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Reliability Comparison Between Different 400 kV Substation Designs.

Master of Science Thesis

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Göteborg, Sweden, 2008

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Summary

This thesis examines how the unavailability for OKG will be affected by the planned replacement of the 400 kV substation at Simpevarp. The evaluation has been based on calculation of unavailability due to both faults and maintenance, fault and maintenance frequencies and estimated costs for the different substation designs. Four different variations of two-breaker arrangement designs have been simulated and been compared to simulations of the existing substation.

To perform the calculations a program has been developed in java that simulates the different substation designs. The fault probabilities used in this study has primarily been taken from fault statistics for the Swedish grid but has also been compared to the assumptions used in other substation reliability studies.

The results of this thesis show that the unavailability is likely to be higher for the proposed two-breaker arrangement design without separate disconnectors compared to the existing substation. When the two-breaker arrangement simulation instead included separate disconnectors the unavailability was found to be lower for the two-breaker arrangement design compared to the existing substation. The study also showed that the two-breaker arrangement designs had considerably lower fault frequencies compared to the existing substation. The thesis found that the unavailability that will be caused by maintenance can be significant and are likely to be higher than the unavailability caused by faults. The amount of unavailability caused by maintenance was, however, found to be uncertain because a large part of it can be performed during planned outage. Furthermore, it was found that the two-breaker arrangement design with and without disconnectors had similar expected present value of costs if the maintenance costs were excluded. This indicates that the best substation option from an economic point of view is determined by the maintenance costs.

Acknowledgement

I want to express my gratitude towards OKG and especially towards Fredrik Heyman and Bertil Svensson who have been supportive and helpful while in the same time given me a large flexibility to structure my thesis work. I am very grateful that I was given the opportunity to do this master thesis and I want to express many thanks for the friendly and welcoming atmosphere at OKG.

I also want to express my gratitude towards my tutor and examiner Tuan Le at Chalmers who has been supportive and shown his interest in my work.

Finally, I want to thank Sture Lindahl for his wise comments on my thesis.

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1. Introduction

1.1 Background

The dependency of secure power is increasing in the society which leads to higher demands on the availability of electric power. The availability (Willis 2000) can be defined as the fraction of time that the electric power is available in a certain point in the network during a given time interval. The complement to availability is called unavailability and is the fraction of time that the electric power is unavailable in a certain point in the network during a given time interval. Most of the electric power in Sweden is transmissioned through the 400 kV substations that are parts of the main grid. Many of the 400 kV substations in the main grid are today old and needs to be modernized. It has also in the last years occurred a number of faults in these substations that has increased the actuality of making the substations more reliable. The term reliability (Willis 2000) is closely related to the term availability and can be defined as the probability of failure-free operation of a system for a specified period of time in a specified environment. One major difference between the reliability concept and the availability concept is that the availability can be decreased by both planned and unplanned unavailability while the reliability concept only considers the equipments ability to function correctly when it is in service. The nuclear power stations O1, O2 and O3 in Simpevarp (OKG 2008), which are owned by the company OKG AB, produces approximately 10% of the total consumption of electricity in Sweden. O2 and O3 are directly connected to a 400 kV substation owned by Svenska Kraftnät that is built on OKG’s territory. O1 is as well connected to the 400 kV substation but through a 130 kV substation. The 400 kV substation needs now to be replaced due to its age and due to the upgrades of active power output capability of the generators in O2 and O3. Svenska Kraftnät has proposed a two-breaker arrangement design for the new substation and asked OKG AB to give their opinion on the suggested design. The suggested design consists of double busbars and double disconnecting circuit breakers, DCBs, which has the disconnector function integrated in the circuit breaker. The DCBs are meant to replace the conventional combination of circuit breakers and separate disconnectors. The existing substation consists of four busbars of which one is a transfer busbar used to bypass faults in the event of fault in any of the devices in the substation. The existing substation has a relatively large flexibility to change connection by operation of circuit breakers and disconnectors.

1.2 Problem Discussion

It has been questioned by OKG if faults on the disconnecting circuit breaker in the proposed substation design will cause high unavailability for OKG. This thesis has investigated how the unavailability will be affected on the incoming lines to the substation, that are connected between OKGs power transformers T7,T2 and T3 and the 400 kV substation. However, when replacing an old system with a new one it is of importance to not only consider the improvement of the new system, but also consider the possible drawbacks. To do this it necessary to define the requirements on the system. The substation could be seen as a part of a larger electricity system that consists (Li 2006) of generation, distribution and consumption of electricity. The demands on the larger electricity system is to continuously produce and distribute electricity of good quality to satisfy the instantaneous electricity consumption in each point of the grid. The quality of the electricity is of importance to make the equipment connected to the grid function correctly without being damaged. From this discussion it is possible to derive two requirements on the substation. First, it should under normal conditions continuously distribute and be able to switch the electric power that the generators are producing. Second, it should minimize the function loss of the substation when a failure occurs and it should help to maintain the quality of the electricity. For the first requirement, the substation needs to contain switching devices and control equipments for the switches. The function of the switches is to control the connection and disconnection of the incoming power from the three nuclear power stations at Simpevarp and to switch the connection to the outgoing lines. The switching can both be controlled by manual operation and by the protection system, which mainly consists of circuit breakers and protection systems. The circuit breaker can from a reliability point of view be seen as 1) an high voltage apparatus that can cause short circuit or earth faults and 2) a switching device that is used to break load and fault current. The purpose of the protection system is to sense if a fault condition occurs in the protected zone and send a tripping signal to the concerned circuit breakers around the protected zone. When a component has been disconnected it will be unavailable. To determine the unavailability in a point of the protection system it is necessary to consider the basic criteria's of a protective systems that commonly includes (Hewitson et al 2004) the following factors (1) selectivity, (2) speed of operation (3) reliability, (4) simplicity and (5) costs.

1.2.1 Discussion of Selectivity

Selectivity can be defined as the protection systems ability to detect and isolate only the faulty item while not interrupting other parts of the power system that is functioning correctly (Hewitson et al 2004). When considering a fault in the breaker the selectivity will be affected by the change from the existing substation to the new substation design with disconnecting circuit breakers. A fault in a circuit breaker in the existing design could be isolated by just opening the disconnectors around the breaker while it in the suggested busbar design is more complicated to break the power on both side of the circuit breaker which is necessary for a safe repair or replacement. The selectivity will due to its importance for availability be considered in this thesis.

1.2.2 Discussion of Speed

The protection system should operate fast when a fault is detected to minimize the damage to surrounding equipments and personnel. The speed of the protection system in the busbars is also of great importance for the function of the generators where severe faults that are not cleared fast enough may cause the generators to lose synchronization. However, the speed of operation of the relays and the circuit breaking time will be assumed to be similar or faster than in the existing system and no detailed study of this will be done in this thesis.

1.2.3 Discussion of Reliability

The reliability concept are closely related to the availability and measures, as mentioned earlier, the probability of failure-free operation of a system for a specified period of time in a specified environment. The reliability of a protection system consists of two factors (Hewitson et al. 2004). The first factor is dependability, which means that the operation of the protection system should operate on a certain fault and function correctly when this type of fault occurs. The other factor is security, which means that the power system should not trip unintentionally for condition that is not classified as a fault. The reliability of the existing and the suggested substation configuration will be the main focus in this thesis.

1.2.4 Discussion of Simplicity

The simplicity or complexity factor can affect the availability in several ways, the construction of a more complex system can increase the risk of mechanical failure or it can be harder to understand and repair, which can lead to higher repair times. A simpler system is in general preferable if the two systems can deliver the same benefits. The simplicity factor for the different components will, however, already be included in the failure probability calculations. The simplicity factor is included in the fault calculations done in this thesis.

1.2.5 Discussion of Costs

In general financial theories all companies are assumed to be profit maximizers which mean that they will not invest more in a protection system than the value of the benefits they expect to obtain by installing it. In this case both OKG and Svenska Kraftnät will have different costs and benefits from the construction of the new substation, which mean that they are likely to have some different preferences. The costs and benefits for the two companies are for this reason important to consider. The cost of the substation is often a limiting factor for the choice of protection system for the substation and has for this reason been considered.

1.2.6 Discussion of Interests

Finally, it could also be of interest to investigate the different interests of the users of the substation. This can be divided into four groups. First, OKG that supply the grid with power. Second, Svenska Kraftnät that owns the substation and has the main responsibility for the function of the main grid. Third, the electricity consumers that is dependent of the supply of electric power and fourth, the other electricity producers that is dependent on a well functioning grid to be able to deliver and sell their production of electric power. All of these can be assumed to be interested in a well functioning substation. However, OKG and Svenska Kraftnät can have different priorities concerning where in the grid it is important to have high availability. Svenska Kraftnät have responsibility for the availability in the whole main grid while OKG interest is more concerned with the ability to deliver its produced electricity to the main grid. This thesis will only concentrate on how the production availability for OKG is affected by the suggested new substation design. The factors that are important for OKGs ability to deliver its power is both the unavailability on the incoming lines and on the outgoing lines. The incoming lines are the lines connected between the power transformers and the substation. The outgoing lines are the transmission lines leaving the substation and they are included in the study because the loss of load might force OKG to limit its production of electricity. For this reasons the study will concentrate on determining the unavailability in both the incoming and outgoing lines in the substation.

1.2.7 Other Important Factors to Consider

Other factors that earlier have been mentioned as being of importance for the choice of substation design are the space that the construction will require and the possible affect the construction will have on the environment. This thesis will not further consider space limitation of the substation configurations. The new DCBs (ABB 2007) contain the gas SF_6 which is a gas that contributes to the greenhouse effect. The handling of the gas needs to be done in an environmental friendly way which increase the demands on the maintenance, like for example refilling of the gas and testing of the gas pressure. The environmental aspect has not been considered further in this thesis.

1.3 Thesis Problem

The researched problem in this thesis was to analyze how the suggested two-breaker arrangement design will differ from the existing substation considering the following aspects:

- Expected unavailability due to faults and maintenance
- Fault and maintenance frequencies
- Costs of the different substation designs

1.4 Purpose

The purpose of this thesis was to construct a program that can be used for reliability calculations and to use this program to compare and evaluate how the suggested two-breaker arrangement design and the existing 400 kV substation in Simpevarp will differ in terms of production availability for OKG.

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2. Methodology

This chapter starts with a motivation of the chosen methodology. It continues with an explanation of how the study was performed and how the data was collected. Next follows a discussion of the validity of the study and in the end there is an explanation of how the factors that affect the availability have been measured.

2.1 Motivation for the Chosen Methodology

The determination of the expected future reliability (Li 2005) of a system is done by a risk evaluation. Power system risk evaluation normally includes these four tasks:

1. Determination of component outage model
2. Selecting possible states of the system and calculating the probabilities.
3. Evaluating the consequences of selected system states
4. Calculating the risk indices

The purpose of a risk evaluation is often to manage the expected risk. Risk management normally includes:

1. A risk evaluation to determine the quantative risk
2. Determination of measures to reduce risk
3. Evaluation and justification of an acceptable risk level.

For power systems the acceptable risk level is always a balance between costs and the reliability of the system. There are a few different techniques that traditionally have been used in reliability evaluations of substations and their substations. These techniques can be divided into two categories. In the first category the failure states are selected deterministically, these are often referred to as state enumeration techniques and can include Markow chains, fault tree analysis, cut set methods and linear programming. In the second category the fault states are determined stochastically with a Monte Carlo analysis. The main advantage of state enumeration techniques over the stochastically technique is its simplicity and it is normally preferable when dealing with smaller systems. For larger systems that are more complex, Monte Carlo simulation are instead normally preferred.

This study is based on a state enumeration technique given by Meeuwsen and Kling (1997) who introduced a technique to deal with the complex switching options in a substation. Many earlier studies have neglected the complex switching option, which is to switch disconnectors to bypass faults, and instead chosen to evaluate simpler configurations which many times are inconsistent with the real case where switching normally has been possible.

2.2 How the Study Was Performed

The researched problem was solved in the following steps:

- First, a description of the equipment and the protection system in the existing and in the suggested design was performed.
- Second, a study of earlier work concerning fault statistics for high voltage switchgear equipment and availability studies was performed.
- Third, an analysis of where in the substation faults can occur was performed and the necessary breaker actions were listed.
- Fourth, a simulation program was programmed in java that calculates expected unavailability.
- Fifth, the input probabilities and the results of the simulations were compared to earlier substation reliability studies.
- Sixth, a function to calculate the expected unavailability due to maintenance was implemented in the java program.
- Seventh, a Life Cycle Cost analysis tool was implemented to the java program.
- Eighth, the results of the study were analyzed.

2.3 Data Collection

The study has primarily been based on secondary data collected from OKG's intranet as well as from the databases and literature available through Chalmers library. Most of the reliability studies that have been used for comparison have been obtained from the database IEEE. For a general understanding of the function of the substation has one guided visit to the 400 kV substation at Simpevarp been made which included a visit to the control house. The function of the substation and its protection system has been explained by personnel at OKG.

2.4 Validity of the Study

The validity of the result of this study is highly dependent on the quality of the data used to appreciate the failure rates and the repair times as well as on the model that is used to calculate the availability. The statistical data used in this study suffers from a few unavoidable problems. First, the number of faults that occurs in substation equipment is generally quite low and with a small statistical population follows a high uncertainty. Second, there are only a few sources available for fault statistics for the Swedish grid and these are in general limited to just showing the average fault values and no variance is for this reason possible to obtain. The data used for the fault frequencies and repair times are historical data collected from a grid with a large part of ageing components and might not be representative for a newly build substation. However, a large part of the uncertainties with the point estimation of the input data used in the model is avoided by performing a sensitivity analysis that makes it possible to make some more general conclusions about the relative advantages between the different designs.

3. Description of the Existing Substation

This chapter includes a description of the existing substation and its protection system.

3.1 General Description

The existing substation, shown in figure 1, has 4 busbars including one reserve busbar used to bypass different sections in case of a fault in one of the devices or in case of maintenance. During normal operation busbar A and B are connected. The outgoing lines to Nybro (L2) and Glan (L3) are connected to either busbar A or B while the outgoing lines to Alvesta (L1) and Kimstad (L4) are connected to busbar D. The incoming lines are connected to transformers labeled T7, T2 and T3. T7 are connected to busbar B and to the generator at Oskarshamn 1,O1, through a 130 kV substation. T2 is connected to busbar B and to the generator at Oskarshamn 2, O2. T3 is connected to busbar D and to the generator at Oskarshamn 3, O3.

All bays in the substation can be connected to the transfer busbar C by changing states of disconnectors and circuit breakers. By connecting one of the bays to busbar C the breaking control signal (Trulsson 1997) from the relay connected to that bay will automatically be connected to the reserve breaker. The bays to which the incoming lines from T7, T2 and T3 are connected to are owned by OKG (Selin et al. 2008), including the disconnectors and breakers in those bays. The rest of the substation is owned and controlled by Svenska Kraftnät.

