out of line b	$Q_{average}$ = 2,47E-5	TOD = 0,2176 hr/yr →$Q_{average}$= 2,48E-5	2.093E-6	TOF = 0,0184 /yr →W = 2.1E-6

Remark: $Q_{average} = TOD / 8760\,hr/yr$ $W = TOF / 8760\,hr/yr$

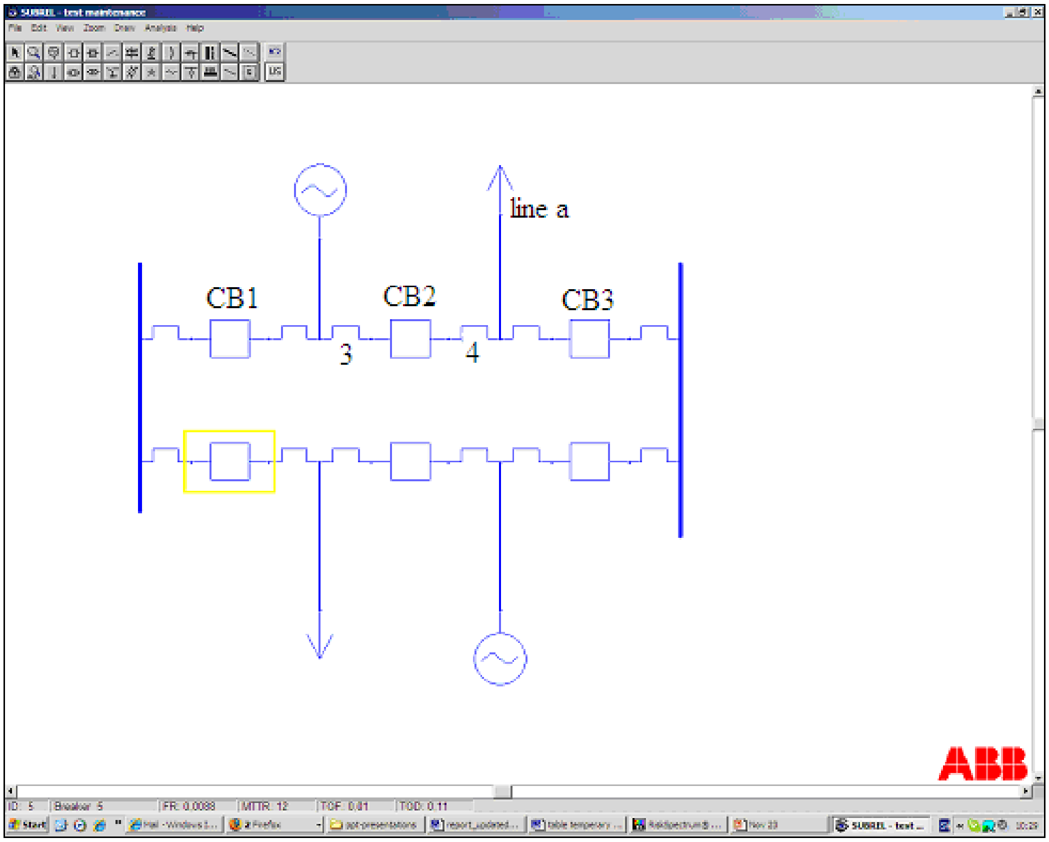
The results from Riskspectrum are consistent with those from Subrel with a negligible difference due to the unit conversion. The consistency of the results from both simulation tools validates the logic of constructing a fault tree to assess the reliability of the breaker and a half arrangement. Such fault tree modeling technique, ‘component unavailable’ and ‘no power flows into the component when it is available’, can be expanded to evaluate a more complex system structure, for instance breaker and a half arrangements with disconnectors or transducers. Moreover, Riskspectrum offers minimal cut sets of all events defined in the fault tree, it is observed that the most significant contributing factors that cause ‘no power flows out of line a’ are ‘CB 2 short circuit fault’, ‘CB 3 short circuit’ and ‘line a short circuit outage’, attached in Appendix A.

Notice that there are a few assumptions made in the fault tree construction and Subrel that may affect actual substation design selection. For instance, breaker capacity is assumed to be enough for one breaker to break in case of fault clearance or transfer all power flow in case of maintenance. Also, thermo-capacity of buses needs attention in actual design. Consider the case when all middle breakers are in maintenance state, and all incoming power is flowing into Bus 1 through side breakers, which make them under harsh thermal condition. However, in our analysis, breakers and buses are assumed to have enough capacity to transfer power flow, so that salient features of the breaker and a half arrangement can be utilized in case of fault or maintenance. On the other front, it may happen that a system that contains breakers connected in parallel to a bus may fail if a certain number of them fail under severe thermal condition, and this can be modeled by using a K-out-of N gate in a fault tree.

Maintenance of breaker and a half arrangement in this project is not included. However, it can be modeled by adding a basic event of the repairable model to represent maintenance operation under those gates representing ‘component unavailable’. In case that there are certain rules in real maintenance operation, such as two breakers in the same diameter do not perform maintenance operation at the same time, etc, XOR or NOT gates can be used to simulate the maintenance rules.

4.1.5 Breaker and a half arrangement with disconnectors

A more realistic breaker and a half arrangement is to place two disconnectors on both sides of each breaker to perform maintenance and fault isolation. More reference on disconnectors can be found in section 2.1 and 2.22. Subrel layout is shown in Fig 4.21.



ID: 5 | Breaker 5 | FR: 0.0088 | MTTR: 12 | TOF: 0.01 | TOD: 0.11

Fig. 4.21 Subrel layout of breaker and a half arrangement with disconnectors

All input parameters remain the same except adding the input data of disconnectors. λ = 0.0053, MTTR = 24 hours. The results from both Riskspectrum and Subrel are listed in Table 4.3.

Table 4.3 Simulation Results of Simplified Breaker and a Half Arrangement

	Riskspectrum	SUBREL	Riskspectrum	SUBREL
Results from two software	Average Unavailability ($Q_{average}$)	Total Outage Duration (TOD)	Unconditional Failure Intensity (W)	Total Outage Frequency (TOF)
No power flows out of line a	$Q_{average}$ = 2,98E-5	TOD = 0,2608 hr/yr →$Q_{average}$= 2,98E-5	1,30E-6	TOF = 0,029 /yr →W = 3,3E-6
No power flows out of line b	$Q_{average}$ = 2,98E-5	TOD = 0,2608 hr/yr →$Q_{average}$= 2,98E-5	1,30E-6	TOF = 0,029 /yr →W = 3,3E-6

Discussion: The average unavailability Q and the total outage duration TOD are the same with little discrepancy due to the unit conversion as mentioned in the previous section. The major differences between two methods are the simulation results in the unconditional failure intensity W and the total outage frequency TOF. To compare W with TOF, let us convert the unit to TOD for simplicity. $W = 1.3E-6 \Rightarrow TOF = 0.0114$. Considering the outgoing line a outage, Subrel considers the short interruption when breaker 2 or 3 experiences a fault. To be specific, considering the case when breaker 2 experiences a fault, breaker 1 and 3 trip to protect further propagation of the impact on the substation. Before disconnector 3 and 4 open to isolate the faulted breaker, line a experiences a short interruption. Similar analysis can be applied to the case when CB 3 experiences a fault. However, due to the lack of concern of the short interruption, the modeling technique in fault tree analysis only considers the long interruptions that the outgoing line experience. Nevertheless, as we can observe in the table, Q without disconnectors is in the same order of magnitude of that with disconnectors. W's follow the similar trend that they are in the same order of magnitude in both cases.

4.2 Double Breaker Arrangement

One task of the research is to compare the reliability of the breaker and a half arrangement with the double breaker arrangement. The double breaker arrangement is analyzed in a similar pattern using both Riskspectrum and Subrel. First of all, all assumptions made in analyzing the breaker and a half arrangement are still valid in the double breaker analysis. In the double breaker arrangement on the component level, two buses connect four diameters, which forms a similar two-input-two-output arrangement as that in the previous breaker and a half arrangement. The single line diagram of the arrangement is shown below.

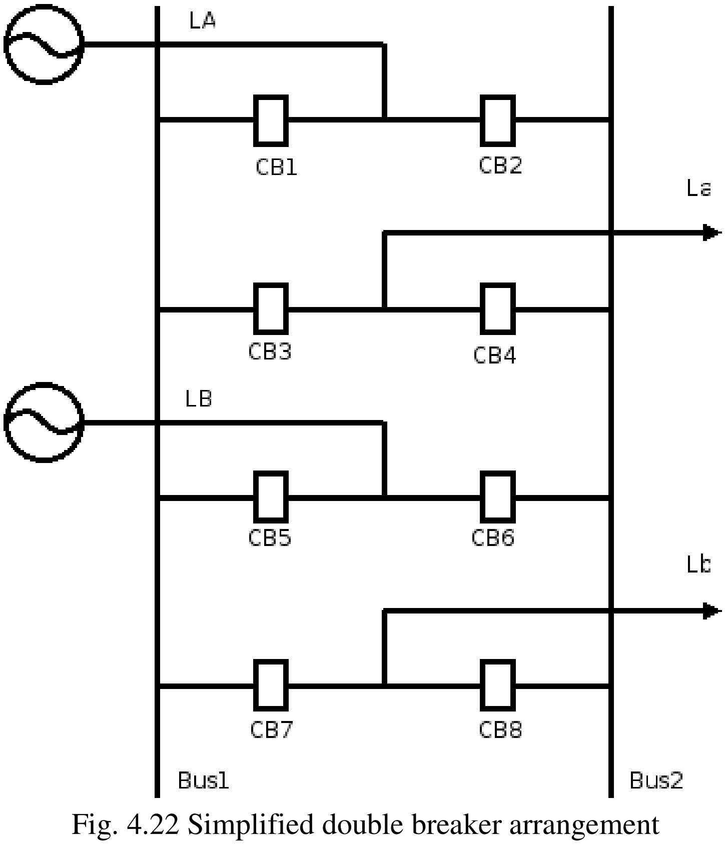


Fig. 4.22 Simplified double breaker arrangement

4.2.1 Fault tree analysis of double breaker arrangement

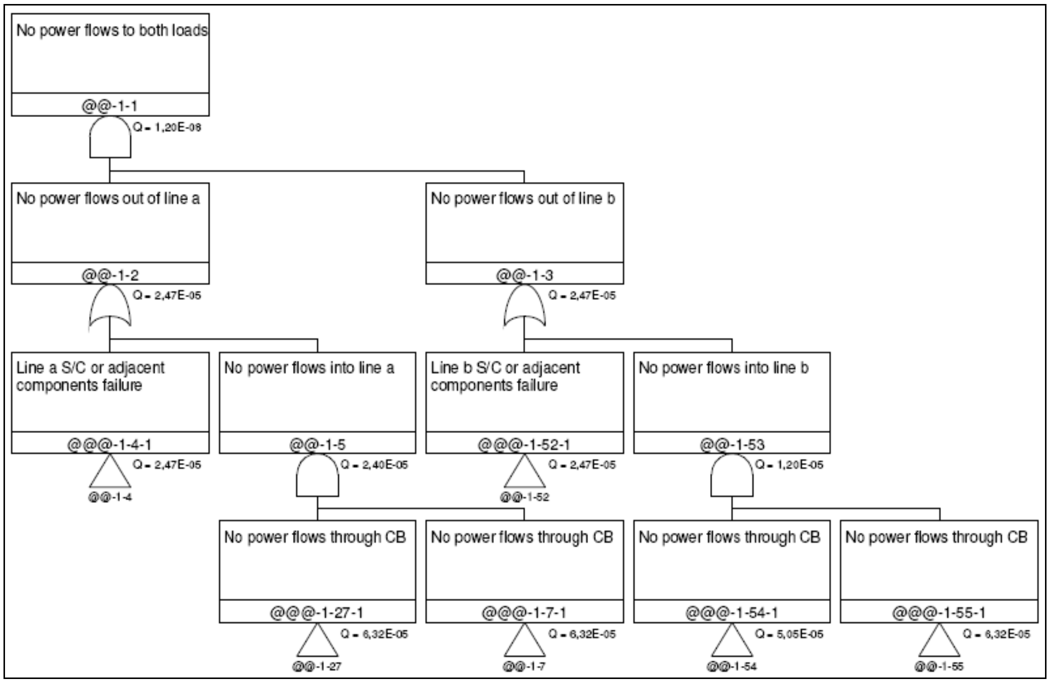


Fig. 4.23 Fault tree of top event

The top event of the fault tree analysis in the double breaker arrangement is defined as ‘no power flows to both loads’, representing that both outgoing line a and line b are experiencing power outage at the same time. Since line a and line b are symmetrically located in the layout, only outgoing line a is analyzed in detail.

The strategy remains the same, as the reason for the power outage is either due to ‘component unavailable’ or ‘no power flows into the component even it is in the available state’. Two reasons cause the occurrence of no power flows out of line a, namely ‘Line a S/C (short circuit) or adjacent components failure’ or ‘no power flows into line a’. The former reason can be further specified as follows in Fig. 4.24.

