Applications of High Voltage Circuit-Breakers and Development of Aging Models

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Phuwanart Choonhapran

Contents

1 Introduction

1.1 Motivation

Due to the deregulation of electricity markets, reliability, stability and availability of power systems must be improved in order to increase the competitiveness of electricity markets. In order to improve such aspects, power systems should be operated with minimal abnormal conditions and those conditions must be cleared as soon as possible. Therefore, HV circuit-breakers, designed to interrupt faulted conditions, have played an important role in power systems over 100 years since the first introduction of oil circuit-breakers.

Although the technology of an interrupting medium used in HV circuit-breakers has not been considerably changed since the introduction of SF_6 circuit-breakers in 1960s, the development and studies in other areas, such as, materials, structures, arc models, monitoring, maintenance techniques and asset management are still continued. At present, HV circuit-breakers are basically designed to fit in the networks for any applications; for instance, capacitance switching, line closing, shunt reactor switching, transformer switching and generator protection. It is believed that designing general HV circuit-breakers to fit all purposes is cost effective and easy to maintain. However, it is found that there are many over-designed HV circuit-breakers installed in the networks during the past 30 years.

It is believed that the most practical and realistic method to study HV circuit-breaker reliability is a statistical method. Worldwide surveys of HV circuit-breakers, 63 kV and above had been carried out by CIGRE 13.06 in 1974-1977 for the first phase [1] and 1988-1991 for the second phase [2]. The first survey focused on all types of HV circuit-breakers, whereas the second survey focused only on single-pressure SF_6 HV circuit-breakers. The comparison represented that single-pressure SF_6 circuit breakers have less major failure rate than older-technology circuit breakers. Nevertheless, the minor failure rate of single-pressure SF_6 circuit breakers is higher than older-technology circuit breakers [3]. It is concluded from the second survey that the minor failures result from operating mechanism, SF_6 tightness, electrical auxiliary and control circuits. Stresses of HV circuit-breakers in terms of loading current and short-circuit current (123 kV, 245 kV and 420 kV) during operation in the networks of German utilities are also investigated and studied [4].

As the number of minor failures increase, the issues of how to conduct better maintenance are becoming interesting. It cannot be avoided that better maintenance comes with the higher maintenance costs which are not desirable for utilities. Hence, it is very challenging for engineers to improve the maintenance programs while keeping the maintenance costs at an acceptable level. This is among the most discussed issues in the asset management area, since maintenance costs are considered as the large part of the operation costs.

There is some literature proposing the HV circuit-breaker optimal maintenance models but most of them present only the strategies without the references from the failure databases. It is still a challenge to design and investigate the reliability and maintenance models with reference to the failure database collected from utilities. In addition, with the combination of risk assessment, it is possible to design the reasonable optimal maintenance programs.

Influences of HV circuit-breaker specifications to the main components are of interest, since they are the keys to investigate cost structure. As a result, it can lead to the optimal design of HV circuit-breakers.

1.2 Research Objectives

The maintenance programs of HV circuit-breakers have been long performed by using the manufacture guidelines and experiences of operators. They have hardly been proved that they are really effective in terms of performance and costs. With emerge of deregulation electricity markets, maintenance costs considered as the large part of operation costs of utilities should be reduced in order to keep competitiveness of utilities.

To design new and optimal maintenance programs, it requires the knowledge of failure database analysis, failure modes and effects analysis, reliability investigation and risk assessment. The objectives of this work are mainly comprised of those mentioned aspects. The failure database collected from utilities is deeply investigated to establish the probabilistic models. These models can represent the probability of failures and how the failures are developed during the lifetime of HV circuit-breakers. For instance, the treeing model of failures shows the distribution of failures from the first to the following failures in any subsequent years. The cascading reliability model is an extension of treeing model to investigate the reliability of HV circuit-breakers after consecutive failures. In addition, the application of the Markov model can represent how the components of HV circuit-breakers fail.