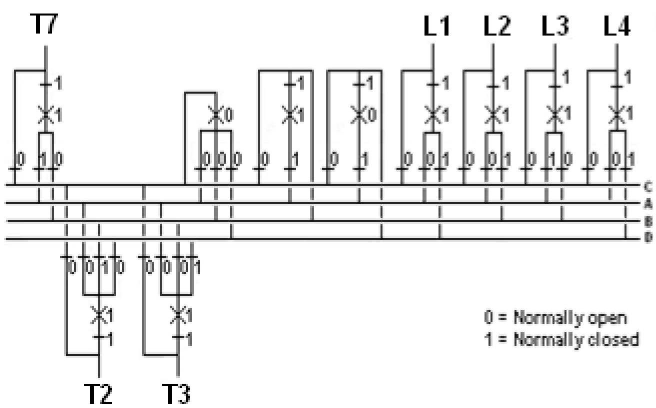

Figure 1: Existing substation

The substation consists of 12 different bays consisting of:

- One bay connected to 130 kV through T7.
- Bay connected to O2 through T2.
- Bay connected to O3 through T3.
- Reserve breaker bay for busbar A, B, C and D.
- Connection breaker for busbar A and B. (Normally closed)
- Connection breaker for busbar A and D. (Normally open)
- 4 bays for outgoing lines. (Glan, Alvesta, Kimstad and Nybro)
- Two reserve bays (consists only of saved land space for new connections).

The bays connected to the incoming and outgoing lines are equipped with disconnectors, circuit breakers, earthing switches, current transformers and voltage transformers. The bays used for dividing the busbars in sections are equipped with current transformers but not voltage transformers. All bays and busbars have permanently mounted earthing switches.

The existing substation has 10 minimum oil circuit breakers and 39 disconnectors of which 18 are in the closed state and 21 are in the open state under normal operation. There are both central break disconnectors and pantograph disconnectors in the substation but this thesis will assume that both types have the same fault and maintenance characteristics.

3.2 The Fault Clearing System

The general purpose of the fault clearing system (Hewitson et al.2004) is to keep the power system in operation without major breakdowns. To do this it should detect faults and isolate only the smallest possible area of the grid that are surrounding the fault. To perform this task it normally gets both voltage and current as input signals. If a condition occurs that by the relay is classified as a fault, the relay will send a signal to the breaker to open the circuit. The protection system is usually redundant, which mean that there are normally two separate trip circuits used so that the protection can still function even if one of the trip circuits fails. The two trip circuits used in Simpevarp are called sub 1 and sub 2.

3.2.1 Relays in the Bays for Outgoing Lines

The substation has 4 outgoing lines (Magnusson 1998) which all have redundant protection systems. The relays used in sub 1 and sub 2 are shown below.

Sub 1

Sub 1 consists of

- distance protection,
- earth fault protection,
- breaker failure protection,
- zero voltage protection
- communication unit
- automatic reclosing equipment

Sub 2

Sub 2 consists only of one distance protection relay. The distance protection relay in Sub 2 can detect both short circuits and earth faults.

3.2.2 Relays in the Bays for Incoming Lines

The bays connected to the incoming lines from T2 and T3 are also equipped with redundant protection systems. The setup for T7 is somewhat different but will, for simplicity reasons, in this thesis be considered to have the same protection characteristics as the lines from T2 and T3. The relays used in sub 1 and sub 2 (Magnusson 1998) are shown below

Sub 1

Sub 1 consists of

- distance protection,
- earth fault protection,
- breaker failure protection,
- zero voltage protection

Sub 2

Sub 2 consists of one distance protection relay and an interface to the telecommunication equipment in Sub 1. The distance protection relay in Sub 2 can detect both short circuits and earth faults.

3.2.3 Relays in the Section Connection Bays

The bays that divide the busbars in sections are equipped with automatic zero voltage protection and breaker failure protection.

3.3.4 Busbar protection

All busbars have busbar protection systems (Svensson 2007) consisting of one differential protection for each busbar and one differential protection that protects all busbars. The differential protection measures the current in the bays connected to the busbar. The protection will be activated if the current entering the protected zone differ more than a certain value from the current leaving the protected zone. A block diagram of the differential protection is shown in figure 2.

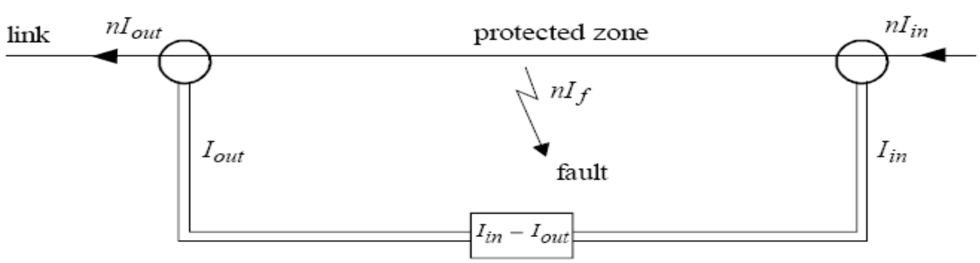

Figure 2: Block diagram of differential protection

4. Description of Simulated Two-breaker arrangement Designs

This chapter includes a description of the new substation design proposed by Svenska Kraftnät and the variations of it that has been simulated.

4.1 Simulated Designs for the Two-breaker arrangement Simulations

Design one, shown in figure 3, includes two double busbars with double disconnecting circuit breakers and a line connecting the two busbar pairs called Ekhyddan FT61 and Ekhyddan FT62. This simulation will be called DB 4L because it has double breakers and 4 outgoing lines.

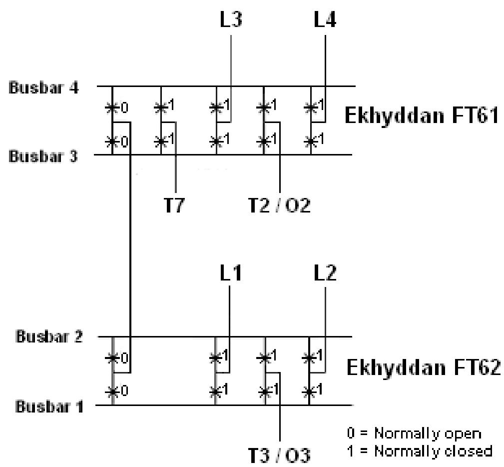

Figure 3: Two-breaker arrangement with 4 outgoing lines – DB 4L.

Design two, shown in figure 4, is the same as DB 4L except that it has separate disconnectors and normal circuit breakers instead of disconnecting circuit breakers.

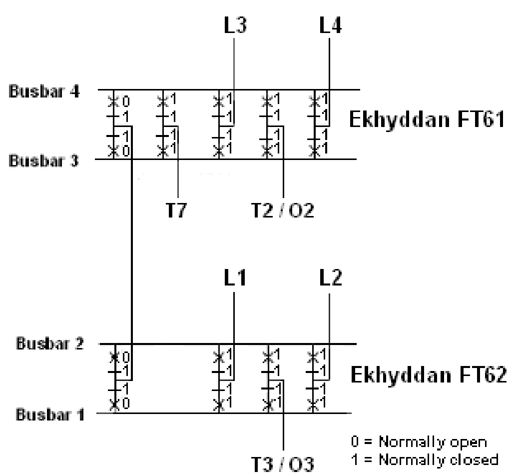

Figure 4: Two-breaker arrangement with 4 outgoing lines and disconnectors – DB Disc.

Design three, shown in figure 5, is the same as DB 4L except that T7 is connected to all 4 busbars so that there will be two connection lines between the two double busbar pairs. This was suggested in the pre-study done by Svenska Kraftnät (Selin et al 2008). This requires one extra bay compared with the DB 4L design.

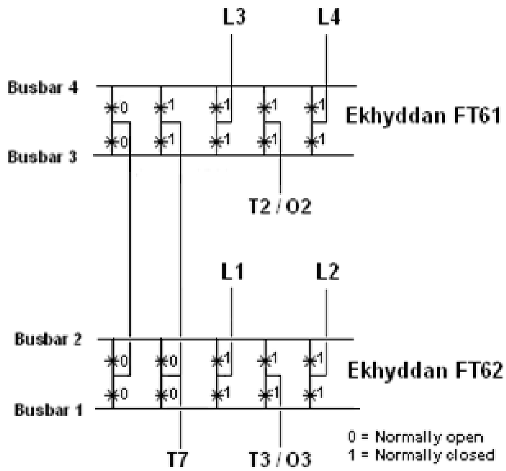

Figure 5: Two-breaker arrangement with 4 outgoing lines and T7 connected to both double busbars– DB T7.

Design four, shown in figure 6, is the same as DB 4L except that it includes one extra power line and one extra bay to which the power line is connected.

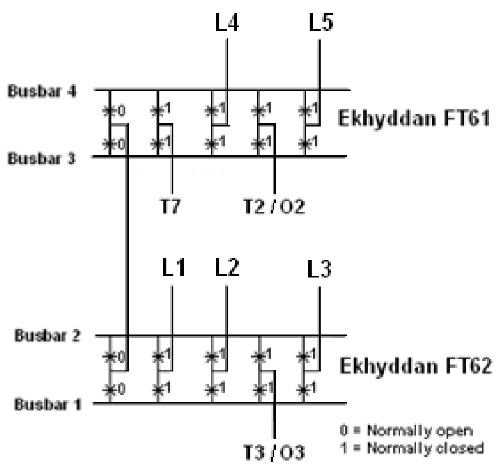

Figure 6: Two-breaker arrangement with 5 outgoing lines – DB L5.

4.2 The Disconnecting Circuit Breaker

The proposed substation design will be equipped with disconnecting circuit breaker, DCBs. The DCB (ABB 2007) integrates the disconnector function in the circuit breaker and the substation could for this reason be built without separate disconnectors. The DCB was developed by ABB and uses SF_6 gas as arc extinction medium.

Figure 7: Disconnecting Circuit Breaker

Earthing switch in unearthed position Earthing switch in earthed position.

The DCB is equipped with a fixed earthing switch so that the breaker can be grounded during maintenance. The control of the breaker function, the disconnecting function and the earthing function is performed remotely by computer signals. Before maintenance on the DCB, both the disconnecting function and the earthing function should be secured by using two padlocks that lock the breaker in the open position and the earthing switch in the closed position. The disconnecting function is performed within the circuit breaker which means that there are no possibilities to see the disconnecting function.

4.3 The Protection System

The protection system for the new substation will be decided by Svenska Kraftnät. The protection system will again consist of a sub 1 and sub 2 but more modern relays and equipments will be used. What is different from the existing system is that the protection system will be equipped with double communication units on the outgoing lines and double busbar protections for each busbar.

5. Fault Statistics

This chapter contains fault statistics from Nordel and fault statistics used in other studies.

5.1 Statistics from Nordel

Nordel publish each year a fault statistics report with fault statistics for Sweden, Finland, Denmark and Norway. The following statistics Nordel (1999-2006) shows the average fault frequencies for the Swedish for 400 kV power transformers, circuit breakers, control equipment, power lines and instrument transformers for the period from 1990 to 2006.

5.1.1 Circuit Breakers

The failure rate per 100 circuit breaker years has been decreasing slighly from an average of 2,2 faults (1990-1999) to 1,7 faults (1997-2006) per 100 circuit breaker years.The failure rate include all types of faults including unintended operation of the circuit breaker.

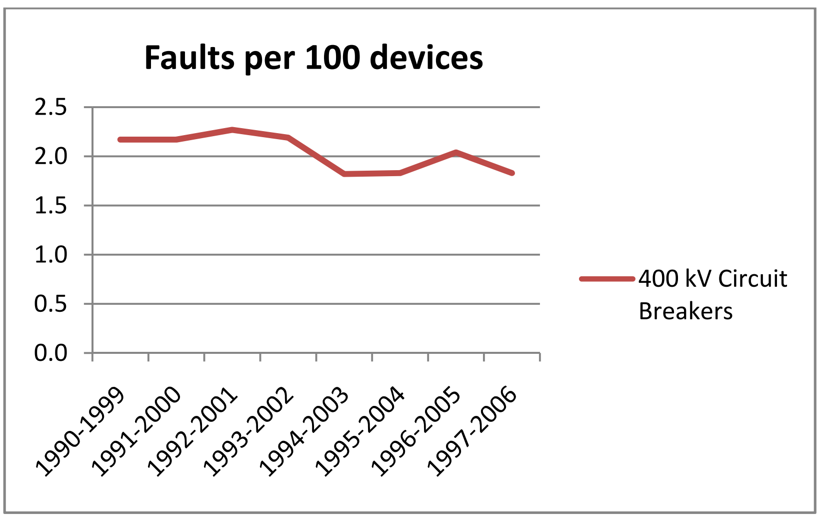

Figure 8: The failure rate per 100 circuit breaker years

5.1.2 Control Equipment

The number of faults per 100 control equipment years have according to the graph been increasing from 7 faults (1990-1999) to 12 faults (1997-2006) per 100 control equipment years. The total number of faults caused by control equipment has, however, been decreasing during this period and the increasing trend of number of faults per control equipment can be explained with that the control equipment are more sophisticated today and can perform more functions. This has made it possible to reduce the numbers of control equipment used but the fault rate has, as can be seen increased due to the higher complexity of the protection.

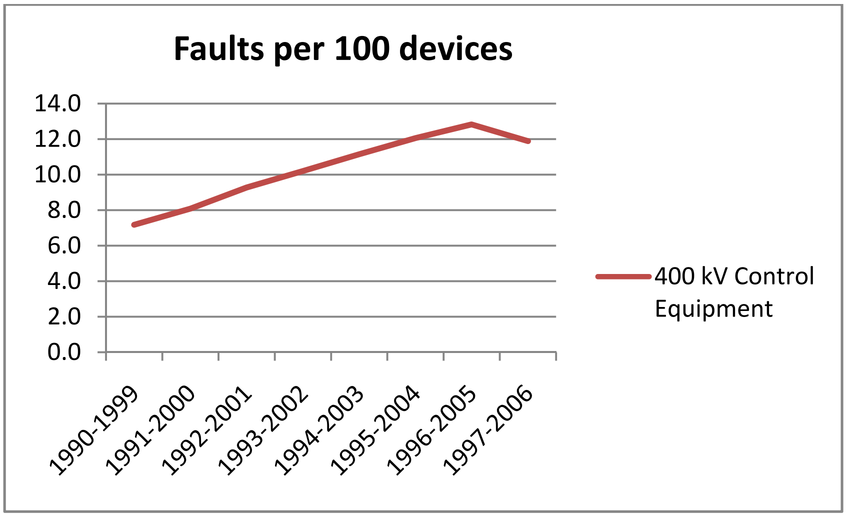

Figure 9: The number of faults per 100 control equipment years.

5.1.3 Power Lines 400 kV

The power line faults per 100 km has been increasing from an average of a little bit above 0.3 faults per 100 km during 1990-1999 to 0.4 faults per 100 km during 1997-2006.