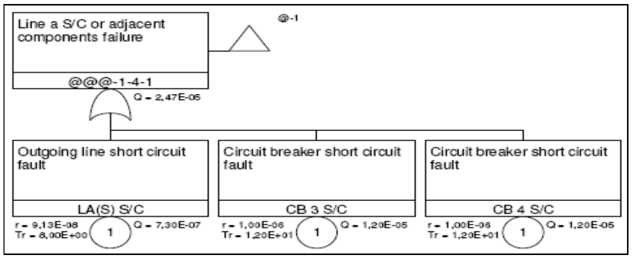


Fig. 4.24 Fault tree of outgoing line a fault or adjacent components fault

The latter reason is divided into two sub-categories. From the power flow point of view, ‘no power flows into outgoing line a’ is either ‘no power flows through CB 3’ or ‘no power flows through CB 4’.Once again, only one case is discussed in detail due to the highly symmetrical structure of the arrangement. Let us take ‘no power flows through CB 3’ for example. The power flow direction is illustrated in Fig. 4.25. The fault tree is constructed in Fig. 4.26.

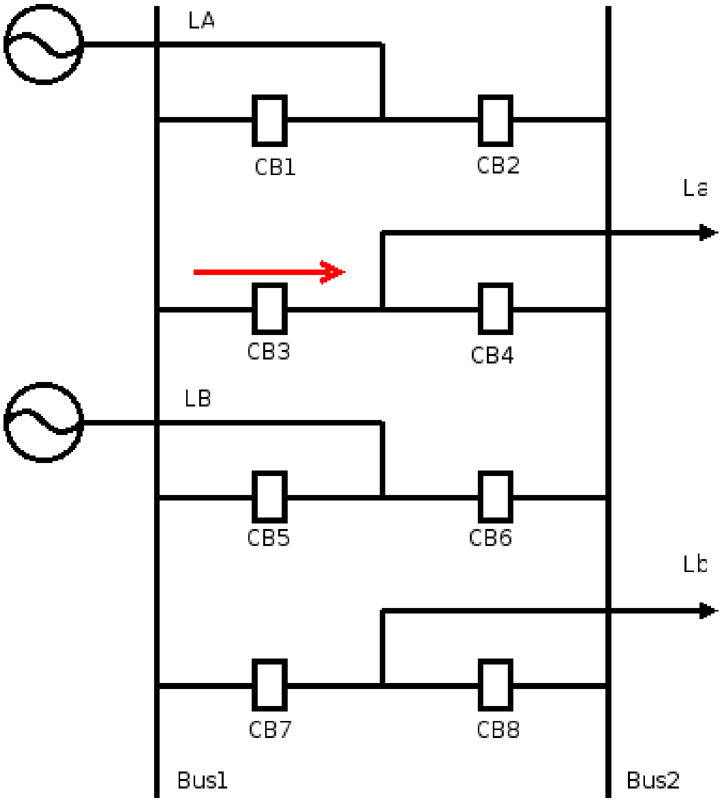


Fig 4.25 Power flow direction through CB 3

Following the strategy previously mentioned, ‘No power flows through CB 3’ can only be caused by ‘CB 3 unavailable’ or ‘no power flows into CB 3’. By tracing the power flow direction, ‘bus 1 unavailable’ or ‘no power flows into bus 1’ become only two reasons that cause the power outage flowing into CB 3. The power may come from three paths through CB 1, CB 5 or CB 7. To evaluate the occurrence of the power failure of bus 1, all power flow from CB 1, CB 5 and CB 7 have to experience outage at the same time, shown in Fig. 4.27, and thus and ‘AND’ gate is used to represent the modeling logic.

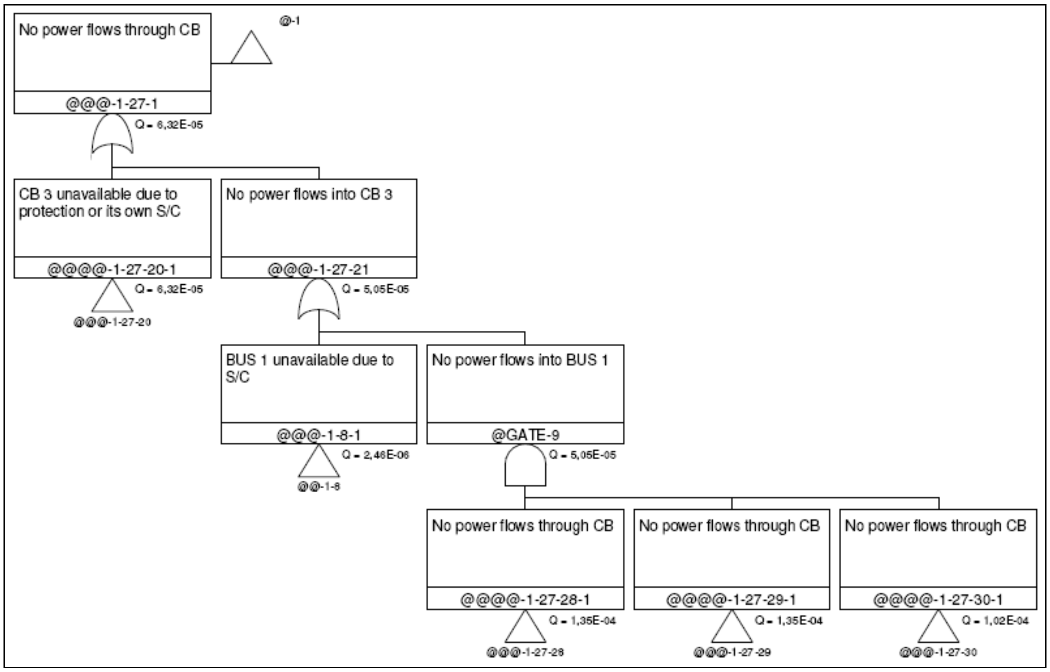


Fig. 4.26 Fault tree of no power flows through CB 3

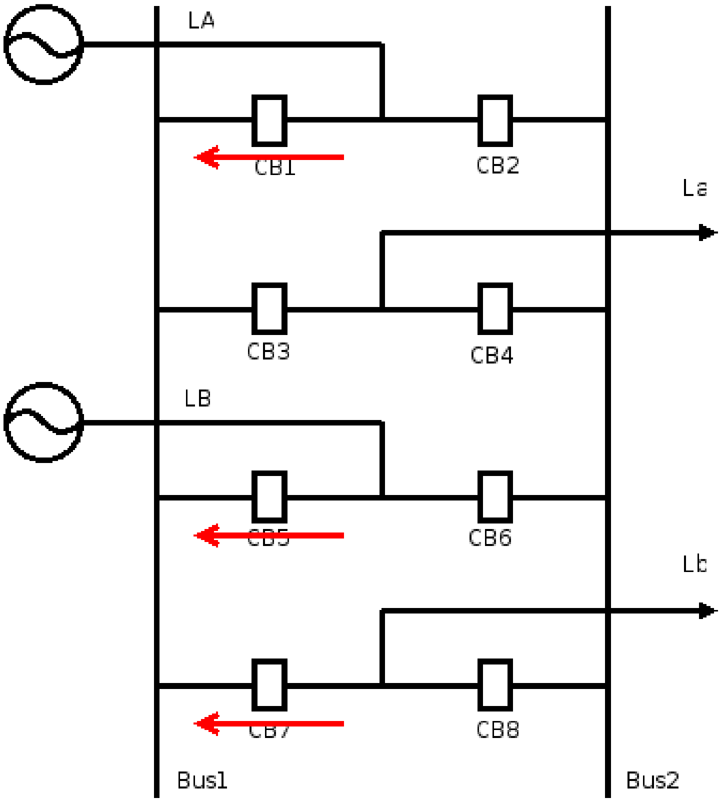


Fig. 4.27 Power flow direction into bus 1

To assess the power outage through CB 1, shown in Fig. 4.28, one can follow the power flow direction by tracing all components that the power passes through. Let us focus on ‘no power flows through CB 1’ for instance. The intermediate event may occur, because either CB 1 is in unavailable state or the power feeding into CB 1 may experience outage. The latter event is further specified into ‘no power flow coming into Line A from generation’ and ‘no power flows through CB 2’ at the same time.

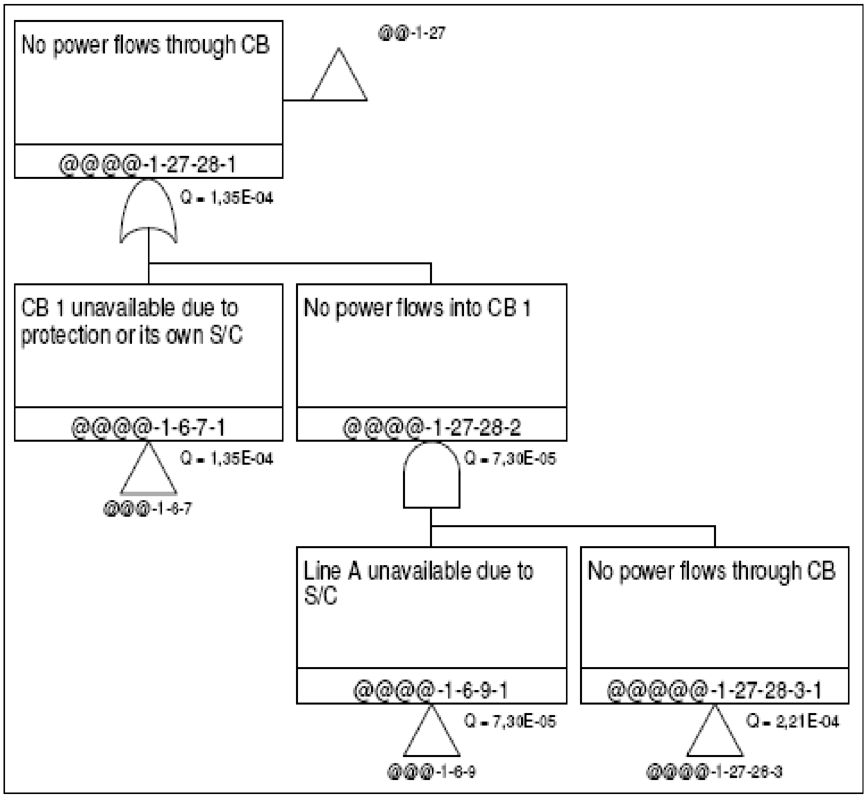


Fig. 4.28 Fault tree of no power flows through CB 1

Continue to track the power flow direction, shown in Fig. 4.29, power outage at CB 2 may either be its own unavailable or the power outage from Bus 2. The fault tree is presented in Fig. 4.30. The latter event is specified into ‘bus 2 unavailable’ or ‘no power flows into bus 2’. Up to this point, the only reason that there is no power flow feeding into bus 2 is that CB 6 is in the unavailable state, which directly points out the possible reason of incoming line B failure or CB 5 short circuit failure.