One of the main objectives of this work is failure modes and effects analysis of HV circuit-breakers. This is the technique used to investigate failures and consequences of HV circuit-breakers with reference to their functions and their components. The result of the investigation represents the severity ranking of failures, which is important for the asset managers to make decisions as to which failures must be intensively taken into account. The consequence of this analysis results in risk assessment of HV circuit-breakers which can be used to design the asset management.

Other objectives of this work dealing with asset management are cost structure analysis and maintenance optimization. Cost structure analysis is able to breakdown the costs of HV circuit-breakers with regard to the specifications and the components. Consequently, it enables manufacturers to design the optimal HV circuit-breakers based on this cost analysis. The “when and how” to perform maintenance tasks of HV circuit-breakers to increase the reliability are of interest and are included in maintenance optimization.

1.3 Thesis Organization

The thesis contributions can be mainly divided into three phases: failure modes and effects analysis, probabilistic models and maintenance optimization. The extra phase is the investigation of stresses of HV circuit-breakers from the simulation and the statistical method. The organization of this thesis can be described as followed:

- Fundamentals of HV circuit-breakers composed of functions and components of HV circuit-breakers, types of HV circuit-breakers and switching transients are represented in Chapter 2.

- Chapter 3 represents the switching stresses of HV circuit-breakers. In this chapter, the stresses of HV circuit-breakers regarding different types of applications are investigated by simulation method. The other stresses regarding the number of faults and their severity are investigated by using statistical method.
- Based on the failure database developed by the Institute of Power Systems, Darmstadt University of Technology, it is possible to investigate failures of HV circuit-breakers by using a failure modes and effects analysis method. The chapter 4 describes how to conduct this process and presents the result of investigation. The risk assessment is also considered in this chapter.
- The fundamentals of probability and reliability are first introduced in chapter 5. Then developed models, a treeing model and a cascading reliability model are introduced. With these models, the reliability and probability of HV circuit-breakers subject to failures can be determined.
- The application of Markov process used to investigate steady-state probabilities is introduced in chapter 6. The parallel Markov model for HV circuit-breakers is developed to examine the state probabilities. Different types of HV circuit-breakers with different driving mechanisms are taken into consideration.
- Chapter 7 is the last part of this thesis representing cost structure analysis and maintenance optimization. A decision matrix approach is implemented in order to figure out the importance of parameters relating to costs of HV circuit-breakers. Apart from cost structure analysis method, maintenance optimization by using different methods is introduced in this chapter.
- Finally, the conclusion is made in chapter 8 to summarize the results of this thesis and to propose the direction of the future development.

2 Fundamentals of HV Circuit-Breakers

2.1 Functions and Components of HV Circuit-Breakers

HV circuit-breakers are among the most important equipment in power systems. They are designed to use as interrupting devices both in normal operation and during faults. It is expected that HV circuit-breakers must be operated in any applications without problems. Moreover, it is expected that they must be ready to be operated at anytime, even after a long period of non-operating time. The main functions of HV circuit-breakers can be categorized into four functions:

- Switching-off operating currents
- Switching-on operating currents
- Short-circuit current interruption
- Secure open and closed position

Apart from the main functions, they are required to fulfil the physical requirements as follows:

- Behave as a good conductor during a closed position and as a good isolator during an open position.
- Change from the closed to open position in a short period of time.
- Do not generate overvoltages during switching.
- Keep high reliability during operation.

More details of HV circuit-breaker functions and requirements under special conditions can be reviewed in [5], [6] and [7]. Components of HV circuit-breakers regarding basic functions can be divided into five groups [8]:

1. Insulation:

The electric insulation of HV circuit-breakers is provided by a combination of gaseous, liquid and solid dielectric materials. The failure of insulation can lead to severe damage such as flashover between phases, to ground or across the opening poles resulting in major repair or replacement. In order to prevent such failures, the insulation must be maintained and monitored. For example, the quantity of insulating medium must be continuously monitored; the quality of insulation has to be checked by diagnostic techniques periodically and the insulation distance should be monitored by using position transducers and visual inspection.