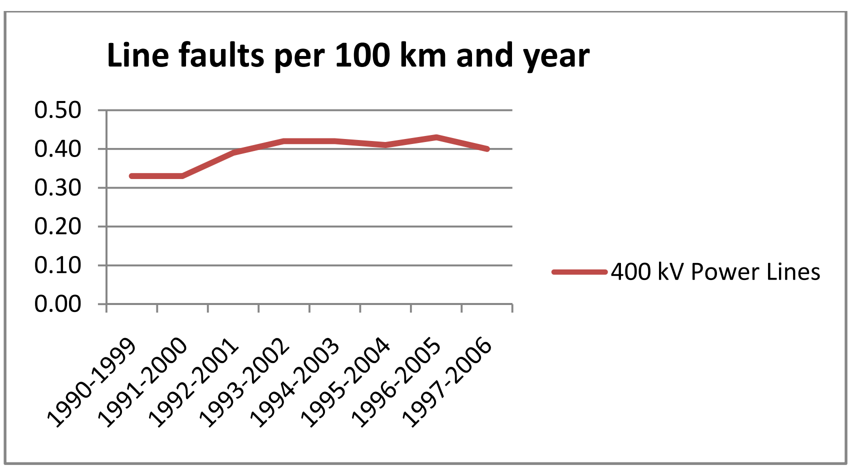

Figure 10: Line faults per 100 km and year for 400 kV power lines.

5.2 Fault Statistics used in Other Studies

This part compares the assumed fault probabilities, repair times, stuck condition probability and probability for unintentional operations for this thesis to assumptions used in other reliability studies.

5.2.1 Fault Probabilities

Table 1 shows the different fault probabilities used in other studies and in this study. To note is that the fault probability for power lines normally are given in faults per kilometer or in faults per 100 km. However, when calculating the reliability for the substation a fault probability for each line must be assumed where the probability are highly dependent on the length of the line. The input assumption for this study has primarily been based on the fault frequencies found in the master thesis performed for Svenska Kraftnät (Nyberg 2003) where fault statistics for the whole Swedish 400 kV grid was collected and analyzed for a period of 5 years.

Table 1: Fault probabilities used in other studies and statistics for the Swedish grid.

	Power Lines (per line)	**Disconnector**	**Circuit Breaker**	**Busbar**
ABB 2007	0.015768	0.0025	0.004	0.0026
Nyberg 2003 (SvK)	**(0.005 per km)**	0.00149	0-0.0215	0.0269
Nordel Sweden 2007	**(0.004 per km)**	-	0.018	-
Dortolina et. al. 1991	0.680	0.002	0.045	0.010
Billinton & Lian 1991	0.09	-	0.02	0.024
Meeuwsen & Kling 1997	1.00	-	0.02	0.025
Karlsson et al 1997	-	-	0.013 (Line CB) 0.045 (Reactor CB)	-
Brown & Taylor 1999	0.105	0.01	0.006	
Atanackovic et al 1999	-	-	0.045 (315 kV) 0.099 (500 kV)	-
Xu et al 2002	0.15 (500 kV)	0.002 (500 kV)	0.06 (500 kV)	0.02 (500 kV)
Tsao & Chang 2003	0.046	-	0.006	0.001
Suwantawat & Premrudeepreechacham 2004	0.01437	0.0897	-	0.000125
Retterah et al 2004	0.105	0.02	0.02	0.010
Billinton & Yang 2005	-	-	0.01	0.025
Bezhadi Rafi et al 2006	-	0.01	0.01	0.01
Sidiropoulos 2007	1.0	-	0.18	0.09
Banejad et al 2008	0.014	0.01	0.015	0.014
This study	0.60 (outgoing line 0.004 (incoming line)	0.002	0.01	0.027

To notice about the statistics is that these are average values per type of device and year and that the fault probability can be dependent on several factors that generally not can be obtained from the existing statistics.

5.2.2 Repair Time

The expected unavailability of a device depends on the fault probability for the device and the repair time, which is the expected time it takes from that a fault causes disconnection of the device until the device is connected and back in normal operation again. The assumption of repair time is equally important as the fault probability for the results of the unavailability calculations. Table 2 shows the repair time assumed in other studies and in this study. The repair time for this study has mainly been decided by the results in the thesis by Nyberg (2003). The input assumption in the different studies varies the most for circuit breakers while the variation is less for power lines, disconnectors and busbars.

Table 2: Repair times used in other studies and statistics for Swedish grid. [hours: minutes}

	Power Lines	Disconnector	Circuit Breaker	Busbar
ABB	-	10:00	16:00	-
Nyberg 2003 (SvK)	5:03	4:03-40:47	6:00-24:00	3:25
Dortolina et. al. 1991	7:29	12:00	24:00	24:00
Billinton & Lian 1991	7:20	-	3:00	2:00
Meeuwsen & Kling 1997	10:00	-	12:00	25:00
Karlsson et al 1997	-	-	48:00	-
Brown & Taylor 1999	8:00	4:00	4:00	-
Atanackovic et al 1999	-	-	-	-
Xu et al 2002	15:00 (500 kV)	12:00 (500 kV)	100:00 (500 kV)	24:00 (500 kV)
Tsao & Chang 2003	8:00	-	4:00	2:00
Suwantawat & Premrudeepreechacham 2004	4:20	-	6:00	9:30
Retterah et al 2004	5:00	-	4:00	-
Billinton & Yang 2005	-	-	93:36	10:00
Bezhadi Rafi et al 2006	-	4:00	12:00	4:00
Sidiropoulos 2007	10:00		160:00	6:00
Banejad et al 2008	4:20	4:00	70:00	9:30
This study	5:00	10:00	16:00	3:30

To notice is that these repair times are average values and that there might be great variations depending on, for example the type of fault in the device, if spare parts for repair are closely available and, in case of an unrepairable damage, if a new device can be obtained and installed in a short time. A good example of the large variations is the power lines, where most of the faults are momentary where the fault will be cleared when the recloser tries to connect the line again. For those types of faults the effect on the unavailability will be negligible. In other cases there can be more severe faults, for example can collapsing towers create persisting faults that give high unavailability.

5.2.3 Probability of Stuck Condition

The relevant measure for stuck probability is the numbers of failures to open and interrupt the fault current divided by the number of commands. The probability normally include both opening and closing operations while only the breaking operation is of major concern for the unavailability when a fault occurs. When a circuit breaker fails to close a circuit on command it is in most cases not as severe case as then the circuit breakers fails to open the circuit. The stuck probabilities assumed in this study and in other studies are shown in table 3.

Table 3: Assumed probabilities of stuck condition in other studies. [per breaker]

ABB	**-**
Nyberg 2003 (SvK)	-
Dortolina et. al. 1991	0.005
Billinton & Lian 1991	-
Meeuwsen & Kling 1997	0.06
Karlsson et al 1997	**(0.000177 per operation cycle))**
Brown & Taylor 1999 (ABB)	0.05
Atanackovic et al 1999	-
Xu et al 2002	-
Tsao & Chang 2003	-
Suwantawat & Premrudeepreechacham 2004	-
Retterah et al 2004	-
Billinton & Yang 2005	-
Bezhadi Rafi et al 2006	0.1
Sidiropoulos 2007	-
Banejad et al 2008	-
This study	0.0045

There was one case reported in the master thesis done for Svenska Kraftnät (Nyberg 2003) where one disconnector was stuck. A stuck condition of disconnector will be neglected in this thesis because of the low probability of such event.

5.2.4 Probability of Unintentional Operation

The probability of unintended operation for circuit breakers in the Swedish grid was found to be 0.00123-0.00243 per circuit breaker and year (Nyberg 2003). The corresponding probability for disconnectors was found to be 0,000139 per disconnector and year. The probability of unintentional operation was normally not given in the other reliability studies that has been used for comparison.

6. Reliability Calculation Theory

6.1 Calculating Unavailability

Unavailability is normally expressed either as a fraction of time per year that one point in the system is unavailable or in hours per year. In this thesis the unavailability will be expressed in minutes or hours per year because this will yield less numbers of decimals and be easier to interpret. The unavailability can further be divided into planned unavailability and unplanned unavailability. All unavailability due to faults is normally unplanned while the unavailability due to maintenance can be either planned or unplanned unavailability. An example of unplanned unavailability is when a device in the substation during an inspection is found to be in a condition that is believed to increase the risk of failure. The device may in that case be disconnected from the rest of the substation for immediate maintenance. In this thesis the unavailability will be calculated as the sum of the unavailability that is caused by faults and the unavailability caused by maintenance according to the formula below.

$$U_{total} = U_{faults} + U_{maintenance}$$

6.2 Categorization of Faults

The various types of faults that can occur in the substation (Meeuwsen & Kling 1997) can be classified in the following categories:

- Active failure events
- Passive failure events
- Stuck-condition of breakers
- Overlapping failure events

An active failure occurs if the fault is detected by the relay and the circuit breakers trip to interrupt the fault currents. This can for example be a short circuit. In this thesis all single faults except unintended operations of circuit breakers and disconnectors has been considered to be active faults. The reason for this generalization is the lack of statistical data that makes it possible to correctly categorize all types of faults.

Passive failures are defined as faults that are undetected by the protection system and do not cause any operation of the circuit breakers. Examples of passive failures are open circuits in a device or unintended operation of circuit breakers or disconnectors. In this thesis only unintended operations of circuit breakers and disconnectors will be classified as passive faults.

If the fault is detected and a tripping signal has been send but the breaker fail to operate it is called a stuck-condition. In that case should the breaker failure protection act and send a tripping signal to the circuit breakers that are closest around the fault and the failing breaker.

The last category of faults is the overlapping failure events, which occur when another fault occurs in the substation during the repair time of the first fault. The probability for two faults to overlap each other is low and the probability for higher order of overlapping faults is considered to be neglible if the faults are considered to be independent. The assumption of independent faults is, however, not always true in real life where cases like vandalism or fire in the substation might lead to several faults caused by the same source. Dependent faults are statistically hard to evaluate and will for that reason be neglected. However, a stuck condition event is also an example of a dependent fault and this type of dependent faults has not been neglected.

6.3 Calculating Unavailability without Using Switching Option

This section explains how the unavailability and failure frequency is calculated without switching disconnectors to bypass faults. All substation designs have first been simulated without switching disconnectors to bypass faults. If the substation design has disconnectors the program has also calculated the unavailability and failure frequency with the switching option. The unavailability due to faults has been categorized according to the earlier given categories passive faults, active faults, stuck condition and overlapping faults.

6.3.1 Active Faults

The unavailability for active faults was calculated by multiplying the active failure rate for device i with the expected repair time for device i. The total unavailability in minutes for line x was then calculated as the sum of the unavailability for all passive faults that will cause disconnection of line x.

$$U_{ac,line\ x} = \sum_{i=1}^{n} U_{ac,i} = \sum_{i=1}^{n} \lambda_{ac,i} \cdot r_i$$

The expected failure frequency for line x was calculated as the sum of all failure rates for active faults that will cause disconnection of line x.

$$f_{ac,line\ x} = \sum_{i=1}^{n} \lambda_{ac,i}$$

Where

$\lambda_{ac,i}$ $= failure\ rate\ of\ active\ failure\ event$
r_i $= repair\ time\ for\ device\ i$ in hours
$U_{ac,i}$ $= expected\ unavailability\ in\ hours\ per\ year\ for\ device\ i$
$U_{ac,line\ x}$ $= expected\ unavailability\ in\ hours\ per\ year\ for\ line\ x\ due\ to\ active\ faults$
i $= the\ number\ of\ the\ active\ fault\ that\ can\ cause\ disconnection\ of\ line\ x$
n $= total\ number\ of\ active\ faults\ that\ can\ cause\ disconnecyion\ of\ line\ x$
$f_{ac,line\ x}$ $= failure\ frequency\ for\ line\ x\ due\ to\ active\ faults$ x

6.3.2 Passive Faults

The unavailability for device i due to passive faults was calculated by multiplying the passive failure rate for device i with the expected repair time for device i. The unavailability in hours per year for line x was then calculated as the sum of unavailability for all passive faults that will cause disconnection of line x.

$$U_{p,line\ x} = \sum_{i=1}^{n} U_{p,i} = \sum_{i=1}^{n} \lambda_{p,i} \cdot r_i$$

The expected failure frequency for line x due to passive faults was calculated as the sum of all failure rates for passive faults that will cause disconnection of line x.

$$f_{p,line\ x} = \sum_{i=1}^{n} \lambda_{ac,i}$$

Where

$\lambda_{p,i}$ $= failure\ rate\ of\ passive\ failure\ event$
$U_{p,i}$ $= expected\ unavailability\ in\ hours\ per\ year\ for\ device\ i$
$U_{p,line\ x}$ $= expected\ unavailability\ in\ hours\ per\ year\ for\ line\ x\ due\ to\ passive\ faults$
i $= the\ number\ of\ the\ passive\ fault\ that\ can\ cause\ disconnection\ of\ line\ x$
n $= total\ number\ of\ active\ faults\ that\ can\ cause\ disconnection\ of\ line\ x$
$f_{p,line\ x}$ $= passive\ failure\ frequency\ for\ line\ x$

6.3.3 Stuck Condition

The expected unavailability for device i due to stuck condition of one breaker after an active fault was calculated as the unavailability due to active faults for device i multiplied with the probability of stuck condition of the surrounding circuit breakers j.

$$U_{st,line\ x} = \sum_{i=1}^{n} U_{st,i} = \sum_{i=1}^{n_1} \sum_{j=1}^{n_2} \lambda_{ac,i} \cdot P_{stuck,j} \cdot r_i$$

The expected failure frequency due to stuck condition for line x was calculated as the sum of all stuck condition probabilities for all faults that can cause disconnection of line x The probability for a stuck condition was calculated by multiplying the probability for active failure in device i with the probability of stuck condition for circuit breaker j .

$$f_{ac,line\ x} = \sum_{i=1}^{n_1}\sum_{j=1}^{n_2} \lambda_{ac,i} \cdot P_{stuck,j}$$

Where

P_{stuck} $= the\ probability\ of\ a\ stuck\ condition\ of\ the\ breaker$
$\lambda_{ac,i}$ $= failure\ rate\ of\ active\ failure\ event$
r_i $= repair\ time\ for\ device\ i$
$U_{stuck,i}$ $= unavailability\ in\ minutes\ for\ device\ i\ due\ to\ stuck\ condition$
$U_{stuck,line\ x}$ $= unavailability\ in\ minutes\ for\ line\ x\ due\ to\ stuck\ condition$
i $= the\ number\ of\ the\ active\ fault\ that\ can\ cause\ disconnection\ of\ line\ x$
n $= total\ number\ of\ active\ faults\ that\ can\ cause\ disconnection\ of\ line\ x$
$f_{ac,line\ x}$ $= failure\ frequency\ for\ line$

6.3.4 Overlapping faults

The expected unavailability time for overlapping faults was approximated by taking the sum of the probabilities for all multiple faults that disconnect line x. The probabilities for the multiple faults was approximated by multiplying the two failure rates for device i and j with the repair time for device i and j and divide it with numbers of hours per year.

$$U_{mu,line\ x} = \sum_{i=1}^{n}\sum_{j=1}^{n} \lambda_i \cdot \lambda_j \cdot \frac{r_i \cdot r_j}{hours\ per\ year}$$

The expected failure frequency for line x due to overlapping faults was approximated as the sum of all failure rates for overlapping faults that will cause disconnection of line x. Where the failure rates was calculated by multiplying both the probabilities for the two single faults with the sum of the repair times for the two single faults.

$$f_{mu,line\ x} = \sum_{i=1}^{n}\sum_{j=1}^{n} \lambda_i \cdot \lambda_j \cdot (r_i + r_j)$$

Where

λ_i $= \lambda_{ac,i} + \lambda_{p,i}$
λ_j $= \lambda_{ac,j} + \lambda_{p,j}$
r_i $= repair\ time\ for\ device\ i\ in\ hours$
r_j $= repair\ time\ for\ device\ j\ in\ hours$
$U_{mu,i}$ $= unavailability\ in\ hours\ per\ year\ for\ device\ i\ due\ to\ multiple\ faults$
$U_{mu,line}$ $= unavailability\ in\ hours\ per\ year\ for\ line\ x\ due\ to\ multiple\ faults$
i $= the\ number\ of\ the\ active\ fault\ that\ can\ cause\ disconnection\ of\ line\ x$
j $= the\ number\ of\ the\ active\ fault\ that\ can\ cause\ disconnection\ of\ line\ x$
n $= total\ number\ of\ active\ faults\ that\ can\ cause\ disconnection\ of\ line\ x$
$f_{mu,line}$ $= failure\ frequency\ for\ line\ due\ to\ multiple\ faults$

6.4 Calculating Unavailability when Using Switching Option

The switching option is used both in the simulation for the existing substation and for the two-breaker arrangement configuration with disconnectors.