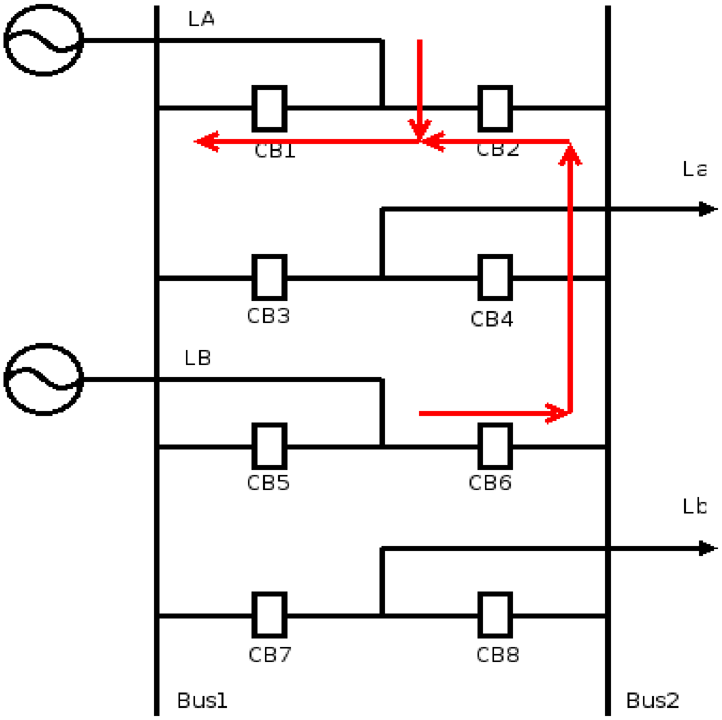


Fig. 4.29 Power flow direction from both incoming lines to bus 1

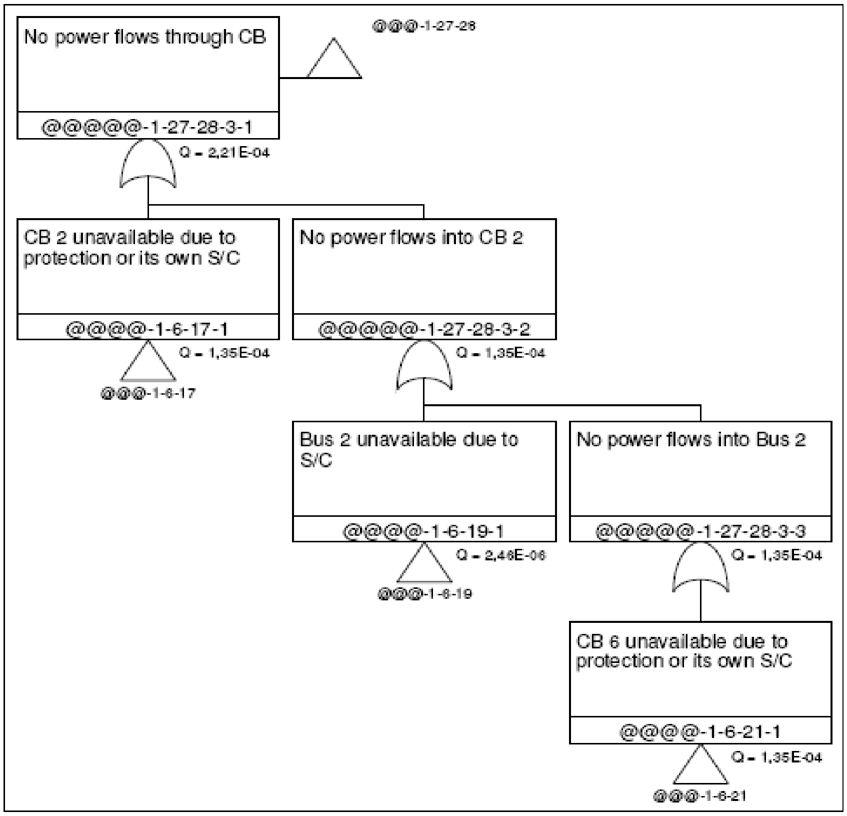
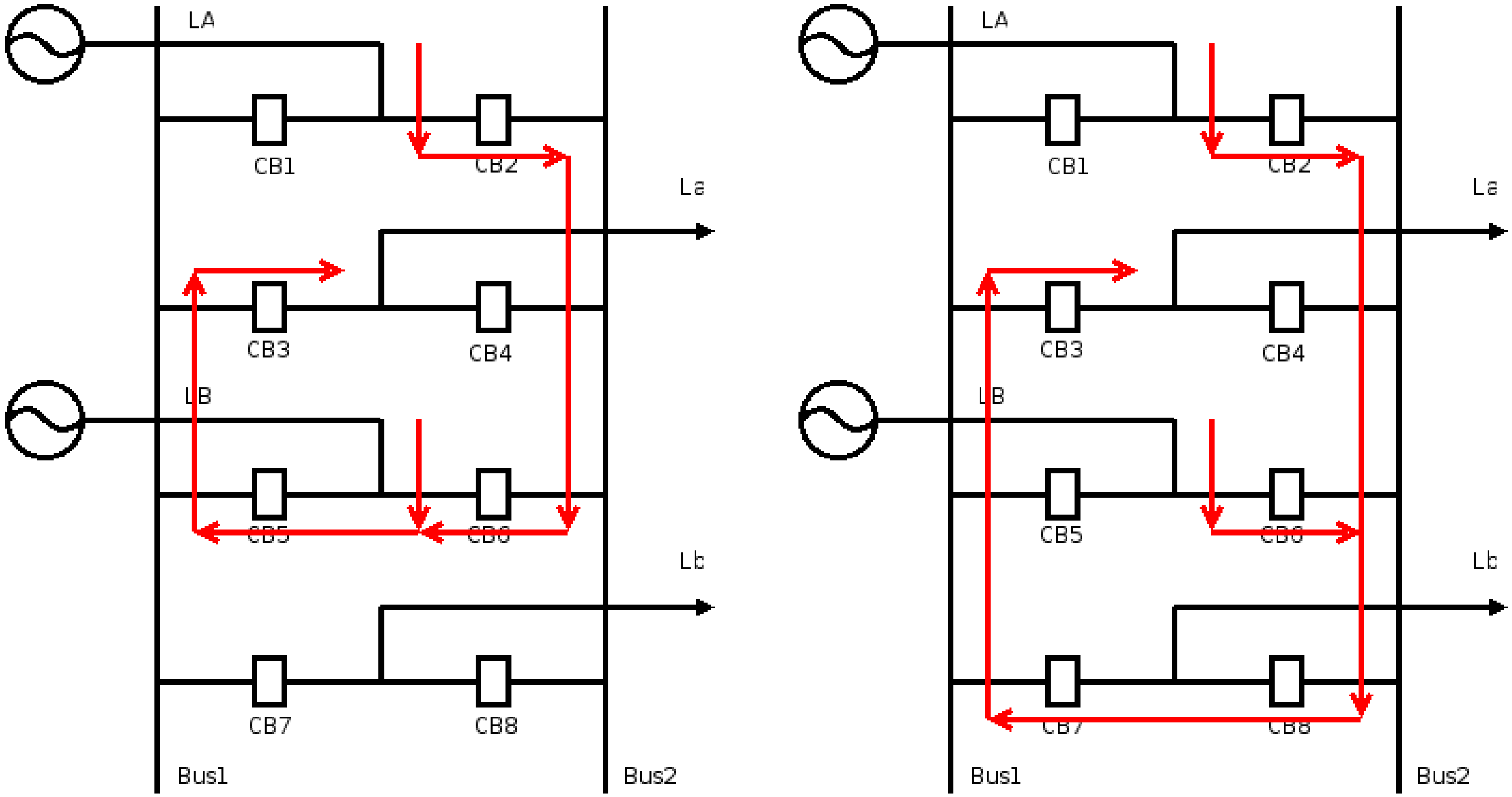


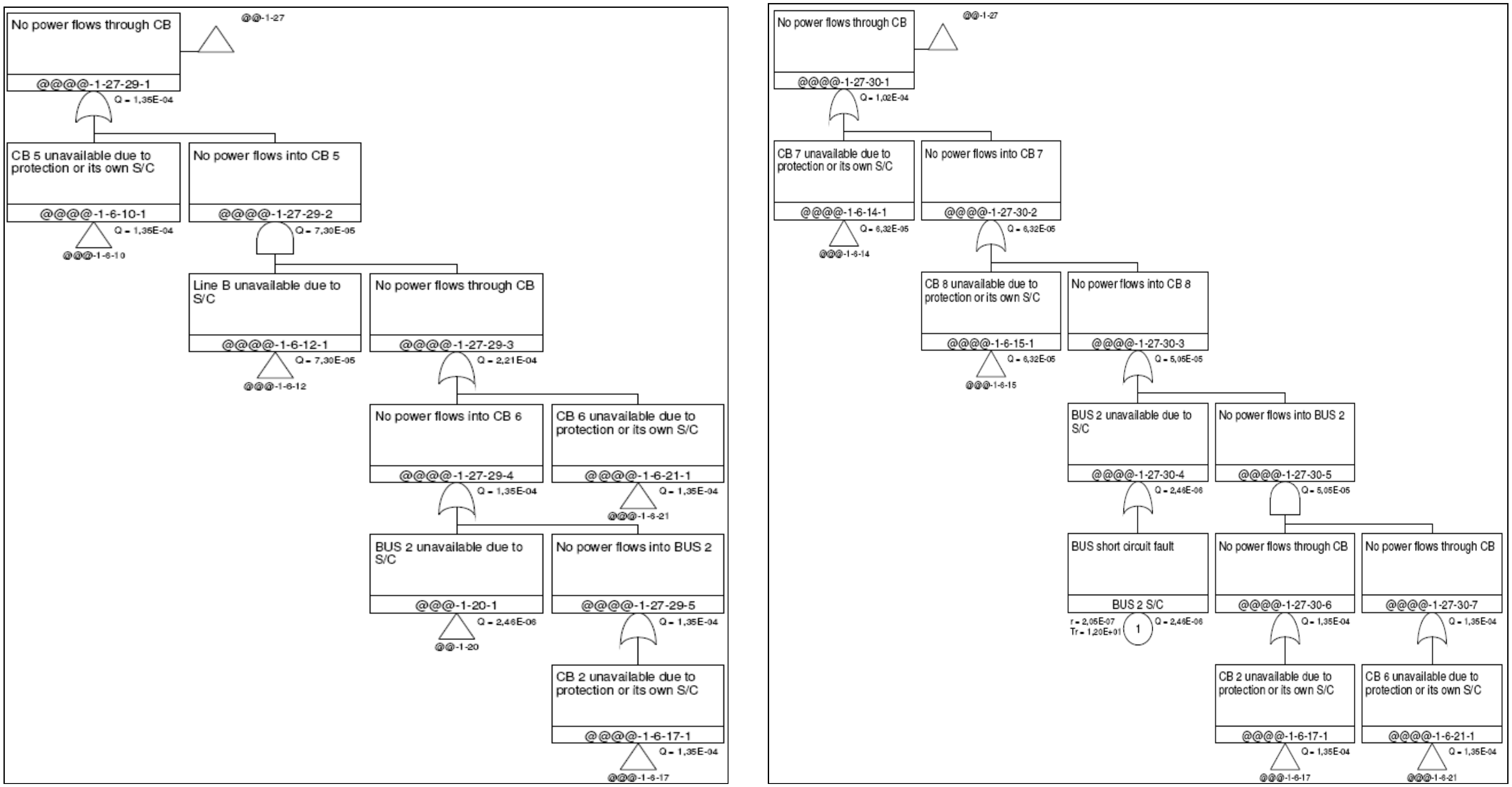
Fig. 4.30 Fault tree of no power flows through CB 2

Back to the intermediate events of ‘no power flows through CB 5’ and ‘no power flows through CB 7’, shown in Fig. 4.26, and Fig. 4.27, the detailed power flow direction is shown as follows in Fig. 4.31, and fault trees corresponding to ‘No power flows through CB 5’ and ‘No power flows through CB 7’ are presented in Fig. 4.32.



(a) (b)

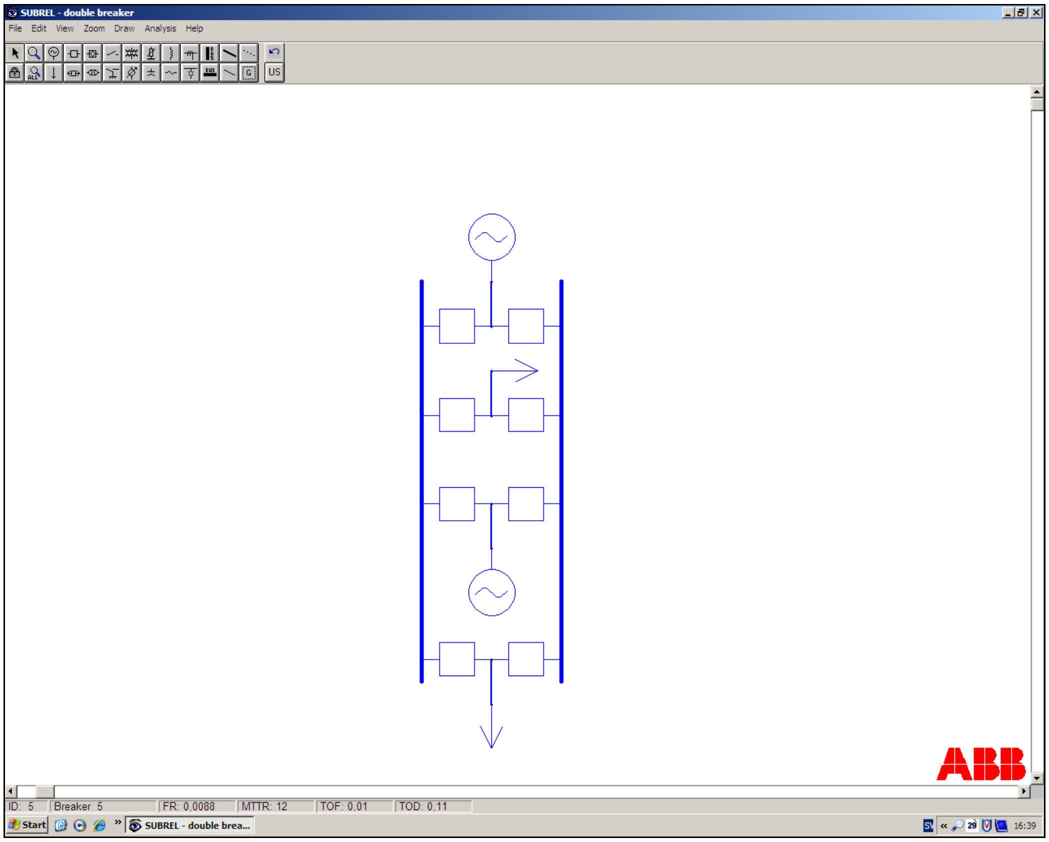
Fig 4.31 (a) Power flow direction from both incoming lines through CB 6 CB 5 and CB 3 (alternative path)
(b) Power flow direction from both incoming lines through CB 8 CB 7 and CB 3 (alternative path)



(a) (b)

Fig 4.32 (a) Fault tree of no power flows through CB 5 (alternative path)
(b) Fault tree of no power flows through CB 7 (alternative path)

4.2.2 SUBREL Simulation



ID: 5 | Breaker 5 | FR: 0,0088 | MTTR: 12 | TOF: 0,01 | TOD: 0,11

Fig. 4.33 Subrel work space of simplified double breaker arrangement

Subrel is performed to simulate the reliability index. In order to validate the results between Riskspectrum and Subrel, and between the breaker and a half arrangement to the double breaker arrangement, input data are selected from the same sources for comparison purposes.