2. Current carrying:

The current carrying parts are significant components that assure the flowing of current in the closed position. The failure of these parts can lead to catastrophic events such as contact welding and severe deterioration of the insulation system. It is however found that it takes several years until the contact degradation process reaches the final states. Practically, the most contact problems can be prevented by using periodic diagnostic testing. The techniques of current carrying testing can be accomplished by monitoring or diagnostic testing of contact resistance, temperature of contacts, load current and content of gas decomposition.

3. Switching:

During operation of HV circuit-breakers, they are subject to electrical, thermal and mechanical stresses. It is required that they should be able to make and break large amount of power without causing failures. The parameters used to monitor and diagnose switching are composed of position of primary contacts, contact travel characteristics, operating time, pole discrepancy in operating times, arcing time and arcing contact wear. Contact travel characteristics are the most widely used parameters in periodic testing in order to investigate the contact movement.

4. Operating mechanism:

The operating mechanism is a part used to move contacts from open to closed position or inversely. The operating mechanism failures account for a large proportion of total failures of HV circuit-breakers. For example, leakage of oil and gas in the hydraulic and pneumatic systems is very common but it can be handled without system interruption. On the other hand, breakdown of shafts, rods and springs could lead to serious failures resulting in the interruption of systems.

5. Control and auxiliary functions:

Control and auxiliary components are the parts controlled by 110-220 volts d.c. The signal is sent to the coil to move a latch or open a valve leading to energy release of a mechanical drive. The control and auxiliary parts, composed of electrical circuits and latches or values, are exposed to failures relatively frequently according to reliability surveys. Typical failures in these parts are failing to close or open on demand as well as delays in the operation. Coil current, voltages, status of auxiliary switches, circuit continuity and the environment of the control cabinet are the parameters relating to control and auxiliary systems which must be monitored.

2.2 Arc Interruption

The switching arc plays a significant role in the interruption process, since it is the element that is able to change from the conducting to non-conducting state. A burning arc is established between the breaker contacts surrounded by extinguishing medium such as oil, air or sulphur hexafluoride (SF_6). At the moment the contacts are going to be apart, the connecting surface is very small. As a result, the high current density at that point can melt the contact material. After that, the melting contact is exploded thus leading to the gas discharge.

The electrical arc is in the form of metal vapour and hot air in case of air circuit-breakers. For oil circuit-breakers, heat within the arc will decompose some oil, thus generating gases. During the contact separation, these gases and metal vapour are ionized. Then, the current can still flow through the arc at this moment. In principle, the arc interruption can be carried out by cooling the arc, increasing the length and splitting it into a number of arcs in series. The plasma channel of the electric arc can be represented in Fig. 2.1 and the temperature distribution is depicted in Fig. 2.2

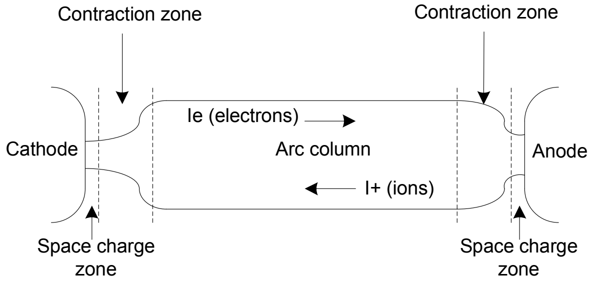


Figure 2.1: The plasma channel of electric arc [9]