6.4.1 Active Faults

The unavailability for active faults was calculated by multiplying the active failure rate for device i with the expected repair time for device i. The total unavailability in minutes for line x was calculated as the sum of the unavailability for all passive faults that can cause disconnection of line x. The factors have been noted with i1 and i2 to stress that the numbers of faults that cause disconnection of line x is smaller after the switching has occurred. In other words, the factors noted with i1 contains all faults that will cause disconnection of line x while all factors noted with i2 contains only faults that cannot be bypassed by switching disconnectors.

$$U_{ac,line\ x} = \sum_{i=1}^{n} U_{ac,i} = \sum_{i1=1}^{n1} \lambda_{ac,i1} \cdot s_{i1} + \sum_{i2=1}^{n2} \lambda_{ac,i2} \cdot (r_{i2} - s_{i2})$$

$\lambda_{ac,i}$ $= failure\ rate\ of\ active\ failure\ event$
r_i $= repair\ time\ for\ device\ i\ in\ hours$
s_{i1} $= switch\ time\ for\ device\ i1\ in\ hours$
s_{i2} $= switch\ time\ for\ device\ i2\ in\ hours$
$U_{ac,i}$ $= expected\ unavailability\ in\ hours\ per\ year\ for\ device\ i$
$U_{ac,line\ x}$ $= expected\ unavailability\ in\ hours\ per\ year\ for\ the\ line\ due\ to\ active\ faults$
i_1 $= the\ number\ of\ the\ active\ fault\ that\ can\ cause\ disconnection\ of\ line\ x$
i_2 $= the\ number\ of\ the\ active\ fault\ that\ can\ cause\ disconnection\ of\ line\ x\ and\ that\ can\ not\ be\ by\ active\ by\ switching\ disconnectors$
n_1 $= total\ number\ of\ active\ faults\ that\ can\ cause\ disconnection\ of\ line\ x$
n_2 $= total\ number\ of\ active\ faults\ that\ can\ cause\ disconnection\ of\ line\ x\ and\ that\ can\ not\ be\ by\ passed\ by\ switching$

6.4.2 Passive Faults

The unavailability for passive faults was calculated in a similar way as described for passive faults without using the switching option. The difference now is that the unavilbility consist of both the lines that are unavailable before the switching occur and the unavailability caused by faults that can not be bypassed by switching disconnectors.

$$U_{p,line\ x} = \sum_{i=1}^{n} U_{p,i} = \sum_{i1=1}^{n1} \lambda_{p,i1} \cdot s_{i1} + \sum_{i2=1}^{n2} \lambda_{p,i2} \cdot (r_{i2} - s_{i2})$$

Where

$\lambda_{p,i}$ $= failure\ rate\ of\ passive\ failure\ event$
r_i $= repair\ time\ for\ device\ i$ in hours
s_i $= switch\ time\ for\ device\ i\ in\ hours$
$U_{p,i}$ $= expected\ unavailability\ in\ hours\ per\ year\ for\ device\ i$
$U_{p,line\ x}$ $= expected\ unavailability\ in\ hours\ per\ year\ for\ the\ line\ due\ to\ active\ faults$
i_1 $= the\ number\ of\ the\ passive\ fault\ that\ can\ cause\ disconnection\ of\ line\ x$
i_2 $= the\ number\ of\ the\ passive\ fault\ that\ can\ cause\ disconnection\ of\ line\ x\ and\ that\ can\ not\ be\ by\ passed\ by\ switching$
n_1 $= total\ number\ of\ passive\ faults\ that\ can\ cause\ disconnection\ of\ line\ x$
n_2 $= total\ number\ of\ passive\ faults\ that\ can\ cause\ disconnection\ of\ line\ x\ and\ that\ can\ not\ be\ by\ passed\ by\ switching$

6.4.3 Stuck Condition

The expected unavailability for stuck condition when switching option was used was also divided in the part of unavailability that exists before the switching occur and the unavailability that exists after the switching has occurred until the failing device has been repaired.

$$U_{st,line} = \sum_{i=1}^{n} U_{st,i} = \sum_{i1=1}^{n1} \lambda_{ac,i1} \cdot P_{stuck} \cdot s_{i1} + \sum_{i2=1}^{n2} \lambda_{i2} \cdot P_{stuck} \cdot (r_{i2} - s_{i2})$$

Where

P_{stuck} $= the\ probability\ of\ a\ stuck\ condition\ of\ the\ breaker$
$\lambda_{ac,i}$ $= failure\ rate\ of\ active\ failure\ event$
r_i $= repair\ time\ for\ device\ i$
$U_{stuck,i}$ $= unavailability\ in\ minutes\ for\ device\ i\ due\ to\ stuck\ condition$
$U_{stuck,line\ x}$ $= unavailability\ in\ minutes\ for\ line\ x\ due\ to\ stuck\ condition$
i $= the\ number\ of\ the\ active\ fault\ that\ can\ cause\ disconnection\ of\ line\ x$
n $= total\ number\ of\ active\ faults\ that\ can\ cause\ disconnection\ of\ line\ x$
$f_{ac,line\ x}$ $= failure\ frequency\ for\ line$

6.4.4 Overlapping faults

The expected unavailability time for overlapping faults was calculated using the formula below. The first part of the formula consist of the unavailability caused by multiple faults that disconnect line x before the switching occurs. The second part of the formula consists of the unavailability caused by faults during the time between switching has occurred until the device is repaired.

$$U_{of,line\ j} = \sum_{i_1=1}^{n1} \sum_{j_1=1}^{n1} \lambda_{i1} \cdot \lambda_{j1} \cdot \frac{s_{i1} \cdot s_{j1}}{hours\ per\ year} + \sum_{i1=1}^{n2} \sum_{j1=1}^{n2} \lambda_{i1} \cdot \lambda_{j1} \cdot \frac{(r_{i1} - s_{i1}) \cdot (r_{j1} - s_{j1})}{hours\ per\ year}$$

Where

$\lambda_i \quad = \lambda_{ac,i} + \lambda_{p,i}$
$\lambda_j \quad = \lambda_{ac,j} + \lambda_{p,j}$
$U_{of,line\ x} = unavailability\ in\ hours\ per\ year\ for\ line\ x\ due\ to\ multiple\ faults$
$i \quad = the\ number\ of\ the\ active\ fault\ that\ can\ cause\ disconnection\ of\ line\ x$
$j \quad = the\ number\ of\ the\ active\ fault\ that\ can\ cause\ disconnection\ of\ line\ x$
$n \quad = total\ number\ of\ active\ faults\ that\ can\ cause\ disconnection\ of\ line\ x$

7. Structure of the Developed Simulation Program

7.1 Functions in the Program

The developed program that was used to answer the problem for this thesis was programmed in java. A screenshot from the program can be seen in appendices 1. The program uses input assumptions for fault probabilities, repair time, maintenance frequency and maintenance duration to calculate the unavailability and the yearly frequency of unavailability due to maintenance and faults for the power lines connected to the substation.

The faults can be studied in four different complexity levels which make it easier to study the reliability of the different substation in depth. In the first complexity level it is possible to graphically look at each single fault and the circuit breaker actions that follow. In this complexity level it is also possible to see which disconnectors and circuit breakers that needs to be switched to bypass the fault. This makes it possible to graphically study each fault to see that every fault is simulated correctly. In the second complexity level the unavailability and unavailability frequency that each group of devices causes for the power lines are calculated. This makes it, for example, possible to see how much of the unavailability on T3 that is caused by circuit breakers. In the third complexity level, the total unavailability and unavailability frequency is calculated for the power lines for the specific substation design. In the fourth complexity level, the unavailability and unavailability frequency are shown for all the different simulated substation designs, which make it easy to compare the results from the different simulations.

The program also simulates the four different types of faults given in the previous chapter and shows the results for each category. That is active faults, passive faults, stuck condition events and overlapping failure events.

The program also has a function for calculating the life cycle costs of the different substation designs where the unavailability is directly taken from the program to calculate the opportunity costs due to undelivered power.

7.2 Basic Structure of the Program

The programs algorithm is based on the formulas given in the previous chapter. The state of the different devices is given in separate columns of a matrix and the different faults are given in different rows of the matrix. Devices that are connected, or are in closed state, are marked with value 1 in the matrix. Devices that are disconnected, or are in open state, are marked with the value 0. When fault number 1 is simulated the program reads row number 1 of the matrix for the specific substation matrix that is simulated to draw the different states for the substation devices on the screen. The states of the different devices are indicated with red colour if they are in the disconnected state and in black if they are connected. For the calculations the program reads all rows of the matrix to see for which faults that the power lines are disconnected and then uses the input fault probabilities and repair time to find the results. The results of the calculation are then shown directly on the screen.

8. Simulation of Unavailability and Fault Frequencies

8.1 Input Variables

Table 4 shows the input assumption that was used for the point estimation of the unavailability. Due to the rather high uncertainties in the fault probability values, which was shown by the wide spread of assumptions used in other studies, any choice of point estimation could be criticized as favoring a certain result depending on where in the uncertainty range the values are chosen. To avoid this dilemma a sensitivity analysis will be done in the next chapter that gives more information about the system behavior than the simple point estimation. The point estimation is, however, necessary to perform as a starting point for further analysis and should as well as possible represent the most likely case.

Table 4: Used probabilities for calculation of unavailability due to faults.

	Incoming Line	Outgoing Line	Busbar line	Discon-nectors	CB / DCB	Busbar
Probability active	0.004	0.6	0.0004	0.002	0.01	0.027
Probability passive	0	0	0	0.00014	0.002	0
Repair time	5:00	5:00	5:00	10:00	16:00	3:30
Switch time	1:00	1:00	1:00	1:00	1:00	1:00

To note is that

- Active faults probabilities include all single faults except unintended operations of circuit breakers and disconnectors.
- Passive faults only include the probabilities of unintended operations of circuit breakers and disconnectors.
- Stuck probability of circuit breakers has been assumed to be 0.0045 per breaker and year.

8.2 Calculated Unavailability

8.2.1 Existing Substation

The calculated unavailability for the incoming power lines labeled T7, T2 and T3 in the existing substation, shown in table 5, was found to be between 51 to 65 minutes per year. The calculated unavailability comes mainly from active faults where the calculated unavailability is a little bit higher for T3. This difference for the incoming lines comes from that there are five disconnectors in the closed position that can cause faults that disconnect T3 while there are only four disconnectors in the closed position that causes disconnection of T7 and T2. The calculated unavailability for the outgoing lines is between 232 to 245 minutes where the difference in unavailability comes from the numbers of disconnectors and circuit breakers that cause disconnection of the line.

Table 5: Unavailability due to faults for existing substation without switching [minutes / year]

	Total	Active	Passive	Stuck-condition	Overlapping faults
T7	59.93	54.87	2.47	1.55	1.04
T2	51.34	46.47	2.47	1.54	0.85
T3	64.29	58.47	2.47	2.26	1.09
Line 1	244.89	237.27	2.47	2.23	2.93
Line 2	231.99	225.27	2.47	1.51	2.74
Line 3	240.57	233.67	2.47	1.55	2.88
Line 4	244.89	237.27	2.47	2.23	2.93

The calculated unavailability is drastically lowered if the transfer bus is used on the existing substation to bypass a failing device. The total unavailability for the incoming lines, shown in table 6, is reduced to 8.5 to 9.5 minutes. The total unavailability for the outgoing lines is between 188 and 190 minutes where the major part of the unavailability comes from the power lines themselves, which for obvious reasons cannot be bypassed by switching disconnectors.

Table 6: Unavailability due to faults for existing substation with switching [minutes / year]

	Total	Active	Passive	Stuck	Overlapping faults*
T7	8.98	8.34	0.24	0.26	0.15
T2	8.47	7.86	0.24	0.25	0.12
T3	9.46	8.70	0.24	0.40	0.12
Line 1	189.91	187.50	0.24	0.42	1.76
Line 2	188.90	186.66	0.24	0.26	1.73
Line 3	189.34	187.14	0.24	0.27	1.70
Line 4	189.94	187.50	0.24	0.46	1.75

* Rough estimation, additional faults might be possible to bypass by switching disconnectors and some fault combinations that can be bypassed might be considered inappropriate for other reasons. Needs additional analysis for more accurate numbers.

8.2.2 Two-breaker arrangement with 4 Outgoing Lines

The calculated unavailability for the incoming and outgoing lines, shown in table 7, is approximately 26 minutes. The calculated unavailability comes again mainly from active faults. The small difference in total unavailability is caused by stuck-condition of circuit breakers where the calculated unavailability depends on the number of bays connected to the double busbar. Overlapping faults also contribute to a small difference in unavailability which would be shown if more decimals would be used in the overlapping faults category.

Table 7: Unavailability due to faults for DB 4L [minutes / year]

	Total	Active	Passive	Stuck	Overlapping faults
T7	26.25	20.4	4.61	0.75	0.49
T2	26.25	20.4	4.61	0.75	0.49
T3	26.08	20.4	4.61	0.58	0.49
Line 1	208.74	199.2	4.61	2.19	2.74
Line 2	208.74	199.2	4.61	2.19	2.74
Line 3	208.74	199.2	4.61	2.36	2.74
Line 4	208.74	199.2	4.61	2.36	2.74

8.2.3 Two-breaker arrangement with 4 Outgoing Lines and Disconnectors.

This is the same as previous simulation except that disconnectors have been added between the lines and the breakers. If the disconnectors are installed but not used the unavailability increase from 26 minutes to almost 29 minutes due to the fault probability and expected repair time for disconnectors.