Table 4.4 Simulation Results of Simplified Double Breaker Arrangement

	Riskspectrum	SUBREL	Riskspectrum	SUBREL
Results from two software	Average Unavailability ($Q_{average}$)	Total Outage Duration (TOD)	Unconditional Failure Intensity (W)	Total Outage Frequency (TOF)
No power flows out of line a	$Q_{average}$ = 2,47E-5	TOD = 0,2176 hr/yr →$Q_{average}$= 2,48E-5	2.093E-6	TOF = 0,0184 /yr →W = 2.1E-6
No power flows out of line b	$Q_{average}$ = 2,47E-5	TOD = 0,2176 hr/yr →$Q_{average}$= 2,48E-5	2.093E-6	TOF = 0,0184 /yr →W = 2.1E-6

Remark: $Q_{average} = {}^{TOD}\!/_{8760\,hr/yr}$ $W = {}^{TOF}\!/_{8760\,hr/yr}$

4.2.3 Comparison and Discussion

The results from both Riskspectrum and Subrel of a single outgoing line outage are compared for validating the modeling technique. Also, the comparison is made between the breaker and a half arrangement and the double breaker arrangement to assess a more reliable solution out of these two alternatives. To achieve the comparison between two arrangements, all input parameters of double breaker arrangement remain identical as those in the breaker and a half.

The input parameters and simulation results of double breaker arrangement and breaker and a half arrangement are identical. The identical results from both tools once again validate the modeling technique. More importantly, as shown the table 4.1 and 4.4, the results from both tools point out the fact that both substation arrangement have the same reliability considering the case of only a single outgoing line outage under certain assumptions that has been made prior to the assessment. Once again, assumptions are listed as follows.

- The lengths of incoming and outgoing lines are 10km and 0.1km respectively.
- All components only encounter severest failure such as short circuit fault which requires immediate interruption and repair.
- Protection systems functions perfectly, for it is set by default in Subrel [14], and logically modeled in Riskspectrum
- Single component has sufficient thermal and other types of capacity to handle the power flows during maintenance and fault isolation period.
- Disconnectors are not included in this particular assessment, but are included in the following section.
- Maintenance is not modeled in this particular assessment. The idea of the modeling technique is explained in the precious section.

A bit of reality: In actual substation arrangement, line failure consists of over 90% of the overall substation failure, and the protection is not perfectly functioning, so that breaker may encounter primary failures such as 'fail to open on command', 'fail to break the current', etc. In the breaker and a half arrangement, for instance when the incoming line A is experiencing a fault, CB1 and CB2 are supposed to open. However CB 2 does not open on command, so that CB3, as a backup protection, opens to clear the incoming line fault, resulting the outgoing line a experiencing a service interruption. Such event can be avoided in the double breaker arrangement. Similar situation applies that an incoming line failure triggers both breakers, and one of the breakers fails to open on command. All side breakers on the faulted breaker side open to clear the fault as back up protection. However, the service of both loads is not interrupted by such an event in the double breaker arrangement.

The maintenance frequency of disconnectors has been a rising problem recently, comparing with the technical improvement of circuit breakers. Originally, disconnectors were designed to isolate the breaker during maintenance. And one may expect that in old days breakers required more intensive maintenance, so that disconnectors are essential to be placed around the breakers for the maintenance purpose. However, because of the rapid development of the breaker technology, modern breakers requires maintenance less than once per 15 years, and thus the necessity of disconnectors in the substation arrangement requires reconsideration, since maintenance on disconnectors sometimes requires the service interruption on the load. That is, the maintenance frequency of disconnectors may significantly influence the unavailability of the load, and should be taken seriously for the detailed investigation. On the other front, there is an alternative solution to minimize the impact of the disconnector by integrating the disconnecting function into circuit breakers. A new device is named 'disconnecting circuit breaker' is commercially available from ABB.

In terms of cost analysis, the breaker and a half arrangement costs less than the double bus arrangement if only the capital cost of all components is considered. For instance, a typical two-input-two-output breaker and a half requires six breakers, while double breaker arrangement requires eight. To assess the overall cost of both substation arrangements, one should also consider the cost of civil construction, land requirement, protection systems, maintenance, etc.

Chapter 5 Riskspectrum Advanced Simulations

5.1 Breaker and a Half Arrangement

5.1.1 Common Cause Failure

The failure rates of different components in the system have been considered independent to each other so far. However, in practice, there exist dependent failures in which two or more component fault states exist simultaneously, or within a short time interval, and are direct result of a shared cause [25], [30]. Basic events such as high operating temperature, earthquake and other similar factors may cause two or more components in the substation fail at the same time. It is therefore important to identify potential common cause failures and take the necessary precaution to prevent such failures.

The most commonly used (implicit) model for common cause failures is the β-factor model. In this model, a certain percentage of all failures are assumed to be common cause failures, which cause relevant items fail at the same time or during a short interval [25].

The failure rate is therefore to be written as

$$\lambda = \lambda_{(i)} + \lambda_{(c)} \tag{5.1}$$

where $\lambda_{(i)}$ is the failure rate of independent failures that only affect the particular component, and $\lambda_{(c)}$ is the failure rate of common cause failures that will cause failures of all the relevant components.

The common cause factor:

$$\beta = \frac{\lambda_{(c)}}{\lambda_{(i)}} \tag{5.2}$$

The common cause factor is the percentage of common cause failures among all failures of a component.

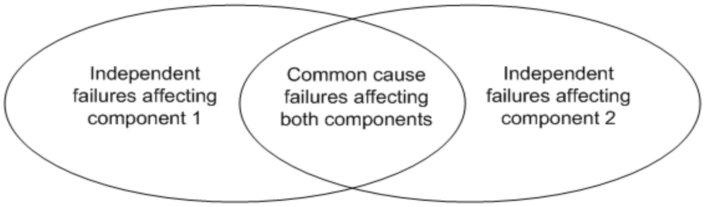


Fig. 5.1 Relationship between independent and common cause failures of a system with two components

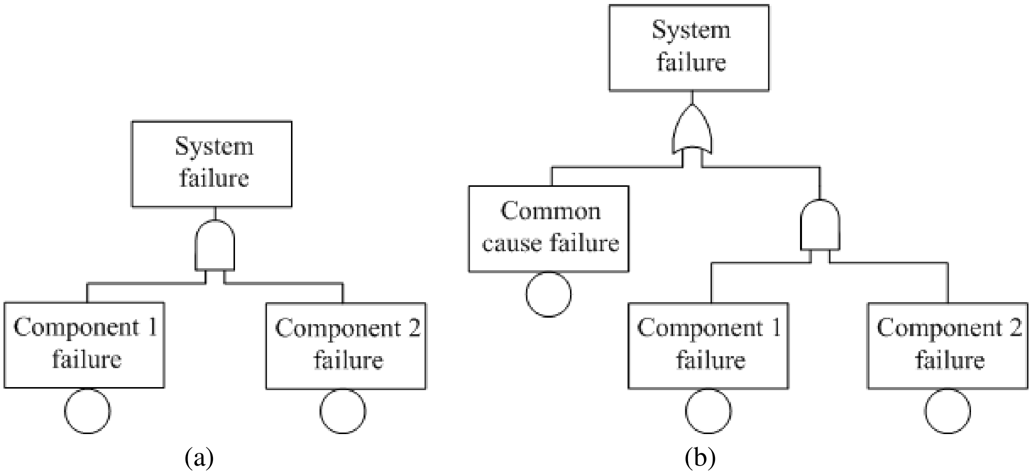


Fig. 5.2 (a) Fault tree without CCF, (b) Fault tree with CCF

The corresponding fault tree of the above model is shown above in Fig. 5.2. The common cause failure will make both component 1 and 2 out of service at the same time and hence leads to the top event. The first fault tree, Figure 5.2 (a), is constructed without considering CCF. The fault tree leads to an inaccurate probability evaluation. To evaluate the difference between Figure 5.2 (a) and (b), let us define Qc as the probability of common cause failure and Qi, i = 1, 2 as the failure probability of the component i, the failure probability of the system in (a) is Qs' = Q1*Q2, and in (b) Qs = Qc + Q1*Q2 – Qc*Q1*Q2. Since Qs > Qs', introducing common cause failure is more realistic and the failure probability of the top event is more conservative than that without analyzing CCF [25].

In the following simulation, beta-factor is set 30% for all components in the breaker and a half arrangement.

Table 5.1 Impact of Common Cause Failure

Evaluated Scenarios	Without CCF	With CCF
Single line outage	Q = 2.47E-5 W = 2.09E-6	Q = 2.88E-5 W = 2.40E-6
Both line outages	Q = 9.88E-9 W = 2.24E-9	Q = 3.60E-6 W = 3.00E-7

By considering 30% of common cause failure, the average unavailability Q of a single line outage increases 16.6%, meanwhile the failure intensity W also increases 14.8%. The increase of Q and W implies that CCF contributes fairly amount to an outgoing line outage. Considering the scenario when both lines are experiencing outage, the average unavailability Q that considers CCF is 3 orders of magnitude higher than the case without considering CCF, meanwhile the failure intensity W is 2 orders of magnitude higher.

On the other front, comparing the results vertically, Q and W of both line outages are 4 and 3 orders of magnitude higher than those of single line outage, without considering CCF. However, by considering CCF, Q and W of both line outages only reduces 1 order of magnitude. That is to say, Q and W of the arrangement do not improve much by installing an additional diameter and an outgoing line.

5.1.2 Uncertainty Analysis

So far, the average unavailability Q has been calculated by all input parameters of failure rate and mean time to repair using arithmetic mean values in Riskspectrum. However, the software offers another way to compute Q using probability density functions to represent the failure rate and mean time to repair. In order to take into account the uncertainty of reliability data, the mean values of each input parameters can be represented by probability density functions. Monte Carlo simulation is then used to run cases where reliability data is chosen randomly according to probability density function of each parameter.

Riskspectrum offers different distribution functions as normal, lognormal and gamma among others. In this work, Gamma distribution is used to model the uncertainty in reliability data of all components in the substation. Gamma distribution is positive defined, and therefore negative values failure rates and mean time to repair in the distribution function are avoided by default.

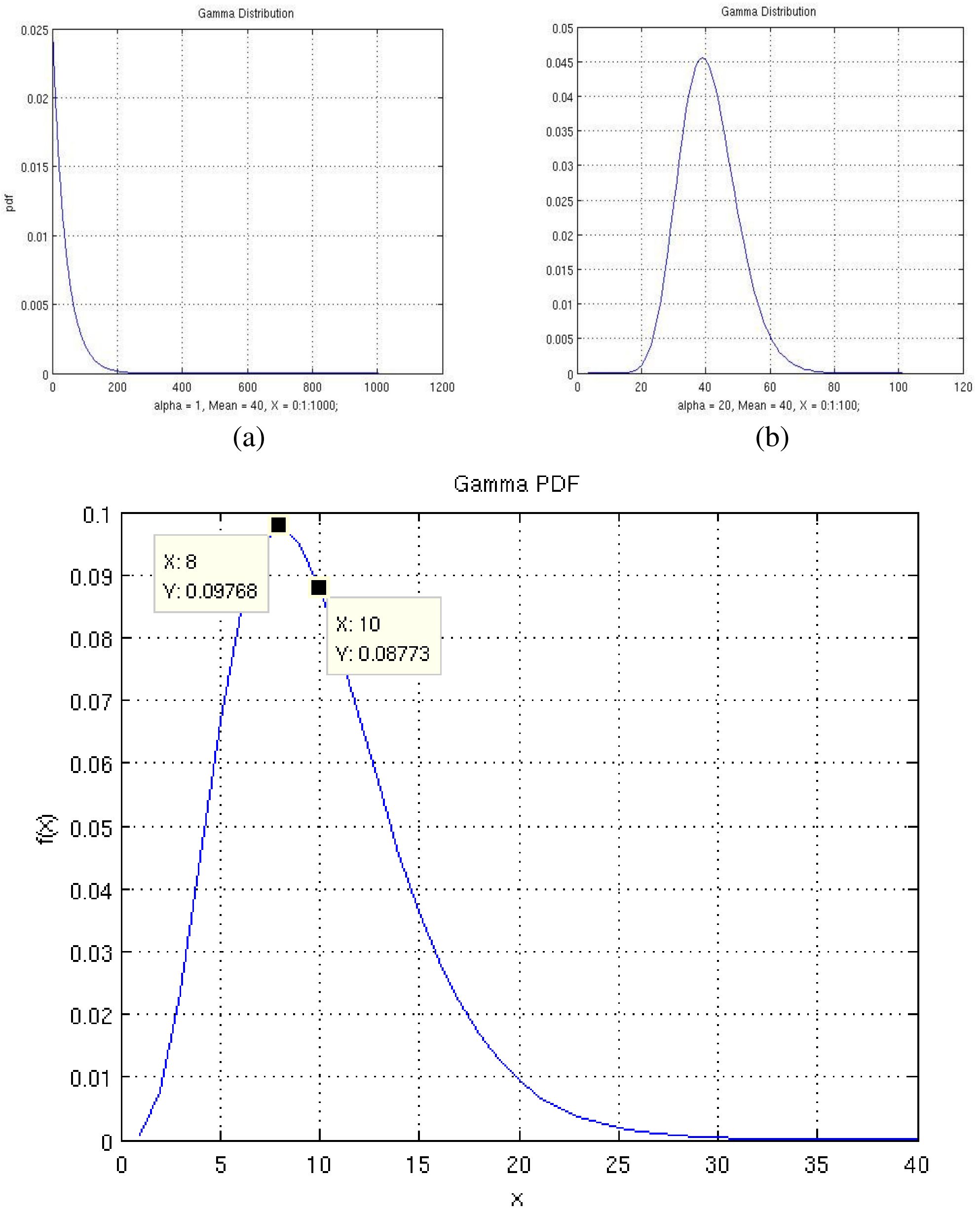
$$f(x,\alpha,\beta) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} \cdot x^{\alpha-1} \cdot e^{-\frac{x}{\beta}} \tag{5.3}$$

Gamma distribution is a non-symmetric and positive biased distribution. In order to fine tune the gamma function of each parameter, the following aspects are taken into account.