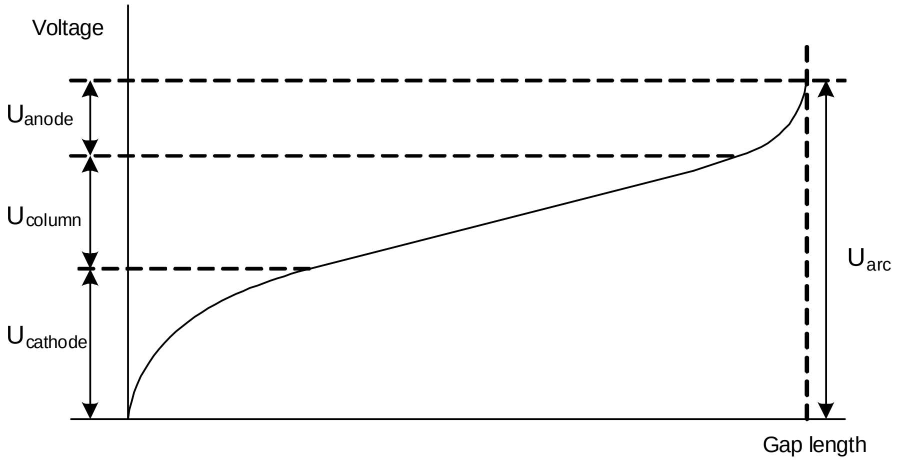


Figure 2.2: The potential distribution along an arc channel [9]

The voltage drop near the cathode region is normally around 10-25 volts, while the voltage drop near anode is around 5-10 volts. The voltage drop in the arc column depends on the types of gases, gas pressure, the magnitude of arc current and the length of column [10].

2.3 Circuit-Breaker Classification

According to many criteria, circuit-breakers can be classified into many groups as follows:

- Circuit-breaker types by voltage class:

The classification of circuit-breakers regarding voltage class can be divided into two groups: low voltage circuit-breakers with rated voltages up to 1000 volts and high voltage circuit-breakers with rated voltages of 1000 volts and above. The second group, high voltage circuit-breakers, can be further subdivided into two groups: circuit-breakers with rated 50 kV and below and those with rated 123 kV and above.

- Circuit-breaker types by installation:

Circuit-breakers can be classified in terms of installation into two types: indoor and outdoor installations. Practically, the only differences between those two types are the packaging and the enclosures.

- Circuit-breaker types by external design:

Outdoor circuit-breakers can be classified with respect to structure design into two types:

dead and live tank types. Dead tank circuit-breakers are the circuit-breakers of which the enclosures and interrupters are grounded and located at ground level, as shown in Fig. 2.3. This type of circuit-breaker is widely used in the United States. Live tank circuit-breakers are circuit-breakers equipped with the interrupters above the ground level, as shown in Fig. 2.4. Their interrupters have the potential.

Figure 2.3: Dead tank circuit-breaker (Source: Manitoba, Canada)

Figure 2.4: Live tank circuit-breaker (Source: ABB AG, Switzerland)

- Circuit-breaker types by interrupting medium:

The interrupting mediums are the main factors in designing circuit-breakers. The technology of air and oil interrupting mediums for circuit-breakers was first developed 100 years ago.

These types of circuit-breakers are still in operation but there is no further development, since they cannot fulfil the higher ratings of power systems nowadays. In addition, there are issues as environmental problems and as to relatively low reliability. The new generation of interrupting mediums is focused on vacuum and sulfurhexafluoride (SF_6). Vacuum circuit-breakers are predominant in medium voltage levels, whereas SF_6 circuit-breakers are widely used in high voltage levels.