Table 8: Unavailability due to faults for DB Disc. without switching [minutes / year]

	Total	Active	Passive	Stuck	Overlapping faults
T7	28.86	22.8	4.78	0.77	0.51
T2	28.86	22.8	4.78	0.77	0.51
T3	28.86	22.8	4.78	0.60	0.51
Line 1	211.40	201.6	4.78	2.21	2.81
Line 2	211.40	201.6	4.78	2.21	2.81
Line 3	211.57	201.6	4.78	2.38	2.81
Line 4	211.57	201.6	4.78	2.38	2.81

Table 9 shows that the unavailability is drastically reduced by using the switching option to decrease the unavailability caused by circuit breakers. The unavailability for the incoming lines was in this case 5.5 minutes which should be compared to the expected unavailability of 26 minutes for the same design without separate disconnectors.

Table 9: Unavailability due to faults for DB Disc. with switching [minutes / year]

	Total	Active	Passive	Stuck	Overlapping faults
T7	5.51	4.8	0.46	0.21	0.05
T2	5.51	4.8	0.46	0.21	0.05
T3	5.50	4.8	0.46	0.20	0.05
Line 1	187.66	183.6	0.46	1.81	1.80
Line 2	187.66	183.6	0.46	1.81	1.80
Line 3	187.67	183.6	0.46	1.82	1.80
Line 4	187.67	183.6	0.46	1.82	1.80

8.2.4 Two-breaker arrangement with T7 Connected to both Double Busbars.

In this simulation T7 is connected to both double busbars. The unavailability for T7 is almost doubled because it is in this case four circuit breakers that can cause disconnection of the line to T7 compared to only two circuit breakers in the case where T7 only is connected to one of the double busbars.

Table 10: Unavailability due to faults for DB T7 [minutes / year]

	Total	Active	Passive	Stuck	Overlapping faults
T7	50.75	39.60	9.22	1.01	0.92
T2	26.24	20.40	4.61	0.75	0.47
T3	26.15	20.40	4.61	0.67	0.47
Line 1	208.99	199.20	4.61	2.36	2.82
Line 2	208.99	199.20	4.61	2.36	2.82
Line 3	208.99	199.20	4.61	2.36	2.82
Line 4	208.99	199.20	4.61	2.36	2.82

8.2.5 Two-breaker arrangement with 5 Outgoing Lines

Table 11 shows the unavailability when one extra line is added to the substation with two-breaker arrangement. The change in total unavailability by adding one extra line is only caused by stuck condition unavailability and overlapping faults and the total change is only 0.1 minute for the incoming line. With the stuck condition probability assumed for this simulation the change in unavailability by adding one extra line can be considered to be negligible.

Table 11: Unavailability due to faults for DB 5L [minutes / year]

	Total	Active	Passive	Stuck	Overlapping faults
T7	26.33	20.4	4.61	0.75	0.57
T2	26.33	20.4	4.61	0.75	0.57
T3	26.33	20.4	4.61	0.75	0.57
Line 1	209.57	199.2	4.61	2.36	3.40
Line 2	209.57	199.2	4.61	2.36	3.40
Line 3	209.57	199.2	4.61	2.36	3.40
Line 4	209.57	199.2	4.61	2.36	3.40
Line 5	209.57	199.2	4.61	2.36	3.40

8.3 Calculated Fault Frequencies

The fault frequencies is considered to be the same either the switching option is used or not because the option of switching disconnectors occurs first after the fault has occurred. In reality there will be a small difference but this has been neglected.

8.3.1 Existing Substation

The expected number of faults that will disconnect one of the incoming lines in the existing substation, shown in table 12, is between 8.5 to 10.5 faults per 100 years. The majority of faults on the incoming lines come from circuit breakers while the majority of faults on the outgoing lines come from the lines themselves.

Table 12: Fault frequency per 100 years for existing substation [faults / 100 years]

	Total	Active	Passive	Stuck	Multiple fault
T7	9.45	8.7	0.27	0.40	0.09
T2	8.65	7.9	0.27	0.41	0.08
T3	10.32	9.3	0.27	0.66	0.10
Line 1	70.19	68.9	0.27	0.64	0.38
Line 2	68.52	67.5	0.27	0.39	0.36
Line 3	69.34	68.3	0.27	0.40	0.37
Line 4	70.19	68.9	0.27	0.64	0.38

8.3.2 Two-breaker arrangement with 4 Outgoing Lines

The expected number of faults that will disconnect one certain incoming line for DB 4L, shown in table 13, is approximately 3 faults per 100 years. The faults on outgoing lines continue to be high because most of the faults occur on the outgoing lines themselves.

Table 13: Fault frequency per 100 years for DB 4L [faults / 100 years]

	Total	Active	Passive	Stuck	Multiple fault
T7	3.02	2.40	0.48	0.10	0.04
T2	3.02	2.40	0.48	0.10	0.04
T3	3.00	2.40	0.48	0.08	0.04
Line 1	63.45	62.00	0.48	0.62	0.35
Line 2	63.45	62.00	0.48	0.62	0.35
Line 3	63.47	62.00	0.48	0.64	0.35
Line 4	63.47	62.00	0.48	0.64	0.35

8.3.3 Two-breaker arrangement with 4 Outgoing Lines and Disconnectors.

The results for the unavailability for the simulation with disconnectors added are shown in table 14. By adding 2 disconnectors between the double circuit breakers and the lines the active fault frequency will be increased with 2 times the fault probability for the disconnectors. Also passive faults, stock condition faults and overlapping faults are increased. The total increase, in faults that disconnect a single incoming line in this example is approximately 13 % compared to the previous simulation.

Table 14: Fault frequency per 100 years for DB Disc. [faults / 100 years]

	Total	Active	Passive	Stuck	Multiple fault
T7	3.45	2.8	0.51	0.10	0.04
T2	3.45	2.8	0.51	0.10	0.04
T3	3.43	2.8	0.51	0.09	0.04
Line 1	63.89	62.40	0.51	0.61	0.36
Line 2	63.89	62.40	0.51	0.61	0.36
Line 3	63.91	62.40	0.51	0.63	0.36
Line 4	63.91	62.40	0.51	0.63	0.36

8.3.4 Two-breaker arrangement with T7 Connected to both Double Busbars.

Table 15 shows that also the fault frequence for T7 increase when T7 is connected to both double busbar pairs.

Table 15: Fault frequency per 100 years for DB T7 [faults / 100 years]

	Total	Active	Passive	Stuck	Multiple fault
T7	5.56	4.40	0.96	0.13	0.04
T2	3.01	2.40	0.48	0.10	0.04
T3	2.99	2.40	0.48	0.09	0.04
Line 1	63.43	62.00	0.48	0.64	0.36
Line 2	63.43	62.00	0.48	0.64	0.36
Line 3	63.44	62.00	0.48	0.64	0.36
Line 4	63.44	62.00	0.48	0.64	0.36

8.3.5 Two-breaker arrangement with 5 Outgoing Lines

Table 16 shows that the fault frequency for faults that disconnects incoming or outgoing lines only was slightly affected by adding one extra line. The increase in fault rate for T3 was only 0.02 faults per 100 years which was caused by stuck condition events.

Table 16: Fault frequency per 100 years for DB 5L [faults / 100 years]

	Total	Active	Passive	Stuck	Multiple fault
T7	3.02	2.40	0.48	0.10	0.04
T2	3.02	2.40	0.48	0.10	0.04
T3	3.02	2.40	0.48	0.10	0.04
Line 1	63.56	62.00	0.48	0.64	0.43
Line 2	63.56	62.00	0.48	0.64	0.43
Line 3	63.56	62.00	0.48	0.64	0.43
Line 4	63.56	62.00	0.48	0.64	0.43
Line 5	63.56	62.00	0.48	0.64	0.43

8.4 Comparison of the Unavailability due to Faults

Figure 11 shows a summary of the unavailability in the different configurations. The line T3 has been used as a reference but the difference in unavailability between the lines has been shown to be small and the graph is for that case considered to be representative for any incoming line. The existing substation has the longest unavailability if the switching option is neglected. However, if the switching option is used, the existing substation has actually lower expected unavailability due to faults compared to the suggested two-breaker arrangement designs without disconnectors. If disconnectors was added to the suggested two-breaker arrangement design, the unavailability was instead lower for the two-breaker arrangement design compared to the existing substation.

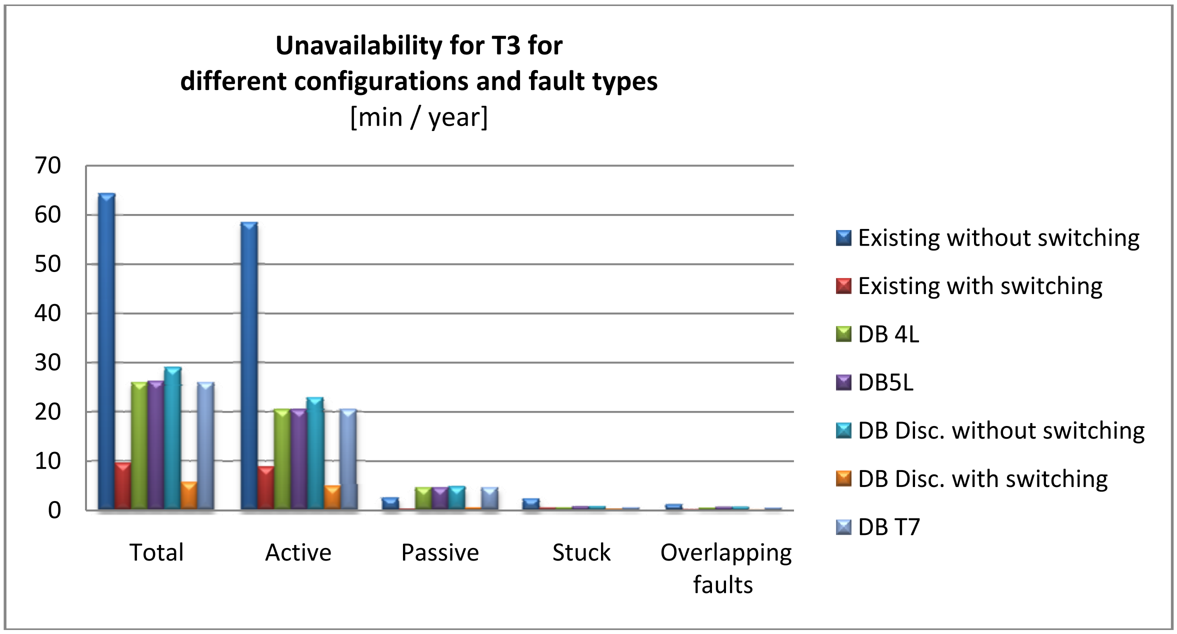

Figure 11: Unavailability for T3 for different configurations and fault types

Figure 12 shows that the expected number of faults that disconnect T3 was more than 3 times as high for the existing substation compared to the two-breaker arrangement designs. The existing substation has a lower unavailability caused by unintended operations of circuit breakers but a higher unavailability caused by stuck condition and overlapping faults compared to the two-breaker arrangement designs.

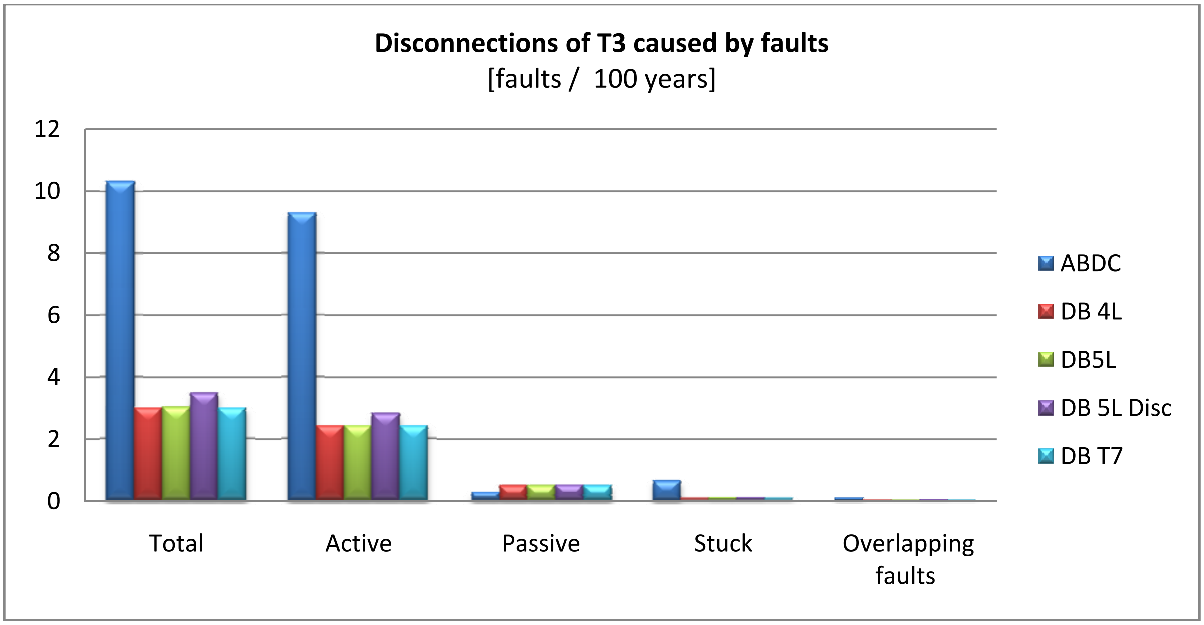

Figure 12: Faults per 100 years that leads to unavailability for T3

9. Sensitivity Analysis

9.1 Unavailability Sensitivity

Figure 13 shows what happens to the unavailability caused by faults if one of the fault probabilities for the devices is raised 10 times. The existing substation and the two-breaker arrangement with disconnectors had the lowest unavailability for all cases except for one case. If the fault probability for the disconnectors was the same or higher as the fault probability for circuit breakers and the two devices were assumed to have the same repair times, then the two-breaker arrangement without disconnectors was preferable from a fault unavailability point of view. The graph also shows that the model was most sensitive to the fault probabilities assumption for circuit breakers, disconnectors and the fault probability for the line itself.