First, it is well known that a small standard deviation means less dispersion in the distribution, i.e. the values are grouped near the mean value. Second, Gamma distribution in Riskspectrum needs only one shape parameter called α as input since the rate parameter β is assessed using the mean value and α, the mean is given by [31].

$$Mean = \alpha * \frac{1}{\beta} \tag{5.4}$$

Third, α is a real number greater than zero that modifies the shape of the function. Riskspectrum constrains α to a range 0.1 to 20. A higher value of α means smaller dispersion in the distribution function, while values towards one mean larger dispersion. The shape of the distribution is shifted to an exponential distribution for values of α less or equal to one, which is avoided in this study.



(a) (b)

(c)

Fig. 5.3 (a) shape factor α = 1, mean = 40
(b) shape factor α = 20, mean = 40
(c) shape factor α = 5, mean = 10

In this study, the mean values of failure rates of each component are assumed one order of magnitude larger than the mode values. For instance, the mean value of the failure rate of a single breaker is 1E-6 times per hour, and the mode is assumed to 1E-7. Then, α and β can be calculated by Eq. 5.4 and 5.5 [31].

$$Mode = (\alpha - 1) * \frac{1}{\beta} \tag{5.5}$$

The mean time to repair is also treated similarly. To calculate the shape parameter α as an input, the mode value is assumed 2 hours smaller than the mean value.

Table 5.2 Parameters of failure rate in uncertainty analysis

Component	Mean value of failure rate	Mode of failure rate	Shape parameter α	Rate parameter β
Breaker	1,00E-06	1,00E-07	1,11	1,11E6
Bus	2,05E-07	2,05E-08	1,11	5,41E6
Incoming line	9,13E-06	9,13E-07	1,11	1,22E5
Outgoing line	9,13E-08	9,13E-09	1,11	1,22E7

Table 5.3 Parameters of MTTR in uncertainty analysis

Component	Mean value of repair time (MTTR)	Mode of Repair time	Shape parameter α	Rate parameter β
Breaker	12 hr	10 hr	6	0,5
Bus	12 hr	10 hr	6	0,5
Incoming line	8 hr	6 hr	4	0,5
Outgoing line	8 hr	6 hr	4	0,5

Note that when the shape parameter alpha is chosen, and the mean value of the gamma probability density function is also given, the rate parameter beta is then calculated. Once these three parameters are defined, the gamma distribution can be plotted. The concern here is that in the gamma probability density function plot whether there are possibilities that the mean value is smaller than the mode value. That is to say, the mean value that we are using in the Riskspectrum input is smaller than the value that is the most frequent occurred. In terms of the unavailability analysis, the concern means that the output calculated from Riskspectrum may be too optimistic from the reality since the input mean value is smaller than the actual mode value in gamma distribution. The mean value of gamma distribution is alpha*(1/beta), and the mode value is (alpha-1)*(1/beta), alpha > 1. Comparing the mean value with the mode, the mean value is 1/beta times larger than the mode. Interpreted in the average unavailability analysis, the mean value we are using as the input in Riskspectrum gives a relatively larger average unavailability, which is a desirable conservative result.

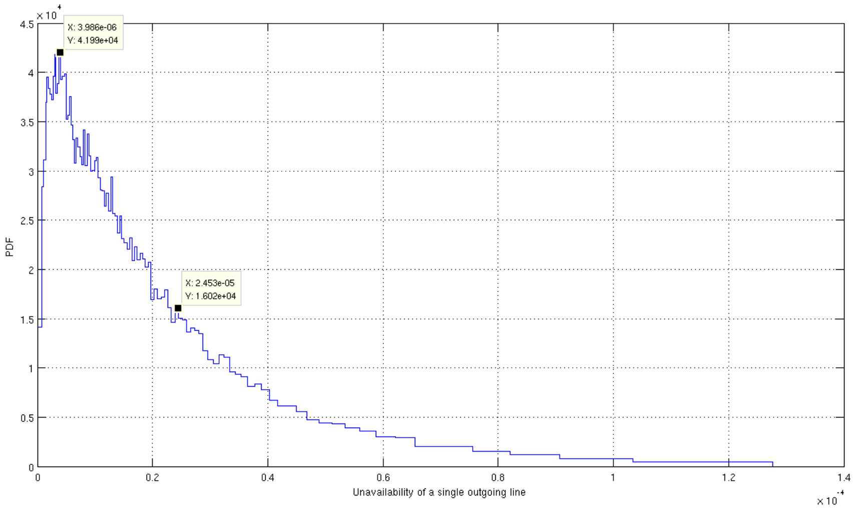


Fig. 5.4 Probability density function of the unavailability of a single outgoing line

Matlab is used to process the output data from Riskspectrum, shown in Fig. 5.4. The x-axis is the unavailability of a single outgoing line, and y-axis the probability density function. The shape of the plot is similar to that of a typical gamma distribution, for each input parameter is randomized based on gamma distribution, and the output data is therefore expected to have the gamma distribution characteristics. Assuming that the output plot is Gamma distribution, the mode is 4.81e-6, and the mean value is 2.47e-5. The mean value of the unavailability, the one that is normally used in the scientific calculation, is one order of magnitude larger than the mode, the number that happens the most. Therefore the mean value is a desirable conservative value that should be used for desirable purposes.

5.1.3 Importance and Sensitivity Analysis

The importance of components in the substation is not equally weighted, That is, components shown up in the 1st order minimal cut sets are more important than those shown up in higher orders of minimal cut sets. Importance analysis is used to identify how much percentage each component contributes to the top or any intermediate events. Sensitivity analysis is used to assess how the system behaves when the input parameters of each component varies. That is to say, the system is more sensitive to some components than other ones, and the analysis is able to list the sensitivity measures in a decreasing or increasing order. The outcomes of both importance and sensitivity analyses offers an insight view of how each component influence the reliability of the system

1. Fussel-Vesely Importance Analysis [32]

The Fussel-Vesely importance for a basic event is calculated in the following way:
a) Calculate the top event unavailability based only on all MCSs where the basic event is included (this is the same as setting the unavailability to zero for all MCSs not containing the basic event)
b) FV importance is the ratio between the unavailability according to item 1 and the nominal top event unavailability:

$$I_i^{FV} = \frac{Q_{TOP}(MCS \text{ including i})}{\mathrm{Q_{TOP}}} \qquad (5.6)$$

2. Sensitivity Analysis [32]

The sensitivity analysis is to show how sensitive the system's reliability would be according to the changes of component reliability.

First, set the values of reliability indices in the fault tree (unavailability, failure frequency, or failure rate) under consideration equal to the nominal value divided by SensFactor. This SensFactor can be any value higher than 1. Then calculate a new top event result of the system reliability indices (unavailability of failure frequency). This new result must be lower than the nominal result as the unavailability and failure frequency is decrease, and the reliability is increased. This new result is denoted as $Q_{TOP,L}$.

Second step is to set the values of reliability indices under consideration equal to the nominal value multiplied by the same SensFactor. If any value is out of the valid range after the multiplication, it will set to be the maximum allowed value. Probability will turn to be 1. Calculate this new top event result. As the unavailability, failure frequency or failure rate is increased, unreliability of the system is increased while the reliability of the system is decreased. Then the new result is denoted as $Q_{TOP,U}$.

Then, the sensitivity of the system can be calculated by the formula below.

$$S = \frac{Q_{TOP,U}}{Q_{TOP,L}} \tag{5.7}$$

Table 5.4 Importance and Sensitivity

No.	ID	FV	Sens. Fraction
1	S/C CB 3	4,85E-01	9,52E+00
2	S/C CB 2	4,85E-01	9,52E+00
3	OUTAGE LA(S)	2,95E-02	1,30E+00
4	OUTAGE LA	2,94E-04	1,00E+00
5	OUTAGE LB	2,51E-04	1,00E+00
6	S/C CB 1	4,83E-05	1,00E+00
7	S/C CB 6	4,12E-05	1,00E+00
8	S/C CB 5	4,12E-05	1,00E+00
9	OUTAGE BUS 2	8,46E-06	1,00E+00

According to Fussel-Vesely index, the faults on circuit breaker 2 and 3 contribute the most on the importance analysis. It is reasonable as they are, with short circuit on the outgoing line itself, two first-order basic events that lead to an outage of a single outgoing line. Sensitivity fraction index also points out that CB 2 and CB 3 faults are very sensitive to the average unavailability so that Q can be significantly changed by altering the reliability index of CB 2 and 3. Graphical illustrations are shown below in Fig. 5.5. and 5.6

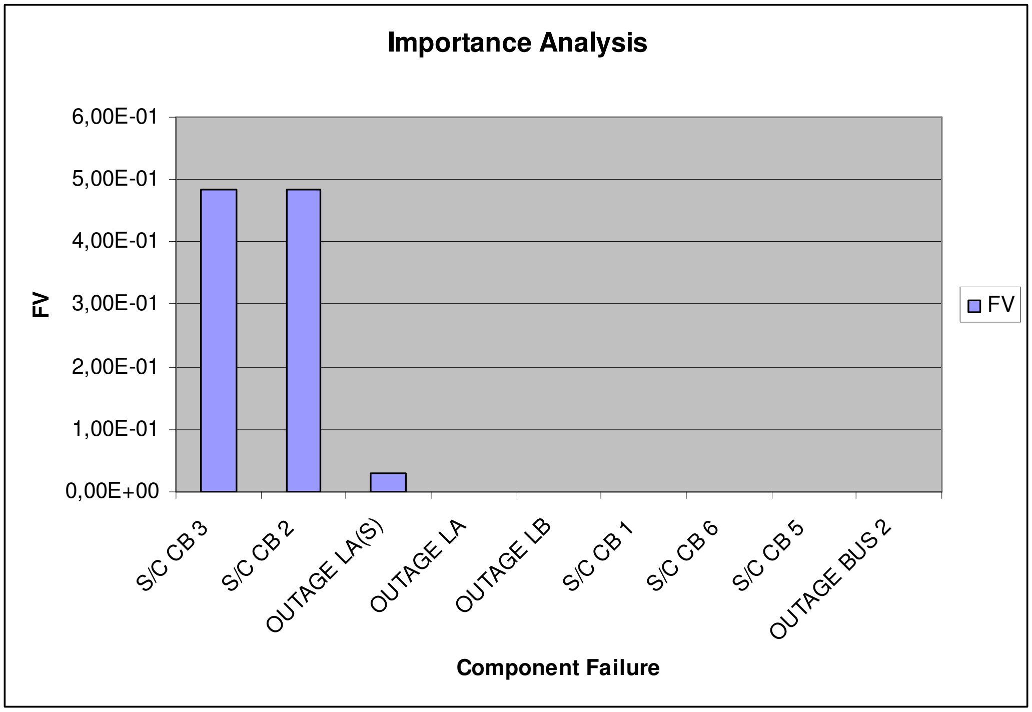


Fig. 5.5 Importance distribution of the unavailability of a single outgoing line

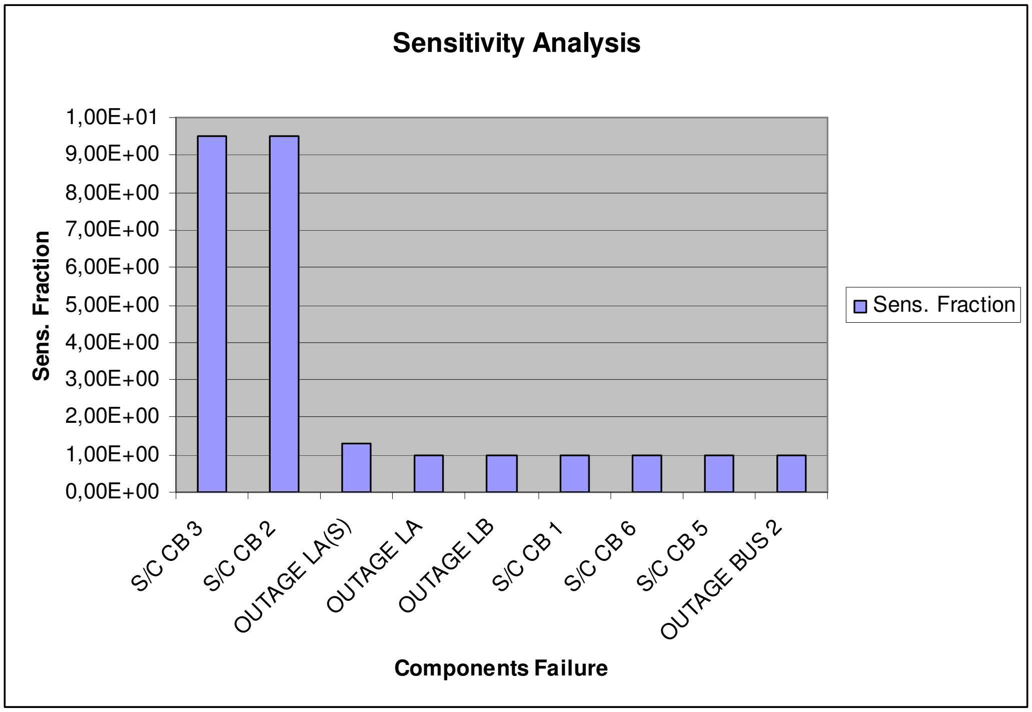


Fig. 5.6 Sensitivity distribution of the unavailability of a single outgoing line

5.2 *Double Breaker Arrangement*

5.2.1 Common Cause Failure

To investigate the impact of CCF on the double breaker arrangement, beta-factor is set 30% of failure rates of all components.