- Circuit-breaker types by operation:

The main purpose of HV circuit-breakers is interrupting abnormal conditions. Nevertheless, different applications of HV circuit-breakers must be taken into account. The applications of HV circuit-breakers can be classified as follows:

- Capacitance switching: capacitor banks and unloaded cable switching
- Line closing: overhead transmission line switching
- Shunt reactor switching
- Transformer switching
- Generator switching

2.4 Types of Circuit-Breakers

Circuit-breakers can be classified according to interrupting mediums into four categories:

2.4.1 Oil Circuit-Breakers

Oil circuit-breakers are the most fundamental circuit-breakers which were first developed in 1900s. The first oil circuit-breaker was developed and patented by J. N. Kelman in the United States. Oil has an excellent dielectric strength which enables itself not only to be used as an interrupting medium but also as insulation within the live parts. The interrupting technique of oil circuit-breakers is called “self-extinguishing”, since the oil can produce a high pressure gas when it is exposed to heat resulting from arc. In other words, arc can be cooled down by the gas produced proportional to arc energy. During the arc interruption, the oil forms a bubble comprising mainly hydrogen. It is found that arc burning in hydrogen gas can be extinguished faster than other types of gases. However, hydrogen cannot be used as interrupting medium, as it is not practical to handle. Oil circuit-breakers can be divided according to methods of arc interruption into two types: bulk oil and minimum oil types.

2.4.1.1 Bulk oil type

The main contacts and live parts are immersed in oil which serves as an interrupting medium and insulates the live parts. Plain-break circuit-breakers are considered as bulk oil type, since the arc is freely interrupted in oil. This type of circuit-breaker contains a large amount of oil and requires a large space. It could cause environmental problems after an explosion. It is therefore limited to the low voltage level. An example of a bulk oil circuit-breaker and its components is represented in Fig. 2.5.

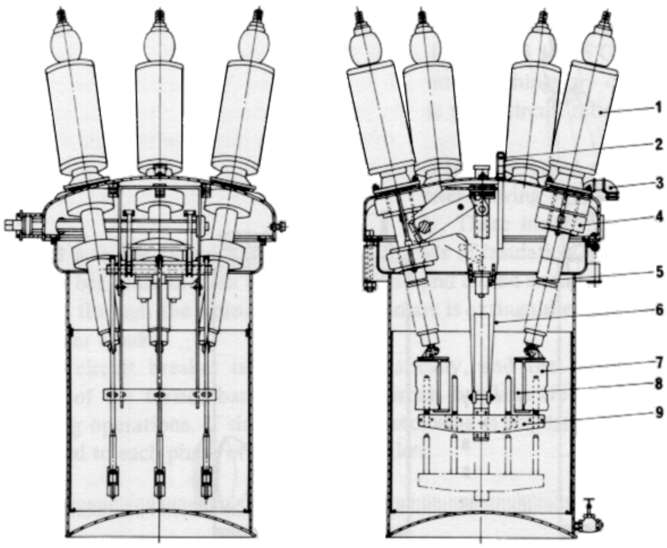


Figure 2.5: Bulk oil circuit-breaker (Source: Allis Chalmers Ltd.)

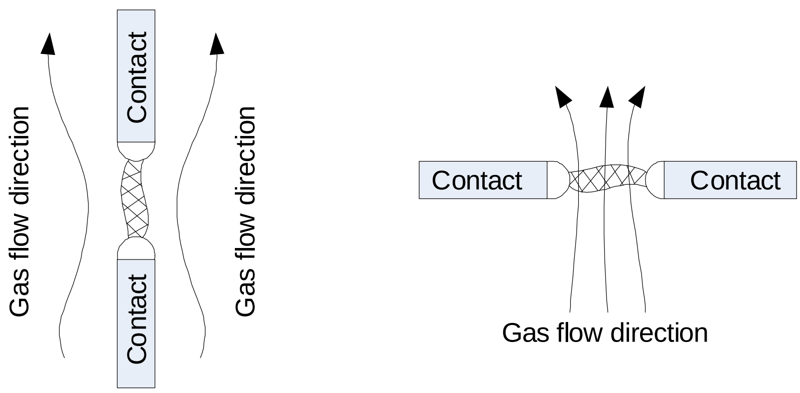
1. bushing	6. plunger guide
2. oil level indicator	7. arc control device
3. vent	8. resistor
4. current transformer	9. plunger bar
5. dashpot	