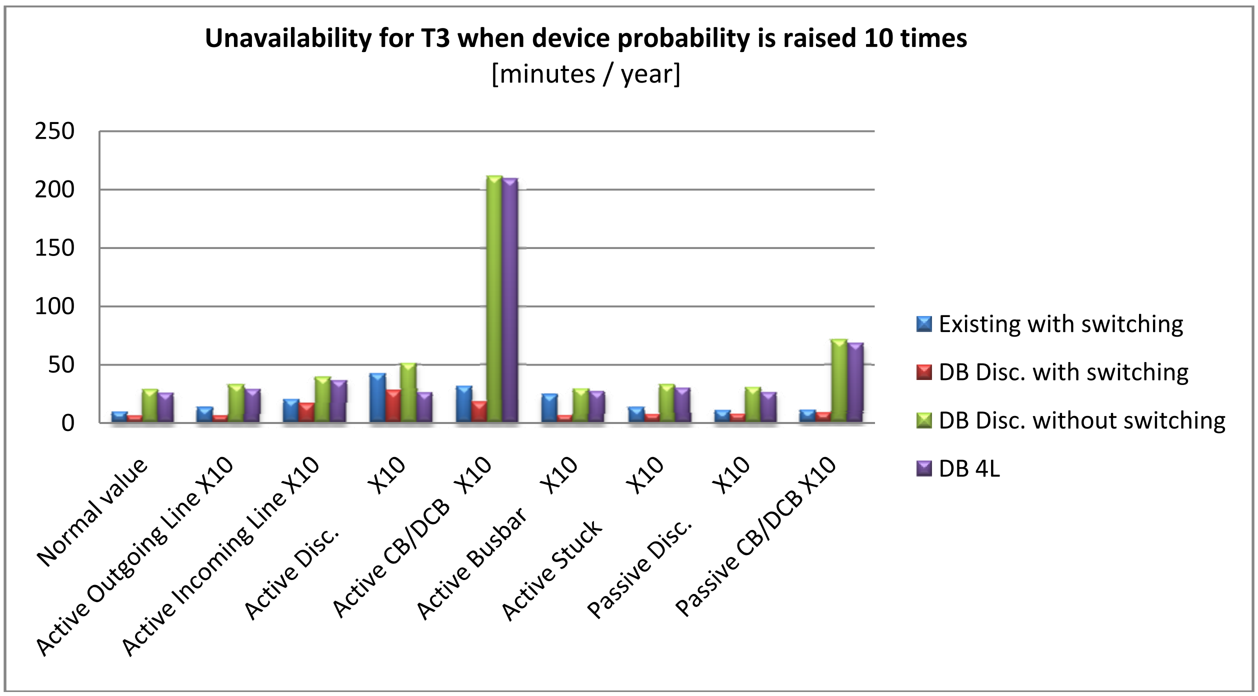

Figure 13: Unavailability for T3 when device probability is raised 10 times

Figure 14 shows what happens to the unavailability caused by faults if one of the fault probabilities for the devices is lowered 10 times. The existing substation and the two-breaker arrangement with disconnectors was found to have the lowest unavailability in all cases.

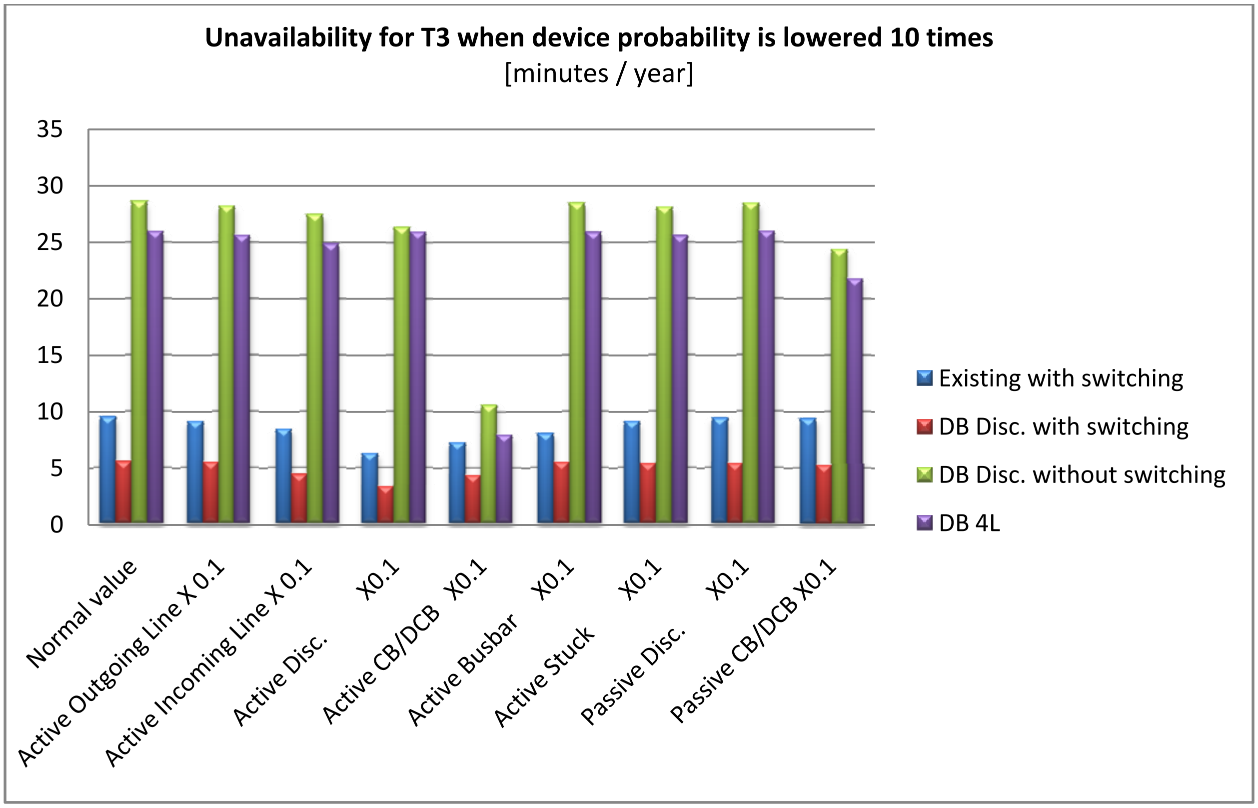

Figure 14: Unavailability for T3 when device probability is lowered 10 times

9.2 Fault Frequency Sensitivity

Figure 15 shiows that the fault frequency was higher for the existing substation no matter which probability that was reduced. The input assumptions that the fault frequency was most sensitive to were the same as stated for the unavailability.

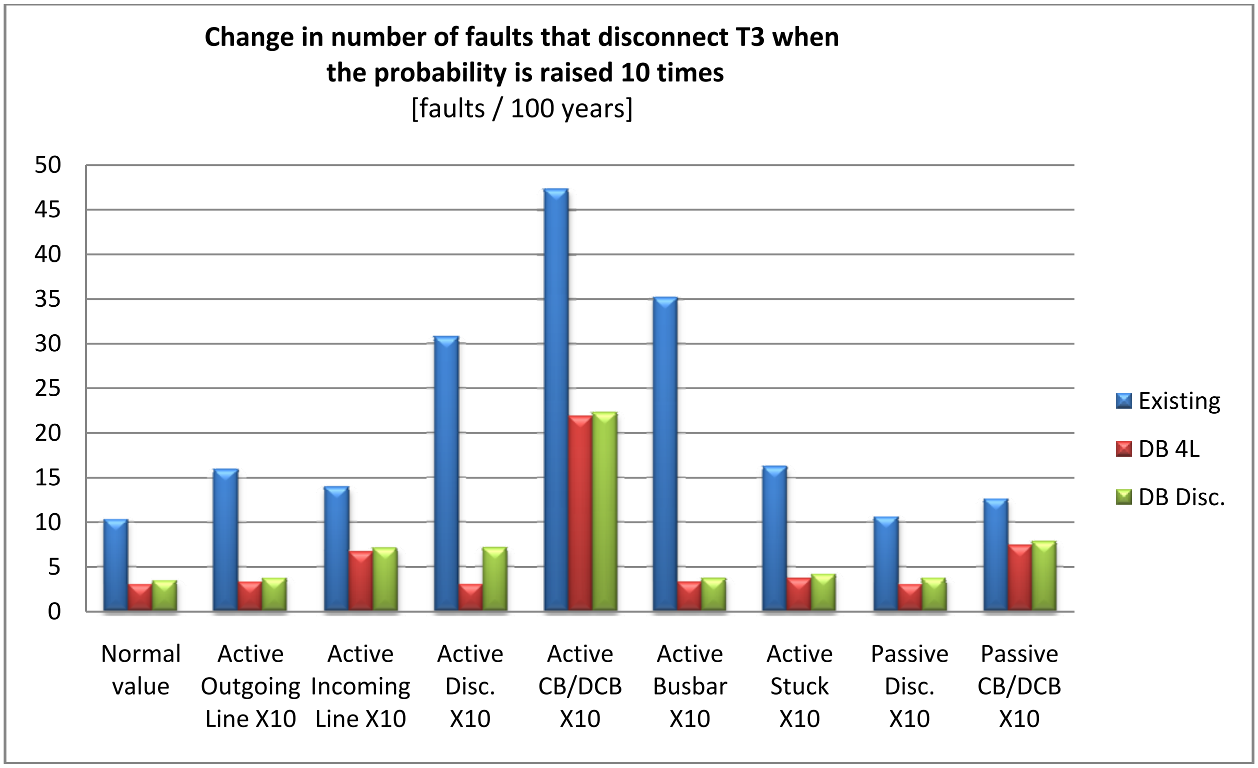

Figure 15: Change in number of faults that disconnects T3 when the probability is raised 10 times

Figure 16 shows what happened to the expected disconnection frequency for a single line when one of the devices probability was lowered with a factor of ten. The graph supports the same conclusions made for the previous graph.

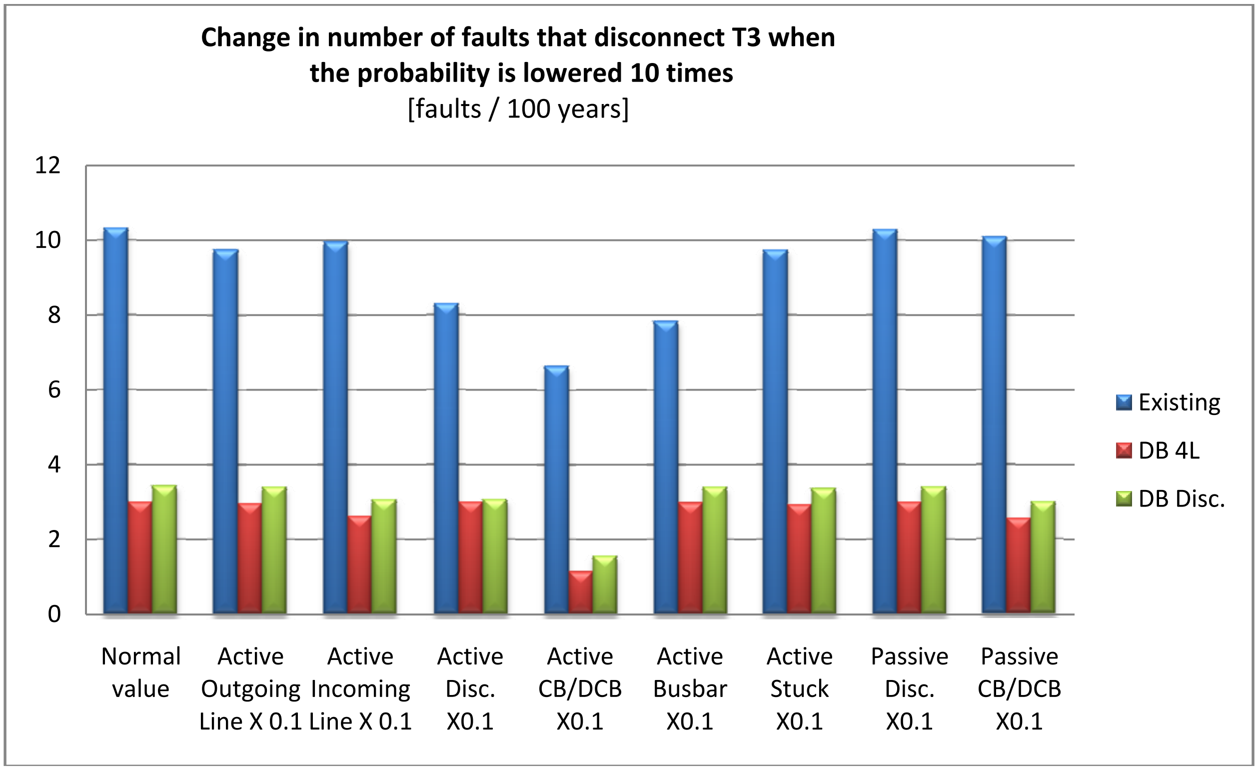

Figure 16: Change in number of faults that disconnect T3 when the probability is lowered 10 times

10. Comparison with Results from Other Studies.

Table 17 shows the results obtained in other reliability studies. The simulated configurations differs somewhat in number of devices connected, techniques used to calculate the unavailability and which switching options that is available, but they are still considered to be useful for comparison reason. Most fault frequencies for the single breaker configuration is between 0.22 to 0.35 faults per year which is a surprisingly narrow range considering the large differences in input assumptions. The fault frequency for loss of one outgoing line in the existing substation was in this study approximately 0.1 faults per year which is a little bit below the results in the other studies. The calculated unavailability for the single breaker design is within the range of the unavailability found in the other studies. Only a few of the other studies had results for the two-breaker arrangement designs. The resulting fault frequency varies between 0.00572 and 0.28 faults per year which is a rather wide spread of results. The results of this study ends up somewhere in the middle of this range. The calculated unavailability in the different studies for the two-breaker arrangement is more consistent and range between 0.72 and 17.8 minutes per year. The results of this study ends up within this range when disconnectors are used and a little over the range for the two-breaker arrangement design without disconnectors. To note is the results from the study "Karlsson et al 1997" that was done by people working on ABB, Svenska Kraftnät and Swedish Transmission Research Institute which has results of the unavailability that are comparable to the results in this study.

Table 17: Comparison between obtained results and results obtained in other studies

	Single Breaker		**Two-breaker arrangement**	
	Fault frequency (f/yr)	Unavilability (min/yr)	Fault frequency (f/yr)	Unavilability (min/yr)
ABB	-	196 (without switching) 8.4 (with switching)	-	-
Nyberg 2003	-	-	-	-
Dortolina et. al. 1991	-	-	-	-
Billinton & Lian 1991	0.22	15	-	-
Meeuwsen & Kling 1997	0.35	60 (without.switching) ~4 (with switching)	0.28	Approximately 2
Karlsson et al 1997	-	72	-	17.8
Brown & Taylor 1999	0.29	41.46	-	-
Atanackovic et al 1999	-	-	-	-
Xu et al 2002	-	-	-	-
Tsao & Chang 2003	0.0459	3.5	0.00572	0.72
Suwantawat & Premrudeepreechacham 2004	0.33	427.2	-	-
Retterah et al 2004	0.22	19.5	0.033	8.8
Billinton & Yang 2005	-	-	-	-
Bezhadi Rafi et al 2006	-	-	-	-
Sidiropoulos 2007	-	-	-	-
Banejad et al 2008	-	-	0.0018	2.52
This study	0.1	51-65 (without switching) 8-10 (with switching)	0.03-0.035	26 (without switching) 5.5 (with switching)

11. Maintenance of Substation Equipment

This chapter starts with a short background theory of maintenance and then continues with a description of Svenska Kraftnät's policy for maintenance. In the end of the chapter are the assumptions and the results for the unavailability due to maintenance given.