Table 5.5 CCF Impact on the double breaker arrangement

Evaluated Scenarios	Without CCF	With CCF
Single line outage	Q = 2.47E-5 W = 2.09E-6	Q = 2.88E-5 W = 2.40E-6
Both lines outages	Q = 1.20E-8 W= 2.59E-9	Q = 3.60E-6 W = 3.01E-7

By considering 30% of common cause failure, the average unavailability of a single line outage increases 16.6% comparing with the outage without taking CCF into account, meanwhile the failure intensity increases 14.8%. However, considering outages of both outgoing lines at the same time, then Q with CCF consideration increases two orders of magnitude, meanwhile W increases two orders of magnitude as well. That is, Q and W are influenced by the presence of common cause failure. This is especially true in case that both outgoing lines experience faults at the same time.

Comparing the outage of a single outgoing line with outages of both lines, Q and W of both lines outages do not improve much, only one order of magnitude. That is to say, if a single line outage can cause the station failure, then adding another outgoing line does not improve much of reliability of the station if common cause failure is taken into account.

Let us make a final comparison of the breaker and a half arrangement and the double breaker arrangement by comparing data from Table 5.1 and 5.5. Firstly, let us compare both arrangements without considering CCF. Both arrangements have the same Q and W of a single outgoing line outage. That is to say, if one outgoing line can cause the station failure, both arrangements have the same reliability. However, Q and W of the breaker and a half arrangement is about 20% less than those of the double breaker arrangement, when both lines outages are concerned. That makes the breaker and a half arrangement a better alternative in this particular comparison.

Secondly, let us take into account CCF. Q's and W's are almost the same in both cases of single line outage and both lines outages. This makes the breaker and a half arrangement is comparable to the double breaker arrangement in terms of reliability analysis.

Let us define Q_a, Q_b, W_a,W_b as the average unavailability and failure intensity of outgoing line a and b in the breaker and a half arrangement, and Q_a',Q_b',W_a',W_b' as those in the double breaker arrangement accordingly. Q_{both} and W_{both} represent Q and W of both line outages in breaker and a half arrangement, and Q_{both}' and W_{both}' represent the same in double breaker arrangement. According to Table 5.1 and 5.5, $Q_a = Q_b = Q_a' = Q_b'$, and $W_a = W_b = W_a' = W_b'$. Why $Q_{both} \neq Q_{both}'$, $W_{both} \neq W_{both}'$? The reason is that Q_a is dependent to Q_b, as well as Q_a' and Q_b', which results in $Q_{both} \neq Q_{both}$'. Same dependency applies to the failure intensity W as well. Instead of considering independent probability calculation, one should evaluate Q_{both}, Q_{both}', W_{both} and W_{both}' using conditional probability.

5.2.2 Uncertainty Analysis

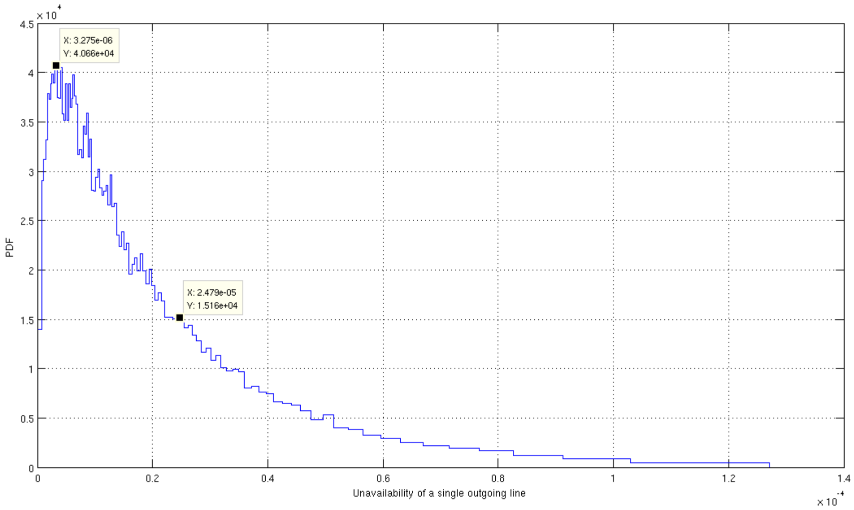


Fig. 5.7 Probability density function of the unavailability of a single outgoing line

5.2.3 Importance and Sensitivity Analysis

Table 5.6 CCF Impact on the double breaker arrangement

No.	ID	FV	Sens. Fraction
1	CB 4 S/C	4,85E-01	9,52E+00
2	CB 3 S/C	4,85E-01	9,52E+00
3	LA(S) S/C	2,95E-02	1,30E+00
4	LA S/C	2,86E-04	1,00E+00
5	LB S/C	2,86E-04	1,00E+00
6	CB 1 S/C	5,99E-05	1,00E+00
7	CB 6 S/C	5,99E-05	1,00E+00
8	CB 2 S/C	5,99E-05	1,00E+00
9	CB 5 S/C	5,99E-05	1,00E+00
10	CB 8 S/C	1,87E-05	1,00E+00
11	CB 7 S/C	1,87E-05	1,00E+00
12	BUS 2 S/C	3,82E-06	1,00E+00
13	BUS 1 S/C	3,82E-06	1,00E+00

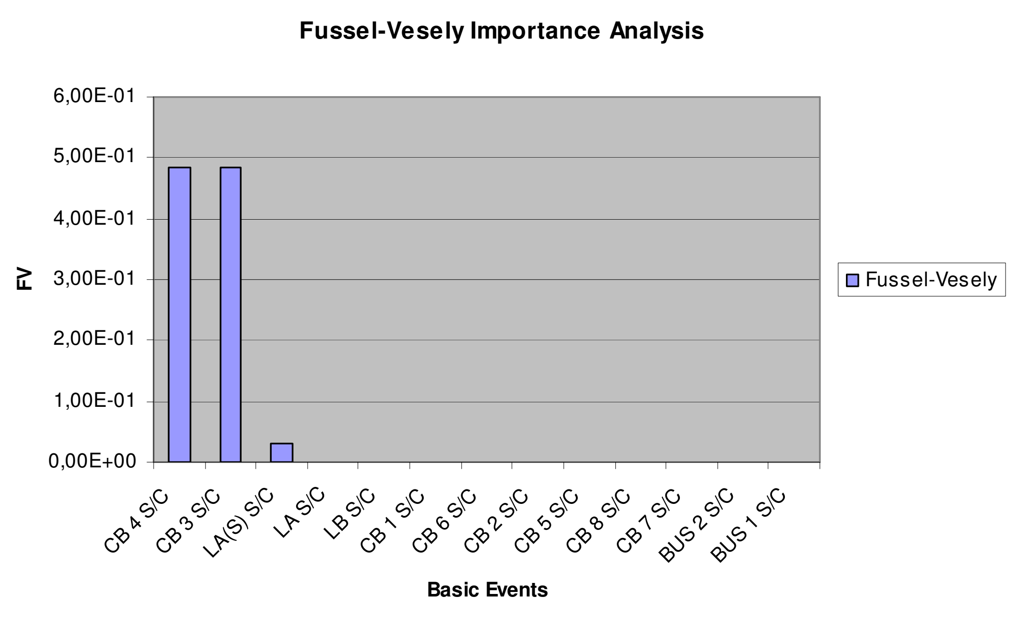


Fig. 5.8 Importance distribution of the unavailability of a single outgoing line

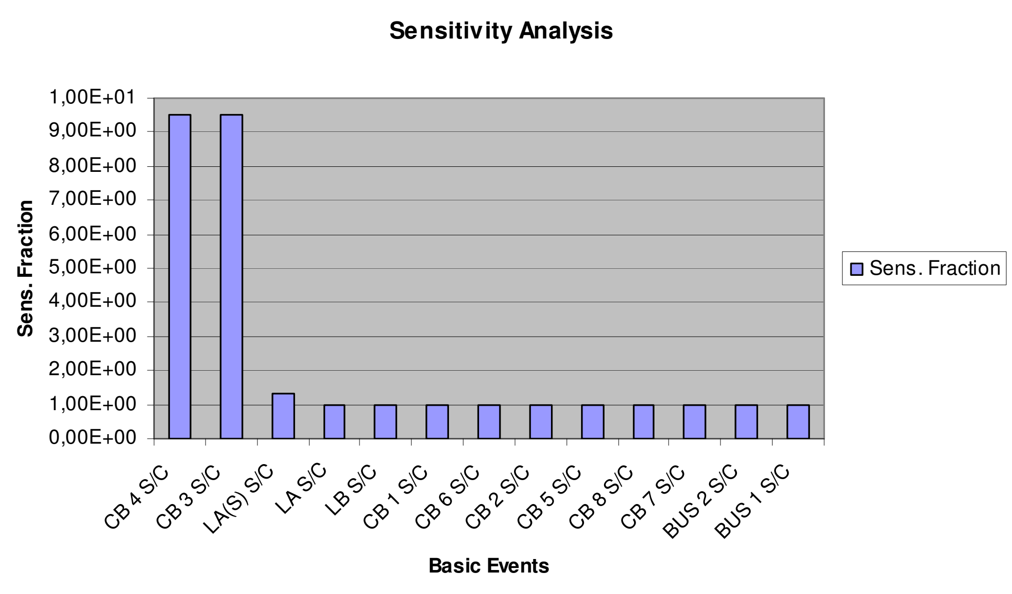


Fig. 5.9 Importance distribution of the unavailability of a single outgoing line

Similar to the fact revealed in the breaker and a half arrangement, two breakers adjacent to the outgoing line are the most important and sensitive in contributing the single outgoing line outage. The fault on the outgoing line itself also contributes a small part in both analyses. To improve the continuity of the power flow out of a single line, two breakers adjacent to the outgoing line draws immediate attention, since the reliability of these two breakers have very strong impact on the power delivery of the load.

Chapter 6 Closure

6.1 Conclusion

The project contains two essential goals. One is to develop guidelines of constructing fault trees to evaluate the breaker and a half arrangement and the double breaker arrangement, which should be further used for other substation breaker arrangements. The modeling technique, in short, is developed based on the fact that the component outage is due to ‘component unavailable’ or ‘no power flows into the component’, and the modeling technique has been validated by Subrel, which is another simulation tool using dynamic state enumeration method to compute the reliability index.

The other goal is to compare two substation arrangements in terms of reliability analysis. The results from two simulation tools point out that both arrangements, breaker and a half and double breaker, have the same reliability index considering the presence of common cause failure and under certain assumptions made prior to the study. Some additional features that Riskspectrum offers such as common cause failure, uncertainty, importance and sensitivity analyses have also been undertaken on both arrangements for obtaining more precise and reasonable results.

Besides the achievements mentioned above, the modeling technique can also be further developed to assess the reliability of substation arrangements in more detail, concerning facts such as maintenance, component thermal capacity, detailed failure modes, etc. The technique presented in the report is a general guideline of modeling the fault tree to evaluate the reliability of a breaker arrangement, and the resolution of the fault tree is determined by basic events that are customary developed.

6.2 Future work

Here are some possible aspects of the modeling technique on substation breaker arrangement that can be further improved.

1. Maintenance operation can be modeled as a basic event. To model maintenance policies, various logic gates such as ‘XOR’, ‘K-out-of-N’ or other available gates in Riskspectrum can be used.
2. Component capacity issue can also be modeled using the ‘K-out-of-N’ gate, which represents the system fails if and only if at least k of the n components fails.
3. Failure modes, depending on user specification of fault tree resolution, can be specified in detail under the intermediate event called ‘component unavailable’.
4. New devices such as disconnecting circuit breakers (DCBs) and disconnecting clamps have been commercially available, and are replacing the traditional CBs to improve the reliability of substations. Their operation modes are different from traditional CBs, and should be modeled in Riskspectrum following the same modeling technique.
5. Other relevant or joint researches on the substation should also be undertaken to evaluate the protection failure, auxiliary power supply failure, signal transmission failure, etc.

6. In order to make a full comparison between two substation layouts, reliability, cost and environmental impact should be considered as a whole.