2.4.1.2 Minimum oil type

This type of oil circuit-breaker was developed in Europe, due to requirement to reduce utilized space and cost of oil. In comparison to the bulk oil type, for the minimum oil type the volume of oil is reduced and used only in an explosion chamber. The other difference from the bulk oil type is the insulation, which is made of porcelain or solid insulating material. Single-break minimum oil circuit-breakers are used in the voltage levels of 33-132 kV. When higher ratings are required, the multi-break type is then applied with a combination of resistors and capacitors. These resistors and capacitors are applied in order to provide uniformity to the voltage distribution.

2.4.2 Air-Blast Circuit-Breakers

The arc interruption of air-blast circuit-breakers is carried out by introducing the high-pressure air flow in axial or cross directions as shown in Fig. 2.6. In axial type, the arc is cooled down in an axial direction until the ionisation is brought down to zero level. The current is then interrupted at this point. In contrast to the axial type, the cross type will compress the air and blow into an arc-chute compartment.



(a) (b)

Figure 2.6: Air blast direction: (a) axial direction, (b) cross direction

The performance of air-blast circuit-breakers depends on many factors, for example, operating pressure, the nozzle diameter and the interrupting current. The advantages of air-blast circuit-breakers can be listed as follows [11]:

- Cheap interrupting medium
- Chemical stability of air
- Reduction of erosion of contacts from frequent switching operations
- Operation at high speed
- Short arcing time
- Being able to be operated in fire hazard locations
- Reduction of maintenance frequency
- Consistent breaking time

The disadvantages of air-blast circuit-breakers are the high-level noise during the operation and the requirement for the air to remain dried. Similar to oil circuit-breakers, resistors and capacitors are needed when air-blast circuit-breakers are used in very high voltage levels. The serious problem which could occur during small current interruption is a chopping current, since the velocity and pressure of air-blast circuit-breakers are independent of interrupted current. An example of air-blast circuit-breaker is represented in Fig. 2.7.

Figure 2.7: Air-blast circuit-breaker (Source: Strathaven substation, Lanarkshire, UK)

2.4.3 Vacuum Circuit-Breakers

The dielectric strength of vacuum is considerably higher than other interrupting mediums. Hence, a contact separation of around 1 cm is enough to withstand high voltages.

Consequently, the power to open and close contacts can be significantly reduced compared with other types of circuit-breakers. In addition, the rate of dielectric recovery of vacuum is much faster than that of air. The interrupting technique of vacuum circuit-breakers is different from other types of circuit-breakers. The arc extinguishing process is governed by a metal surface phenomenon during their contacts part. In other words, the arc is not extinguished by an interrupting medium but by the metal vapour. The vacuum arc can be only cooled down by using a magnetic field which can move the arc over the contact surfaces. In order to do so, the contacts are manufactured with spiral segments as shown in Fig. 2.8. This technique can also prevent contact erosion.

Nowadays, vacuum circuit-breakers are predominant in medium voltage levels. They are also considered as maintenance-free circuit-breakers due to their simple and reliable design.

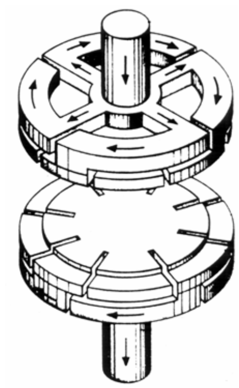


Figure 2.8: Contacts of vacuum circuit-breaker [12]

2.4.4 SF_6 Circuit-Breakers

SF_6 gas and its characteristics were discovered in 1920s but the development of SF_6 gas as an interrupting medium applied for circuit-breakers began in 1940s. However, the SF_6 circuit-breakers first came to the market in 1960s. The properties of SF_6 gas are superior to other interrupting mediums as follows:

- High dielectric withstand characteristic. For example, SF_6 gas at absolute pressure has twice the dielectric strength of air and at 3 bar it is comparable to oil.