11.1 Different Types of Maintenance

Maintenance of substation equipment (Lai et al 1997) can generally be divided into three categories

- corrective maintenance,
- preventive maintenance
- predictive maintenance.

Corrective maintenance means that no maintenance is performed until the device fails or in some other way fail to perform its intended operations. *Preventive maintenance* is performed on a regular basis to extend the expected life time of the devices and reduce the likelihood of faults. *Predictive maintenance* means that maintenance will be done based on an evaluation of the devices condition.

11.2 Maintenance of Disconnectors

The general trend, concerning disconnectors, is that Svenska Kraftnät has moved from a preventive maintenance strategy with periodic maintenance towards a predictive maintenance strategy where maintenance only is done when it has been found necessary after inspection of the disconnectors. The maintenance of the disconnectors is done according to Svenska Kraftnäts maintenance plan (Svensk Kraftnät 2004) which describes four types of inspections

- routine inspection
- specific inspection
- thermographic control and
- function control of the disconnectors.

A routine inspection consists of a general check of the whole substation and is according to the maintenance plan performed with 3 months intervals in substations where the circuit breaker is of the type oil minimum or SF6. During the routine examination the examiner uses sight, smell, hearing and feeling and simpler measurements, but the equipment is normally not taken out of service.

Specific inspection of the disconnectors should be done with 2 year intervals with the disconnectors remaining in service. The purpose is to determine the connector's physical condition and is more comprehensive tests than the routine examination. It seeks to identify any noticeable corrosion, deterioration or damage.

Thermographic control of the disconnectors should be done with 1 year intervals while the disconnectors remain in service. The purpose with the thermal tests is to determine if the device overheats during normal operation (Willis 2000). Overheating can be caused either by internal faults in the device or by a decrease in the device ability to cool itself. Heat is one of the major causes of early deterioration of electrical equipment and reduces the expected life length of the device and can increase the likelihood for failures.

Function control of disconnectors is only done in special cases where inspection is not considered enough. The time that the test should take is said to be one day. (Svenska Kraftnät 2004). This is a type of mechanical test whose purpose is to see that the disconnector function correctly. An example of test that can be done is to make sure that the moving parts of the device move with the speed and smoothness that can be expected of the device.

11.3 Maintenance of Circuit Breakers

The maintenance routine for minimum oil circuit breaker is similar to that of disconnectors and is performed with approximately the same time intervals. The maintenance program that Svenska Kraftnät has established for their minimum oil circuit breakers 130-400 kV can be seen below.

Type of examination	***Interval***
Routine inspection	3 months
Specific inspection	2 years
Thermographing	1 year
Function control	6 years or after 1000 operations
- Function control time:	1.5 days

The disconnecting circuit breakers sold by ABB are based (ABB 2007) on the same technology as their circuit breakers LTB D and HPL B which follows the same inspection program as the existing oil minimum circuit breakers stated above. The planned unavailability will be the same as the scheduled plan for function control, which means that the circuit breaker will be unavailable every 6th year for 1.5 days.

11.4 Maintenance of Protection System.

The redundant protection of the relays in Simpevarp are checked with 4 year intervals. Protections for section bays and busbars are tested with 4 year intervals. In this thesis the tests of the protections are assumed to occur during the planned outage for the different generators at Simpevarp and the testing of the relays are for this reason assumed to not cause any additional unavailability.

11.5 Maintenance Frequency and Duration

Table 18 shows the maintenance frequency assumption used in other studies. Most of the studies has been concentrated on calculating the unavailability due to faults and have for that reason not given any assumptions of maintenance frequency. This study has based its calculation of unavailability on the assumptions given by ABB. The maintenance frequency for circuit breakers given by ABB seems, however, low compared to the assumptions in other studies and the reader should keep this in mind when interpreting the results of this study.

Table 18: Maintenance frequency [times/year]

	Line	Discon-nector	Circuit Breaker	Busbar
ABB	0.00004	0.2	0.067	0
Nyberg 2003	-	0.167	0.167	0
Dortolina et. al. 1991	0	0	0.3	0.34
Billinton & Lian 1991	-	-	0.1	-
Meeuwsen & Kling 1997	-	-	-	-
Karlsson et al 1997	-	-	0.17	-
Brown & Taylor 1999	0.2	0.5	0.2	-
Atanackovic et al 1999	-	-	0.016 (315 kV) 0.017 (500 kV)	-
Xu et al 2002	-	-	-	-
Tsao & Chang 2003	0.5	-	1.0	0.5
Suwantawat & Premrudeepreechacham 2004	0.04	-	0.1	-
Retterah et al 2004	-	-	-	-
Billinton & Yang 2005	-	-	0.2	-
Bezhadi Rafi et al 2006	-	-	-	-
Sidiropoulos 2007	-	-	-	-
Banejad et al 2008	-	-	-	-
This study	0	0.2	0.067	0

Table 19 shows the maintenance frequency assumption used in other studies.

Table 19: Maintenance duration [hours]

	Line	Discon-nectors	Circuit Breaker	Busbar
ABB	48	8	32	0
Nyberg 2003	-	8	8	0
Dortolina et. al. 1991	0	0	24	8
Billinton & Lian 1991	-	-	5	-
Meeuwsen & Kling 1997	-	-	-	-
Karlsson et al 1997	-	-	8	-
Brown & Taylor 1999	50	4	8	-
Atanackovic et al 1999	-	-	-	-
Xu et al 2002	-	-	-	-
Tsao & Chang 2003	8	-	96	8
Suwantawat & Premrudeepreechacham 2004	4	-	4	-
Retterah et al 2004	-	-	-	-
Billinton & Yang 2005	-	-	108	-
Bezhadi Rafi et al 2006	-	-	-	-
Sidiropoulos 2007	-	-	-	-
Banejad et al 2008	-	-	-	-
This study	0	8	32	0

11.6 Unavailability Due to Maintenance

The unavailability for the power lines can easily be calculated by first calculating the unavailability for circuit breakers and disconnectors and then analyse which cases that will cause unavailability for the power lines. The formula below calculates the expected unavailability due to maintenance for circuit breakers.

$$U_{m,CB/DCB} = \lambda_{m.CB/DCB.} \cdot MTTM_{CB/DCB.} = 0.067 * 32 = 2.14\ h/year$$

The same calculation for disconnectors is shown below. To note is that the circuit breaker has a larger average unavailability due to maintenance than disconnectors when ABBs assumptions are used.

$$U_{m,disc.} = \lambda_{m.disc.} \cdot MTTM_{disc.} = 0.2 * 8 = 1.6\ h/year$$

Where

$U_{m,device}$ =*expected unavailability per year for the device due to maintenance*
$\lambda_{m.device} = mainteance\ rate\ per\ year\ for\ the\ device$
$MTTM_{device.} = mean\ time\ required\ to\ maintain\ the\ device\ during\ each\ time$

The resulting unavailability for the power lines due to maintenance of disconnectors and circuit breakers are shown in table 20.

Table 20: Unavailability due to maintenance for the simulated substation designs. [minutes / year]

	Existing without switching	Existing with switching	DB 4L	DB 4L Disc. without switching	DB 4L Disc. with switching	DB 4L T7	DB 5L
T7	320	192	256	448	192	256	256
T2	320	192	256	448	192	256	256
T3	320	192	256	448	192	256	256
Line 1	320	192	256	448	192	256	256
Line 2	320	192	256	448	192	256	256
Line 3	320	192	256	448	192	256	256
Line 4	320	192	256	448	192	256	256
Line 5	-	-	-		-	-	256

11.7 Interruptions on Power Lines Caused by Maintenance

For each line in the existing substation and for the two-breaker arrangement design with disconnectors there are two disconnectors that cause unavailability for the line during maintenance. Each disconnector has a maintenance rate of 0.2 times which yields 0.4 interruptions on the power line per year due to maintenance.. For the other two-breaker arrangement designs there are two disconnecting circuit breakers connected to the line which causes unavailability due to maintenance. The assumed average maintenance rate for the disconnecting circuit breaker is 0.067 times per year which gives an average of 0.134 interruptions per year for the power lines due to maintenance.

Table 21: Number of interruptions due to maintenance. [disconnections /year]

	Existing	DB 4L	DB 4L Disc.	DB 4L T7	DB 5L
T7	0.40	0.13	0.40	0.13	0.13
T2	0.40	0.13	0.40	0.13	0.13
T3	0.40	0.13	0.40	0.13	0.13
Line 1	0.40	0.13	0.40	0.13	0.13
Line 2	0.40	0.13	0.40	0.13	0.13
Line 3	0.40	0.13	0.40	0.13	0.13
Line 4	0.40	0.13	0.40	0.13	0.13
Line 5	-	-	-	-	0.13

12. Cost Calculations

This chapter first show the general formula used for life cycle calculations. The chapter then continues with a description of how the costs in the formula were calculated and in the end the result of the cost calculations is given.

12.1 Life Cycle Costs

The lifecycle costs show the present value of the expected costs during the substations life time. It is calculated (Karlsson et al. 1997) as the present value of the expected cash flows due to investment costs, operating costs, maintenance costs, costs caused by failure and demolition costs.

$$LCC = CI + CO + CM + CF + CD$$

Where

$LCC \ = Life\ cycle\ costs$
$CI \quad = Investment\ costs$
$CO \quad = Operating\ costs$
$CM \ = Maintenance\ costs$
$CF \quad = Outage\ costs$
$CD \ = Demolition\ costs$

Some of these costs can be hard to estimate and this thesis will for this reason do a simplified life cycle cost analysis that only considers the costs that differs between the different substation designs.

One important concept when calculating the life cycle costs is the present value, PV, which shows the value today of the expected future cash flows due to costs given a certain discount rate. The present value of the future cost cash flows has been calculated with an expected life length for the substation of 40 years and a discount rate r that has been assumed to be 6 %. The discount rate for the company´s investments should equal the company´s weighted average cost of capital, WACC, that considers both the company's cost of debt and cost of equity. The formula used to calculate PV is shown below.

$$PV = \sum_{t=1}^{40} \frac{CashF_t}{(1 + \mathrm{r})^{\mathrm{t}}}$$

Where

$PV \qquad = present\ value\ of\ future\ cash\ flows\ due\ to\ costs$
$CashF_t = cash\ flow\ due\ to\ costs\ year\ t$
$t \qquad\ = the\ number\ of\ the\ year\ counting\ from\ when\ the\ first\ cash\ outflow\ occurs$
$r \qquad\ = the\ discount\ rate$

$PV = nuvärdet\ av\ framtida\ kassaflöden$
$CashF_t = kassaflöde\ år\ t$
$t\ = årtal\ räknat\ från\ året\ med\ första\ kassautflödet$
$r\ = diskonteringsränta$

12.2 Calculating Investment Costs

The investment costs was calculated as

$$CI = \sum_{i=1}^{n} NrD_i \cdot CostD_i$$

Where

$NrD_i = Number\ of\ devices\ of\ type\ i$
$CostD_i\ = Cost\ of\ device\ i\ in\ SEK$

The costs for disconnectors, circuit breakers and disconnecting circuit breakers were given by ABB. The price for the circuit breaker DCB HPL420 is 1,500,000 SEK and the price for a circuit breaker without disconnecting function HPL420 is 1,200,000 SEK. The bus lines was assumed to be 100 meter long and have the same costs per km as 400 kV overhead lines, which has been assumed to have a cost of 3.5 to 4.5 million SEK per kilometer. This results in a cost per bus line of 400,000 SEK. The cost per bay excluding disconnectors, circuit breakers, DCBs and bus lines has been assumed to be 15,000,000 SEK per bay. This should be seen as a rough estimation. The numbers of devices and the cost per device is shown in table 22.

Table 22: Number of items in the substations and estimated costs for each item

	Item	**Number of items**					**Costs per item [million SEK]**
	NrD_i	**Existing**	**DB 4L**	**DB 4L Disc.**	**DB 4L T7**	**DB 5L**	$CostD_i$
i=1	Disconnectors	39	0	18	0	0	0.25
i=2	HPL420	10	0	18	0	0	1.2
i=3	DCB HPL420	0	18	0	20	20	1.5
i=4	Installed bays (costs exludes i=1,2,3)	10	9	9	10	10	15
i=5	Bus lines	0	1	1	2	1	0.4

12.3 Operating Costs

The operating costs (Politano & Fröhlich 2006) can consist of

- Electrical losses

- Replacement part storage
- Taxes due to environmental issues
- Monitoring
- Personal costs
- Other fix run costs

The operating costs will be assumed to be the same for all substation designs and will not be considered. An earlier work that studied the reliability and life cycle costs (Karlsson et al. 1997) in the Swedish 400 kV grid found that the present value of the operating and maintenance costs together equaled approximately 25 % of the initial investment costs in that study.

12.4 Maintenance Costs

The maintenance costs (Politano & Fröhlich 2006) consist of

- Time based maintenance costs
- Condition based maintenance costs
- Opportunity costs caused by maintenance
- Repair costs

The time based maintenance is the labor costs for the scheduled control and maintenance. This should be approximately the same for all substation alternatives. An estimation of the costs based on Svenska Kraftnäts maintenance plan is estimated to be 20,000 to 30,000 SEK per year assuming the cost per working hour to be 600 SEK.

The condition based maintenance costs is the labor costs for maintenance of the devices. These costs are assumed to be low compared to the other costs and have been neglected.

12.4.1 Opportunity Costs

The major costs due to maintenance consist of the opportunity costs that come from the loss of revenues due to undelivered power during the maintenance. The opportunity costs are calculated by multiplying the amount of undelivered power in MWh with the profit per MWh. Where the profit is calculated as the revenue per MWh minus the variable costs per MWh.

$$\text{Total opportunity cost} = \left(\frac{\text{revenues}}{\text{delivered MWh}} - \frac{\text{variable costs}}{\text{delivered MWh}}\right) \cdot (\text{Undelivered power in MWh})$$

The market price for electricity for the consumer is at the moment according to E.ON's homepage 0.7966 SEK/kWh (2008-10-21) or 796.6 SEK/MWh. The variable costs for OKG have been assumed to only consist of the fuel costs which on average was 20 SEK/MWh according to table 23. The opportunity costs used in this thesis will be assumed to be 775 SEK/MWh.

Table 23: Calculation of average revenues and average fuel costs for OKG

Year	2003	2004	2005	2006	2007	Average
Power delivered [GWh]	13 791	17 481	16 567	15 736	15 398	**15 795**
Fuel costs [Million SEK]	267	390	355	266	300	**316**
Average fuel costs [SEK/MWh]	19	22	21	17	19	**20**

The undelivered power per incoming line was calculated by multiplying the unavailability in hours per year for each incoming line with the expected amount of delivered power for each incoming line after the upgrade of O2 and O3. The expected delivered power from each generator is given in table 24.

Table 24: Power output from the generators at OKG after the upgrade of O2 and O3.