Reference

[1] D. I. Kang, T. W. Kim, Y. G. Yo, C. K. Park, "Reliability analysis of various switchyard configurations of nuclear power plant," in *PSA/PRA and Severe Accident '94 International Meeting,* pp.82-88

[2] M. J. Beshir, T. C. Cheng, A. S. A. Farag "Comparison of Monte Carlo simulation and state enumeration based adequacy assessment programs: CREAM and COMREL," *IEEE,* 1996

[3] R. Billington, and G. Lian, "Effect of dependent outages on composite system reliability performance", *IEEE*, pp. 127-133, 1993

[4] J. Lu, W. Li, W. Yan, "State enumeration technique combined with a labelling bus set approach for reliability evaluation of substation configuration in power systems," *ELSEVIER,* Apr 2006

[5] R. Billington, and R. Nighot, "Incorporating station-related outages in composite system reliability analysis", *IEE, Proc.-Gener. Transm. Distrib*., Vol. 152, No. 2 March 2005

[6] R. Bono, R. Alexander, A. Dorman, Y. J. Kim, and J. Reisdorf, "Analyzing Reliability—A simple yet rigorous approach", *IEEE Transaction on Industry Applications*, Vol. 40, No. 4, July/ August 2004

[7] K. Koutlev, A. Pahwa, Z. Wang, L, Tang, "Methodology and algorithm for ranking substation design alternatives" *IEEE Transmission and Distribution Conference and Exposition* Sept. 2003

[8] *Power System Protection, Vol. 4 Digital Protection and Signaling,* The Institution of Electrical Engineers, London 1995

[9] *IEEE Recommended Practice for Design of Reliable Industrial and Commercial Power Systems*, IEEE Standard 493-1997, 1998

[10] *Power System Protection, Vol. 2 Systems and Methods,* The Institution of Electrical Engineers, London 1995

[11] Failure Survey on Circuit Breaker Control Systems, CIGRE, Working Group A3.12, Oct. 2004

[12] *Power System Protection, Vol. 1 Principles and Components,* The Institution of Electrical Engineers, London 1995

[13] R. Crowdis, "Substation configurations: A comparison of value and cost effectiveness," *Transmission & Distribution*, pp. 30-34, Sept. 1992.

[14] *SUBREL User's Guide*, ABB Power T&D Company Inc. Power System Center, Raleigh, NC Oct. 2000

[15] *Hydroelectric Power Plants Electric Design*, US Army Corps of Engineers Engineering Manual EM1110-2-3006, Jun. 1994.

[16] D. Nack, "Reliability of Substation Configurations," class notes for EE 653, Department of Electrical and Computer Engineering, University of Iowa State University, 2005

[17] S. A. Boggs and H. Schramm, "Current Interruption and Switching in Sulphur Hexafluoride" IEEE Electrical Insulation Magazine, vol. 6, No.1, pp. 12-17, January/February 1990

[18] I. Manea, C. Chiciu, F. Balasiu, N. Tulici, "Complex methods to diagnose the technical state of the medium and high voltage circuit breaker after short-circuit events," in *16th International Conference and Exhibition* 2001, pp 83

[19] http://www.geocities.com/hemant_thermal/electrical.htm

[20] J. Maté, "How to limit HFC/PFC/SF6 emission? Eliminate them", A Greenpeace Position Paper, Luxemburg, 2000

[21] Live tank circuit breaker buyer's guide, ABB AB, Ed 3, June 2004

[22] R. Svensson, W. Lord, and M. Jarl, "Costsaving and reliability improvement by using innovative technique for refurbishment of a substation", *IEE Conf. Publl.* Vol. 1, No. 482, June 2001

[23] M. Faxå, "Applications of disconnecting circuit breakers", *IEEE PES, Transmission and Distribution Conference and Exposition Latin America*, Venezuela, 2006

[24] Final Report of the Second International Enquiry on High Voltage Circuit-breaker Failures and Defects in Service, CIGRE, Working Group 06 of Study Committee 13, Jun. 1994

[25] N. Limnios, *Fault Tree*, UK. ISTE, 2007

[26] W. E. Vesely, F. F. Goldberg, N. H. Roberts, D. F. Haasl. Fault Tree Handbook, U. S. Nuclear Regulatory Commission. Jan. 1981

[27] M. Rausand, A. Hoyland, *System Reliability Theory Models, Statistical Methods, and Applications*, 2nd ed. New Jersey: Wiley, 2004

[28] *Riskspectrum Professional Training Course* RELCON Risk Management, Stockholm Dec 2006

[29] Riskspectrum PSA Professional, 'Getting Started', Relcon AB

[30] Common-Cause Failure Database and Analysis System: Event Data Collection, Classification, and Coding, Idaho National Laboratory, U.S. Nuclear Regulatory Commission Office of Nuclear Regulatory Research, Washington, DC, 20555-0001

[31] http://en.wikipedia.org/wiki/Gamma_distribution

[32] Riskspectrum PSA Professional, 'Theory Manual', Relcon AB

Appendix A: Minimal Cut Sets of Breaker and a Half Arrangement

Table A.1 Minimal cut set of both line outages in breaker and a half arrangement (without CCF, uncertainty or sensitivity analyses)

	Average Unavailability	Percentage to the Top Event	Basic Event 1	Basic Event 2	Basic Event 3
1	5,33E-09	53,97	OUTAGE LA	OUTAGE LB	
2	8,76E-10	8,87	OUTAGE LB	S/C CB 2	
3	8,76E-10	8,87	OUTAGE LA	S/C CB 6	
4	8,76E-10	8,87	OUTAGE LB	S/C CB 1	
5	8,76E-10	8,87	OUTAGE LA	S/C CB 5	
6	1,44E-10	1,46	S/C CB 1	S/C CB 5	
7	1,44E-10	1,46	S/C CB 2	S/C CB 5	
8	1,44E-10	1,46	S/C CB 2	S/C CB 4	
9	1,44E-10	1,46	S/C CB 3	S/C CB 5	
10	1,44E-10	1,46	S/C CB 1	S/C CB 6	
11	1,44E-10	1,46	S/C CB 2	S/C CB 6	
12	1,44E-10	1,46	S/C CB 3	S/C CB 4	
13	8,77E-12	0,09	OUTAGE LA(S)	S/C CB 4	
14	8,77E-12	0,09	OUTAGE LB(S)	S/C CB 3	
15	8,77E-12	0,09	OUTAGE LB(S)	S/C CB 2	
16	8,77E-12	0,09	OUTAGE LA(S)	S/C CB 5	
17	5,34E-13	0,01	OUTAGE LA(S)	OUTAGE LB(S)	
18	2,16E-15	0	OUTAGE BUS 2	OUTAGE LA	S/C CB 4
19	2,16E-15	0	OUTAGE BUS 1	OUTAGE LB	S/C CB 3
20	3,54E-16	0	OUTAGE BUS 2	S/C CB 1	S/C CB 4
21	3,54E-16	0	OUTAGE BUS 1	S/C CB 3	S/C CB 6
22	1,31E-16	0	OUTAGE BUS 1	OUTAGE LA(S)	OUTAGE LB
23	1,31E-16	0	OUTAGE BUS 2	OUTAGE LA	OUTAGE LB(S)
24	2,16E-17	0	OUTAGE BUS 1	OUTAGE LA(S)	S/C CB 6
25	2,16E-17	0	OUTAGE BUS 2	OUTAGE LB(S)	S/C CB 1

Table A.2 Minimal cut set of outgoing line a outage in breaker and a half arrangement (without CCF, uncertainty or sensitivity analyses)

	Average Unavailability	Percentage to the Top Event	Basic Event 1	Basic Event 2
1	1,20E-05	48,51	S/C CB 2	
2	1,20E-05	48,51	S/C CB 3	
3	7,30E-07	2,95	OUTAGE LA(S)	
4	5,33E-09	0,02	OUTAGE LA	OUTAGE LB
5	8,76E-10	0	OUTAGE LA	S/C CB 5
6	8,76E-10	0	OUTAGE LA	S/C CB 6
7	8,76E-10	0	OUTAGE LB	S/C CB 1
8	1,80E-10	0	OUTAGE BUS 2	OUTAGE LA
9	1,44E-10	0	S/C CB 1	S/C CB 5
10	1,44E-10	0	S/C CB 1	S/C CB 6
11	2,95E-11	0	OUTAGE BUS 2	S/C CB 1

Table A.3 Minimal cut set of outgoing line b outage in breaker and a half arrangement (without CCF, uncertainty or sensitivity analyses)

	Average Unavailability	Percentage to the Top Event	Basic Event 1	Basic Event 2
1	1,20E-05	48,51	S/C CB 5	
2	1,20E-05	48,51	S/C CB 4	
3	7,30E-07	2,95	OUTAGE LB(S)	
4	5,33E-09	0,02	OUTAGE LA	OUTAGE LB
5	8,76E-10	0	OUTAGE LB	S/C CB 2
6	8,76E-10	0	OUTAGE LB	S/C CB 1
7	8,76E-10	0	OUTAGE LA	S/C CB 6
8	1,80E-10	0	OUTAGE BUS 1	OUTAGE LB
9	1,44E-10	0	S/C CB 2	S/C CB 6
10	1,44E-10	0	S/C CB 1	S/C CB 6
11	2,95E-11	0	OUTAGE BUS 1	S/C CB 6

Appendix B: Minimal Cut Sets of Double Breaker Arrangement

Table B.1 Minimal cut set of both line outages in double breaker arrangement (without CCF, uncertainty or sensitivity analyses)

	Average Unavailability	Percentage to the Top Event	Basic Event 1	Basic Event 2
1	5,33E-09	44,46	LA S/C	LB S/C
2	8,76E-10	7,3	CB 6 S/C	LA S/C
3	8,76E-10	7,3	CB 2 S/C	LB S/C
4	8,76E-10	7,3	CB 5 S/C	LA S/C
5	8,76E-10	7,3	CB 1 S/C	LB S/C
6	1,44E-10	1,2	CB 6 S/C	CB 7 S/C
7	1,44E-10	1,2	CB 1 S/C	CB 4 S/C
8	1,44E-10	1,2	CB 2 S/C	CB 5 S/C
9	1,44E-10	1,2	CB 2 S/C	CB 7 S/C
10	1,44E-10	1,2	CB 2 S/C	CB 6 S/C
11	1,44E-10	1,2	CB 3 S/C	CB 6 S/C
12	1,44E-10	1,2	CB 1 S/C	CB 5 S/C
13	1,44E-10	1,2	CB 5 S/C	CB 8 S/C
14	1,44E-10	1,2	CB 4 S/C	CB 5 S/C
15	1,44E-10	1,2	CB 4 S/C	CB 8 S/C
16	1,44E-10	1,2	CB 1 S/C	CB 8 S/C
17	1,44E-10	1,2	CB 3 S/C	CB 4 S/C
18	1,44E-10	1,2	CB 5 S/C	CB 6 S/C
19	1,44E-10	1,2	CB 3 S/C	CB 8 S/C
20	1,44E-10	1,2	CB 1 S/C	CB 6 S/C
21	1,44E-10	1,2	CB 1 S/C	CB 2 S/C
22	1,44E-10	1,2	CB 7 S/C	CB 8 S/C
23	1,44E-10	1,2	CB 2 S/C	CB 3 S/C
24	1,44E-10	1,2	CB 4 S/C	CB 7 S/C
25	1,44E-10	1,2	CB 3 S/C	CB 7 S/C
26	2,95E-11	0,25	BUS 1 S/C	CB 2 S/C
27	2,95E-11	0,25	BUS 2 S/C	CB 3 S/C
28	2,95E-11	0,25	BUS 2 S/C	CB 5 S/C
29	2,95E-11	0,25	BUS 1 S/C	CB 8 S/C
30	2,95E-11	0,25	BUS 2 S/C	CB 7 S/C
31	2,95E-11	0,25	BUS 2 S/C	CB 1 S/C
32	2,95E-11	0,25	BUS 1 S/C	CB 6 S/C
33	2,95E-11	0,25	BUS 1 S/C	CB 4 S/C
34	8,77E-12	0,07	CB 4 S/C	LB(S) S/C
35	8,77E-12	0,07	CB 8 S/C	LA(S) S/C
36	8,77E-12	0,07	CB 7 S/C	LA(S) S/C
37	8,77E-12	0,07	CB 3 S/C	LB(S) S/C
38	6,05E-12	0,05	BUS 1 S/C	BUS 2 S/C
39	5,34E-13	0	LA(S) S/C	LB(S) S/C

Table B.2 Minimal cut set of outgoing line a outage in double breaker arrangement (without CCF, uncertainty or sensitivity analyses)

	Average Unavailability	Percentage to the Top Event	Basic Event 1	Basic Event 2
1	1,20E-05	48,5	CB 4 S/C	
2	1,20E-05	48,5	CB 3 S/C	
3	7,30E-07	2,95	LA(S) S/C	
4	5,33E-09	0,02	LA S/C	LB S/C
5	8,76E-10	0	CB 5 S/C	LA S/C
6	8,76E-10	0	CB 6 S/C	LA S/C
7	8,76E-10	0	CB 2 S/C	LB S/C
8	8,76E-10	0	CB 1 S/C	LB S/C
9	1,44E-10	0	CB 7 S/C	CB 8 S/C
10	1,44E-10	0	CB 1 S/C	CB 5 S/C
11	1,44E-10	0	CB 2 S/C	CB 7 S/C
12	1,44E-10	0	CB 1 S/C	CB 2 S/C
13	1,44E-10	0	CB 1 S/C	CB 6 S/C
14	1,44E-10	0	CB 2 S/C	CB 5 S/C
15	1,44E-10	0	CB 2 S/C	CB 6 S/C
16	1,44E-10	0	CB 5 S/C	CB 6 S/C
17	1,44E-10	0	CB 1 S/C	CB 8 S/C
18	1,44E-10	0	CB 5 S/C	CB 8 S/C
19	1,44E-10	0	CB 6 S/C	CB 7 S/C
20	2,95E-11	0	BUS 1 S/C	CB 2 S/C
21	2,95E-11	0	BUS 2 S/C	CB 7 S/C
22	2,95E-11	0	BUS 2 S/C	CB 1 S/C
23	2,95E-11	0	BUS 1 S/C	CB 6 S/C
24	2,95E-11	0	BUS 2 S/C	CB 5 S/C
25	2,95E-11	0	BUS 1 S/C	CB 8 S/C
26	6,05E-12	0	BUS 1 S/C	BUS 2 S/C