- High thermal conductivity and short thermal time constant (1000 times shorter than air) resulting in better arc quenching.
- Arc voltage characteristic is low thus resulting in reduced arc-removal energy.
- At normal conditions, SF_6 is inert, non-flammable, non-corrosive, odourless and non-toxic. However, at the temperature over 1000°C, SF_6 decomposes to gases including S_2F_{10} which is highly toxic. Fortunately, the decomposition products recombine abruptly after arc extinction (when the temperature goes down).

The problem of moisture from the decomposition products must be considered. The moisture can be absorbed by a mixture of soda lime (NaOH + CaO), activated alumina (dried Al_2O_3) or molecular sieves. The other problem is the condensation of SF_6 at high pressures and low temperatures. For example, at a pressure of 14 bars, SF_6 liquefies at 0°C. In the areas with low ambient temperature such as Canada, Scandinavian countries and Russia, gas heaters must be utilized. The other solution is the introduction of gas mixtures such as nitrogen (N_2). Although the gas mixture of SF_6/N_2 can be used in the low ambient temperature, the dielectric withstand capability and arc interruption performance are reduced. For example, the short-circuit capacity rating of 50kA is reduced to 40kA. The development and types of SF_6 circuit-breakers can be represented as follows:

2.4.4.1 Double-pressure SF_6 circuit-breakers

This type is developed by using principles similar to air-blast circuit-breakers. The contacts are located inside the compartment filled with SF_6 gas. During the arc interruption, the arc is cooled down by compressed SF_6 from a separate reservoir. After the interruption, SF_6 gas is pumped back into the reservoir. This reservoir must be equipped with heating equipment to ensure that the SF_6 will not liquefy. However, failures of heating equipment can result in this type being unable to operate as circuit-breakers. This type of SF_6 circuit-breaker is rarely used in the market nowadays because of its high failure probability.

2.4.4.2 Self-blast SF_6 circuit-breakers

The interrupting chamber of this type of circuit-breaker is divided into two main compartments with the same pressure (around 5 atm). During the arc interruption, the gas pressure in the arcing zone is heated resulting in high pressure. This high pressure gas from the other compartment then blasts into the arcing zone and in the meantime cools the arc column. Finally, the arc is extinguished. This type of circuit-breaker is normally used in high voltage levels up to 123 kV. The interruption principle and structure are shown in Fig. 2.9.