Generator	Power output [MW]
O1	491
O2	840
O3	1450

The total undelivered power was calculated as the sum of the undelivered power on T2 and T3. To note is that the loss of one outgoing line has been assumed not to cause any limitation for the amount of power that can be delivered from OKG. Furthermore, the loss of two outgoing lines can reduce the amount of power that can be delivered but this has a relative low probability and the unavailability on outgoing lines has for this reason been assumed not to cause any power delivery limitations at all for OKG.

In addition to the calculated unavailability due to maintenance, each maintenance that cause disconnection of the incoming line to T2 or T3 has been assumed to cause an additional unavailability of 1 hour. This is assumed to be the time it takes to startup the generator and get it back to normal operation.

12.4.2 Repair costs

One study (Heising 1994) found that the value of the spare parts used for repair per circuit breaker, 300-499 kV, was on average equal to the value of 8 man hours of work per year. Assuming a cost per man hour of 600 SEK this would equal 4800 SEK per breaker. No information has been found on repair costs for disconnectors, but because they are simpler devices with a lower failing frequency and have a lower price than circuit breakers the repair costs per disconnector will be assumed to be only half of the value assumed for circuit breakers, that is 2400 SEK per disconnector and year. Spare parts to other equipment will be neglected and are not believed to cause large cost differences for the different configurations. This calculation is of course only rough estimations. The estimated costs for repair for the different substation designs are shown in table 25. These results are uncertain but they indicate that repair costs can have a significant impact on the total costs and that there can be large variations for different substation designs. The table shows that the expected repair costs will be higher in the substation designs with a larger number of equipments that can fail.

Table 25: Rough estimation of repair costs [SEK]

	Existing	DB 4L	DB 4L Disc.	DB 4L T7	DB 5L
Disconnectors	93,600	0	43,200	0	0
Circuit breakers	48,000	86,400	86,400	96,000	96,000
SUM	141,600	86,400	129,600	96,000	96,000

12.5 Costs due to Faults

The costs (Politano & Fröhlich 2006) that arise because of faults can consist of

- Penalty costs
- Opportunity costs due to faults

The penalties consist of money that OKG has to pay if they fail to deliver a certain amount of energy to the grid but these short interruption caused by fault in the substation will not trigger any penalty costs. The calculated unavailability for the incoming lines cannot be taken directly to calculate the opportunity costs due to faults. This unavailability only considers the time it take to fix the devices that caused the faults and there will be an additional time to this to startup the generators and solve other issues that may have arised with the faults. Experience of earlier faults has shown that it on average can take about 24 hours after a fault has occurred that disconnect the incoming line connected to the power transformer. For this reason has the opportunity costs due to faults been considered to only be dependent on the fault frequency that disconnect the incoming lines and not dependent on the expected unavailability. Each fault that disconnect either the line to T2 or T3 has been assumed to cause 24 hours of unavailability on that line. To note is that O1 is assumed to be able to deliver its power through the 130 kV substation and a loss of the line to T7 will for this reason not cause any power delivery limitations. The formula that was used to calculate the undelivered power is shown below.

$$\text{Undelivered power for line x per year} = f_{line\ x} \cdot 24 \cdot NormDel_{line\ x}$$

Where
$f_{line\ x} = number\ of\ faults\ per\ year\ that\ disconnect\ line\ x$
$NormDel_{line\ x} = Normal\ amount\ of\ delivered\ power\ on\ line\ x$

12.6 Summary of Simplified LCC

The results of the simplified LCC are shown in table 26. The net present value of the future costs is found to be approximately 26 million SEK less for the two-breaker arrangement design with disconnectors compared to the same design, DB 4L, without separate disconnectors. However, the reduction of costs comes from the lower calculated maintenance costs and this cost item are rather uncertain. This will be further discussed in next chapter.

Table 26: Summary of simplified LCC

Present value of life cycle costs [million SEK]*					
	Existing substation	**DB 4L**	**DB Disc.**	**DB T7**	**DB 5L**
CI	171.75	162.40	161.50	180.80	180.40
CO	0	0	0	0	0
CM	85.45	113.99	85.45	113.99	113.99
CF	64.35	20.57	24.00	20.74	20.83
Total cost	321.55	296.96	270.95	315.53	315.22

* Only items that differ between the substation designs have been considered

13. Discussion of Results

13.1 Discussion of Expected Unavailability due to Faults and Maintenance

Three aspects are of major importance when discussing the unavailability. First, how much the unavailability differs between the different substations designs and second, how much of the unavailability is caused by faults and how much is caused by maintenance. The third aspect concerns under which circumstances the unavailability results of this study is valid.

Figure 17 shows a summary of the unavailability results. The graph shows that both the unavailability due to maintenance and due to faults is lower with the substation designs that have disconnectors connected to the incoming and outgoing power lines.

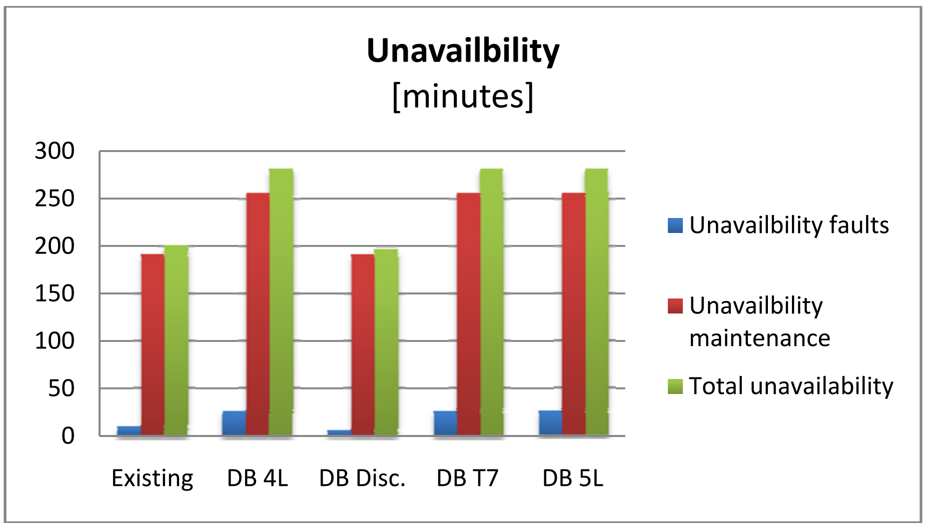

Figure 17: Comparison of unavailability due to faults and due to maintenance

For the unavailability caused by maintenance there is in many cases a large flexibility concerning when the maintenance should be performed. This makes it possible to do the maintenance during the time where the generators have planned outage due to inspection. This type of planned maintenance will not cause any additional unavailability for the power lines. There is, however, some maintenance that cannot be planned and that cannot wait until the next planned outage period for the generators. This unplanned maintenance occurs after a device after an inspection has been found to be in a high fault risk condition. The longer time that the equipment is in service in a high fault risk condition, the higher is the probability that the device will cause a fault. Hence, to decrease the probability for a fault there are three important factors that are vital

- the time it takes between a high risk fault condition arise until the equipment is inspected
- that the high risk fault condition is discovered during the inspection
- the time it takes between the high risk condition is discovered until the equipment is taken out of service for repair.

The ability to identify the condition of the disconnector is largely dependent on the inspectors experience and judgment. The inspectors' ability to determine the condition of the substation devices is for this reason a vital factor to reduce the risk for faults. However, the inspectors are normally working after some bureaucratic principles and it is normally the owner of the substation that takes the final decision if the device should be repaired or taken out of service. Hence, the bureaucratic decision process that follows after the inspectors have inspected the device also becomes a vital factor to reduce the risk for faults. The point in this discussion is that the unavailability for OKG to a large extent can be dependent on Svenska Kraftnät's routines of maintenance. This thesis does, however, not give a clear answer to how much of the unavailability that is caused by unplanned maintenance.

According to the sensitivity analysis the unavailability is most sensitive to the input assumptions for the circuit breakers, the busbars and the disconnectors. The sensitivity analysis also showed that the two-breaker arrangement gave lower unavailability as long as the expected unavailability for the disconnectors was lower than the expected unavailability for circuit breakers. Even if there is an uncertainty of the most appropriate fault frequency and repair time to use, the input assumptions used in other studies and the results from statistical databases indicates that the unavailability will be lower for disconnectors than for circuit breakers. For this reason is the unavailability believed to be significantly lower in the two-breaker arrangement design with disconnectors compared to the same design without separate disconnectors.

If the bays connected to the outgoing lines includes both separate disconnectors and breakers or only disconnecting circuit breakers is not believed to have a large impact on OKGs ability to deliver its power. This is statement is considered to be true as long as the loss of one outgoing line does not cause any power delivery limitations for OKG.

13.2 Discussion of Fault and Maintenance Frequencies

Figure 18 shows that the number of expected interruptions for T3, both due to maintenance and due to faults, is highest for the existing substation. The two-breaker arrangement design with disconnectors has a slightly higher number of interruptions per 100 years due to faults and a considerably higher interruption rate due to maintenance. However, the maintenance can in many cases, as been stated earlier, be done during planned outage for the generators and will in that case not cause any additional interruptions. Furthermore, the interruption rate for the disconnecting circuit breaker is based on the assumptions of ABB and is considered to be underestimated. For this reason is the real interruption rate for the two-breaker arrangement design believed to be only slightly higher than for the same design without disconnectors.

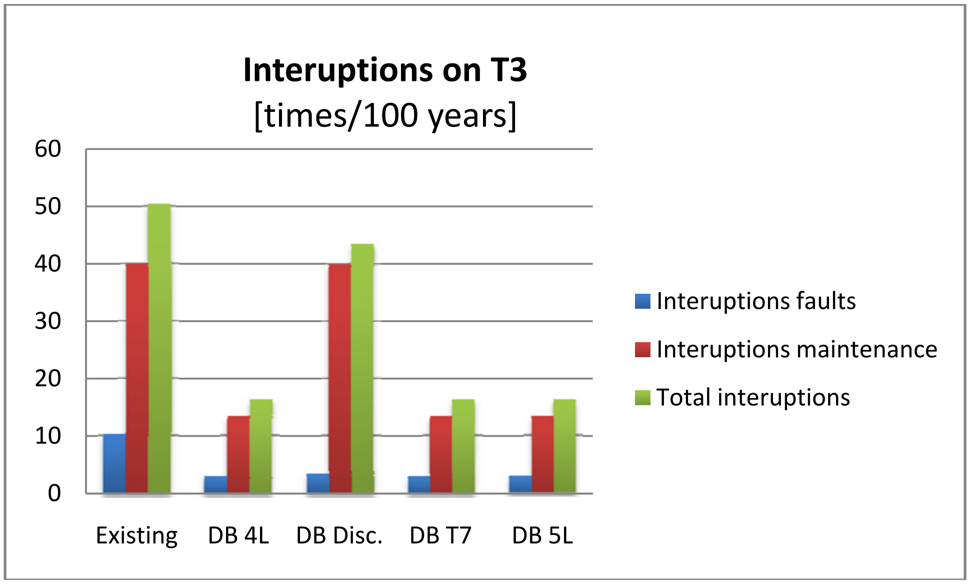

Figure 18: Comparison of interruption frequencies caused by maintenance and faults

13.3 Discussion of Costs

The simplified LCC showed that the two-breaker arrangement design under the given input assumption gives the lowest life cycle costs. However, if the maintenance costs are excluded the the two-breaker arrangement without disconnectors has the lowest present value of costs but the relative difference is small. The best alternative to choose is for this reason dependent on the assumptions made for the unavailability caused by maintenance.

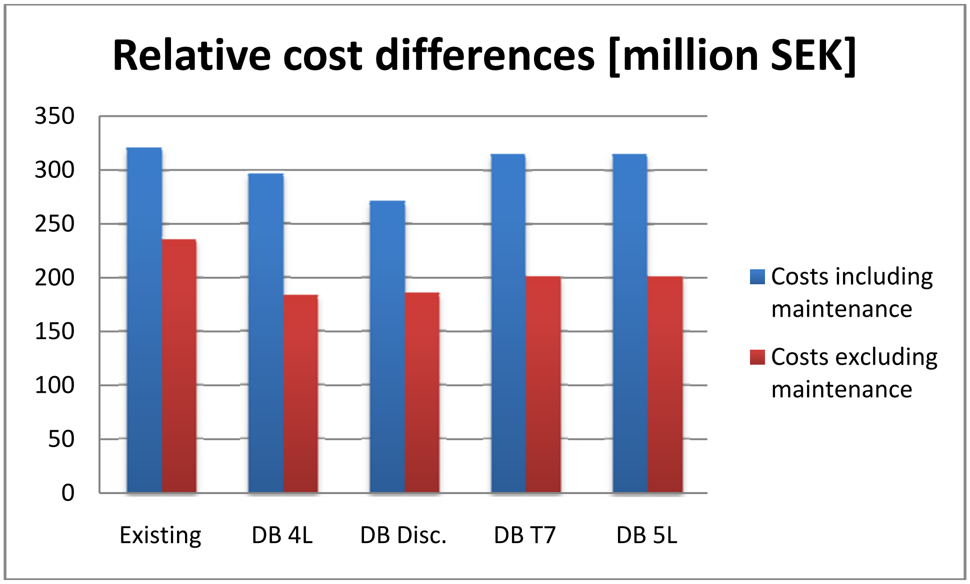

Figure 19: Comparison of costs both including and excluding the costs of maintenance.

14. Conclusions

The results of this thesis shows that the proposed substation with two-breaker arrangement is expected to have a higher unavailability compared to the existing substation. However, if the two-breaker arrangement design instead is build with disconnectors the unavailability is expected to be lower for the two-breaker arrangement compared to the existing substation.

This thesis shows that the expected unavailability due to faults is low and that the unavailability due to maintenance is likely to be higher. The unavailability for OKG on the incoming power lines may for this reason be strongly dependent on Svenska Kraftnäts decision of when and how to do maintenance on the devices that are closest connected to the incoming power lines.

The total number of interruptions on the incoming lines due to faults was found to decrease considerably in all simulated variations of the two-breaker arrangement designs compared to the simulation of the existing substation. The number of average faults per year for the incoming lines was found to be slightly higher for the two-breaker arrangement design with disconnectors compared to the two-breaker arrangement designs without disconnectors.

The sensitivity analysis showed that the two-breaker arrangement design with disconnectors gave the lowest unavailability in all cases except one if the fault probability was raised or lowered with a factor of ten. The probability that switched the order of the simulation results was the fault probability used for disconnectors.

This thesis finds that it is rather the numbers of disconnection of the line in the transformer bay that decides the costs than the calculated unavailability of the line. In the cost analysis the two-breaker arrangement with disconnectors was found to be the best alternative if the cost of maintenance was included. If the cost of maintenance was excluded the two-breaker arrangement was found to have the lowest costs but the difference between the two-breaker arrangement with and without disconnectors was small. For this reason is the costs of maintenance believed to be the critical costs that determines which substation design that are the most beneficial from an economic point of view.

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17. Appendices

17.1 Screenshot from the developed java program