Table B.3 Minimal cut set of outgoing line b outage in double breaker arrangement (without CCF, uncertainty or sensitivity analyses)

	Average Unavailability	Percentage to the Top Event	Basic Event 1	Basic Event 2
1	1,20E-05	48,5	CB 8 S/C	
2	1,20E-05	48,5	CB 7 S/C	
3	7,30E-07	2,95	LB(S) S/C	
4	5,33E-09	0,02	LA S/C	LB S/C
5	8,76E-10	0	CB 6 S/C	LA S/C
6	8,76E-10	0	CB 5 S/C	LA S/C
7	8,76E-10	0	CB 2 S/C	LB S/C
8	8,76E-10	0	CB 1 S/C	LB S/C
9	1,44E-10	0	CB 1 S/C	CB 6 S/C
10	1,44E-10	0	CB 5 S/C	CB 6 S/C
11	1,44E-10	0	CB 1 S/C	CB 5 S/C
12	1,44E-10	0	CB 3 S/C	CB 4 S/C
13	1,44E-10	0	CB 3 S/C	CB 6 S/C
14	1,44E-10	0	CB 2 S/C	CB 3 S/C
15	1,44E-10	0	CB 2 S/C	CB 6 S/C
16	1,44E-10	0	CB 1 S/C	CB 4 S/C
17	1,44E-10	0	CB 1 S/C	CB 2 S/C
18	1,44E-10	0	CB 4 S/C	CB 5 S/C

19	1,44E-10	0	CB 2 S/C	CB 5 S/C
20	2,95E-11	0	BUS 2 S/C	CB 3 S/C
21	2,95E-11	0	BUS 1 S/C	CB 6 S/C
22	2,95E-11	0	BUS 2 S/C	CB 5 S/C
23	2,95E-11	0	BUS 2 S/C	CB 1 S/C
24	2,95E-11	0	BUS 1 S/C	CB 2 S/C
25	2,95E-11	0	BUS 1 S/C	CB 4 S/C
26	6,05E-12	0	BUS 1 S/C	BUS 2 S/C

Appendix C: Minimal Cut Sets of Breaker and a Half Arrangement (Unconditional Failure Intensity)

Table C.1 Minimal cut sets of both lines outage in breaker and a half arrangement (without CCF, uncertainty or sensitivity analyses)

	Unconditional Failure Intensity W	Percentage to the Top Event	Basic Event 1	Basic Event 2	Basic Event 3
1	1,33E-09	59,55	OUTAGE LA	OUTAGE LB	
2	1,83E-10	8,15	OUTAGE LA	S/C CB 5	
3	1,83E-10	8,15	OUTAGE LB	S/C CB 1	
4	1,83E-10	8,15	OUTAGE LB	S/C CB 2	
5	1,83E-10	8,15	OUTAGE LA	S/C CB 6	
6	2,40E-11	1,07	S/C CB 1	S/C CB 5	
7	2,40E-11	1,07	S/C CB 2	S/C CB 5	
8	2,40E-11	1,07	S/C CB 3	S/C CB 5	
9	2,40E-11	1,07	S/C CB 3	S/C CB 4	
10	2,40E-11	1,07	S/C CB 1	S/C CB 6	
11	2,40E-11	1,07	S/C CB 2	S/C CB 6	
12	2,40E-11	1,07	S/C CB 2	S/C CB 4	
13	1,83E-12	0,08	OUTAGE LA(S)	S/C CB 4	
14	1,83E-12	0,08	OUTAGE LA(S)	S/C CB 5	
15	1,83E-12	0,08	OUTAGE LB(S)	S/C CB 3	
16	1,83E-12	0,08	OUTAGE LB(S)	S/C CB 2	
17	1,33E-13	0,01	OUTAGE LA(S)	OUTAGE LB(S)	
18	6,29E-16	0	OUTAGE BUS 2	OUTAGE LA	S/C CB 4
19	6,29E-16	0	OUTAGE BUS 1	OUTAGE LB	S/C CB 3
20	8,86E-17	0	OUTAGE BUS 2	S/C CB 1	S/C CB 4
21	8,86E-17	0	OUTAGE BUS 1	S/C CB 3	S/C CB 6
22	4,37E-17	0	OUTAGE BUS 2	OUTAGE LA	OUTAGE LB(S)
23	4,37E-17	0	OUTAGE BUS 1	OUTAGE LA(S)	OUTAGE LB
24	6,29E-18	0	OUTAGE BUS 2	OUTAGE LB(S)	S/C CB 1
25	6,29E-18	0	OUTAGE BUS 1	OUTAGE LA(S)	S/C CB 6

Table C.2 Minimal cut sets of the outgoing line a outage in breaker and a half arrangement
(without CCF, uncertainty or sensitivity analyses)

	Average Unavailability Q	Percentage to the Top Event	Basic Event 1	Basic Event 2
1	1,00E-06	47,77	S/C CB 2	
2	1,00E-06	47,77	S/C CB 3	
3	9,13E-08	4,36	OUTAGE LA(S)	
4	1,33E-09	0,06	OUTAGE LA	OUTAGE LB
5	1,83E-10	0,01	OUTAGE LA	S/C CB 5
6	1,83E-10	0,01	OUTAGE LA	S/C CB 6
7	1,83E-10	0,01	OUTAGE LB	S/C CB 1
8	3,74E-11	0	OUTAGE BUS 2	OUTAGE LA
9	2,40E-11	0	S/C CB 1	S/C CB 5

10	2,40E-11	0	S/C CB 1	S/C CB 6
11	4,92E-12	0	OUTAGE BUS 2	S/C CB 1

Table C.3 Minimal cut sets of the outgoing line b outage in breaker and a half arrangement
(without CCF, uncertainty or sensitivity analyses)

	Average Unavailability Q	Percentage to the Top Event	Basic Event 1	Basic Event 2
1	1,00E-06	47,77	S/C CB 5	
2	1,00E-06	47,77	S/C CB 4	
3	9,13E-08	4,36	OUTAGE LB(S)	
4	1,33E-09	0,06	OUTAGE LA	OUTAGE LB
5	1,83E-10	0,01	OUTAGE LB	S/C CB 2
6	1,83E-10	0,01	OUTAGE LB	S/C CB 1
7	1,83E-10	0,01	OUTAGE LA	S/C CB 6
8	3,74E-11	0	OUTAGE BUS 1	OUTAGE LB
9	2,40E-11	0	S/C CB 2	S/C CB 6
10	2,40E-11	0	S/C CB 1	S/C CB 6
11	4,92E-12	0	OUTAGE BUS 1	S/C CB 6

Appendix D: Minimal Cut Sets of Double Breaker Arrangement (Unconditional Failure Intensity)

Table D.1 Minimal cut sets of both lines outage in double breaker arrangement
(without CCF, uncertainty or sensitivity analyses)

No.	Unconditional Failure Intensity W	Percentage to the Top Event	Basic Event 1	Basic Event 2
1	1,33E-09	51,45	LA S/C	LB S/C
2	1,83E-10	7,05	CB 6 S/C	LA S/C
3	1,83E-10	7,05	CB 2 S/C	LB S/C
4	1,83E-10	7,05	CB 5 S/C	LA S/C
5	1,83E-10	7,05	CB 1 S/C	LB S/C
6	2,40E-11	0,93	CB 6 S/C	CB 7 S/C
7	2,40E-11	0,93	CB 1 S/C	CB 4 S/C
8	2,40E-11	0,93	CB 2 S/C	CB 5 S/C
9	2,40E-11	0,93	CB 2 S/C	CB 7 S/C
10	2,40E-11	0,93	CB 2 S/C	CB 6 S/C
11	2,40E-11	0,93	CB 3 S/C	CB 6 S/C
12	2,40E-11	0,93	CB 1 S/C	CB 5 S/C
13	2,40E-11	0,93	CB 5 S/C	CB 8 S/C
14	2,40E-11	0,93	CB 4 S/C	CB 5 S/C
15	2,40E-11	0,93	CB 4 S/C	CB 8 S/C
16	2,40E-11	0,93	CB 1 S/C	CB 8 S/C
17	2,40E-11	0,93	CB 3 S/C	CB 4 S/C
18	2,40E-11	0,93	CB 5 S/C	CB 6 S/C
19	2,40E-11	0,93	CB 3 S/C	CB 8 S/C
20	2,40E-11	0,93	CB 1 S/C	CB 6 S/C
21	2,40E-11	0,93	CB 1 S/C	CB 2 S/C
22	2,40E-11	0,93	CB 7 S/C	CB 8 S/C
23	2,40E-11	0,93	CB 2 S/C	CB 3 S/C
24	2,40E-11	0,93	CB 4 S/C	CB 7 S/C
25	2,40E-11	0,93	CB 3 S/C	CB 7 S/C
26	4,92E-12	0,19	BUS 1 S/C	CB 2 S/C
27	4,92E-12	0,19	BUS 2 S/C	CB 3 S/C
28	4,92E-12	0,19	BUS 2 S/C	CB 5 S/C
29	4,92E-12	0,19	BUS 1 S/C	CB 8 S/C
30	4,92E-12	0,19	BUS 2 S/C	CB 7 S/C

Table D.2 Minimal cut sets of the outgoing line a outage in double breaker arrangement
(without CCF, uncertainty or sensitivity analyses)

No.	Unconditional Failure Intensity W	Percentage to the Top Event	Basic Event 1	Basic Event 2
1	1,00E-06	47,76	CB 4 S/C	
2	1,00E-06	47,76	CB 3 S/C	
3	9,13E-08	4,36	LA(S) S/C	

4	1,33E-09	0,06	LA S/C	LB S/C
5	1,83E-10	0,01	CB 5 S/C	LA S/C
6	1,83E-10	0,01	CB 6 S/C	LA S/C
7	1,83E-10	0,01	CB 2 S/C	LB S/C
8	1,83E-10	0,01	CB 1 S/C	LB S/C
9	2,40E-11	0	CB 7 S/C	CB 8 S/C
10	2,40E-11	0	CB 1 S/C	CB 5 S/C
11	2,40E-11	0	CB 2 S/C	CB 7 S/C
12	2,40E-11	0	CB 1 S/C	CB 2 S/C
13	2,40E-11	0	CB 1 S/C	CB 6 S/C
14	2,40E-11	0	CB 2 S/C	CB 5 S/C
15	2,40E-11	0	CB 2 S/C	CB 6 S/C
16	2,40E-11	0	CB 5 S/C	CB 6 S/C
17	2,40E-11	0	CB 1 S/C	CB 8 S/C
18	2,40E-11	0	CB 5 S/C	CB 8 S/C
19	2,40E-11	0	CB 6 S/C	CB 7 S/C
20	4,92E-12	0	BUS 1 S/C	CB 2 S/C
21	4,92E-12	0	BUS 2 S/C	CB 7 S/C
22	4,92E-12	0	BUS 2 S/C	CB 1 S/C
23	4,92E-12	0	BUS 1 S/C	CB 6 S/C
24	4,92E-12	0	BUS 2 S/C	CB 5 S/C
25	4,92E-12	0	BUS 1 S/C	CB 8 S/C
26	1,01E-12	0	BUS 1 S/C	BUS 2 S/C

Table D.3 Minimal cut sets of the outgoing line b outage in double breaker arrangement
(without CCF, uncertainty or sensitivity analyses)

No.	Unconditional Failure Intensity W	Percentage to the Top Event	Basic Event 1	Basic Event 2
1	1,00E-06	47,76	CB 8 S/C	
2	1,00E-06	47,76	CB 7 S/C	
3	9,13E-08	4,36	LB(S) S/C	
4	1,33E-09	0,06	LA S/C	LB S/C
5	1,83E-10	0,01	CB 6 S/C	LA S/C
6	1,83E-10	0,01	CB 5 S/C	LA S/C
7	1,83E-10	0,01	CB 2 S/C	LB S/C
8	1,83E-10	0,01	CB 1 S/C	LB S/C
9	2,40E-11	0	CB 1 S/C	CB 6 S/C
10	2,40E-11	0	CB 5 S/C	CB 6 S/C
11	2,40E-11	0	CB 1 S/C	CB 5 S/C
12	2,40E-11	0	CB 3 S/C	CB 4 S/C
13	2,40E-11	0	CB 3 S/C	CB 6 S/C
14	2,40E-11	0	CB 2 S/C	CB 3 S/C
15	2,40E-11	0	CB 2 S/C	CB 6 S/C
16	2,40E-11	0	CB 1 S/C	CB 4 S/C
17	2,40E-11	0	CB 1 S/C	CB 2 S/C
18	2,40E-11	0	CB 4 S/C	CB 5 S/C
19	2,40E-11	0	CB 2 S/C	CB 5 S/C
20	4,92E-12	0	BUS 2 S/C	CB 3 S/C
21	4,92E-12	0	BUS 1 S/C	CB 6 S/C

22	4,92E-12	0	BUS 2 S/C	CB 5 S/C
23	4,92E-12	0	BUS 2 S/C	CB 1 S/C
24	4,92E-12	0	BUS 1 S/C	CB 2 S/C
25	4,92E-12	0	BUS 1 S/C	CB 4 S/C
26	1,01E-12	0	BUS 1 S/C	BUS 2 S/C