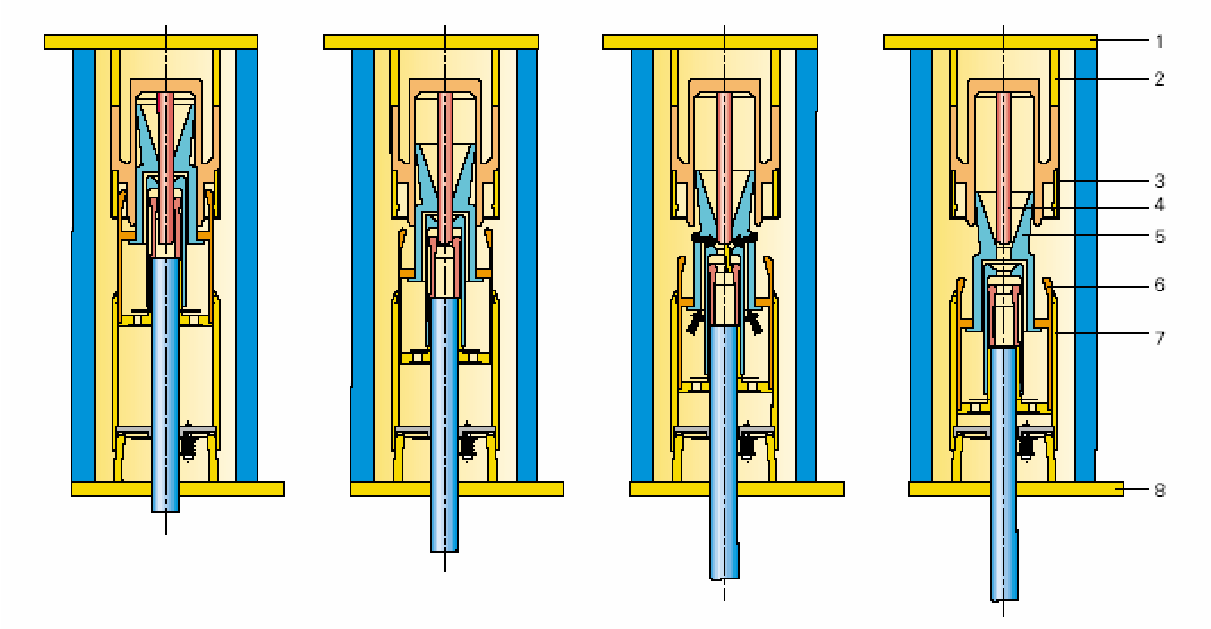


Figure 2.9: Arc interruption principle of self-blast circuit-breakers (Source: SIEMENS)

1. terminal plate
2. contact carrier
3. main contact
4. arcing contact
5. nozzle
6. contact cylinder
7. base
8. terminal plate

2.4.4.3 Puffer-type SF_6 circuit-breakers

The principle of this type is to generate compressed gas during the opening process. The moving contacts move the piston and thus compressing the gas in the chamber. As a result, the compressed gas flows along the arc channel and thereby extinguishing the arc. The development of puffer-type SF_6 circuit-breakers can be divided into two generations: first and second generations. The principle of arc interruption of both generations is similar but the improvements of the second generation concentrate on the better design, improvement of short-circuit rating, arcing contact lifetime and the material of the nozzle [13].

Since the gas has to be compressed, the puffer-type SF_6 circuit-breaker must have a strong operating mechanism. For example, when large current such as three-phase fault is interrupted, the opening speed of circuit-breakers is slowed down because of thermal pressure. The operating mechanism should have adequate energy to move the contacts apart. Consequently, the reliable operating mechanisms dominate the costs of circuit-breakers.

At present, SF_6 circuit-breakers are predominant in high voltage levels with the high short-circuit capability up to 63 kA. They can be used as dead tank circuit-breakers, live tank circuit-breakers and in gas insulated substation (GIS).

2.5 Switching Transients and Applications of HV Circuit-Breakers

Apart from normal load current interruption, the other main purpose of HV circuit-breakers is interrupting short-circuit currents. In addition, different applications of HV circuit-breakers must be taken into account, such as small inductive current interruption, capacitive current interruption, short-line fault interruption and generator protection. The applications of HV circuit-breakers can be summarized as follows:

2.5.1 Three-Phase Short-Circuit Interruption at Terminal

The symmetrical three-phase to ground fault can be represented in an equivalent single-phase diagram as shown in Fig. 2.10. The stray capacitance of the circuit-breaker bushing is represented by capacitance, C. This capacitance affects the shape of the recovery voltage which is established across the circuit-breakers after opening.

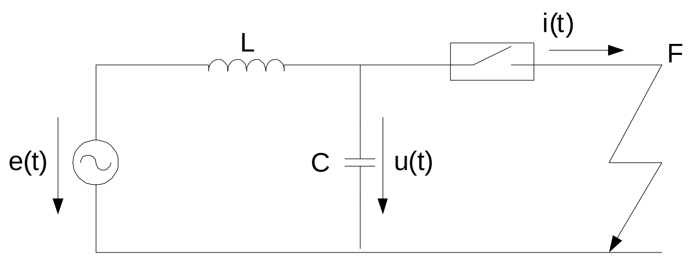


Figure 2.10: Single-phase equivalent diagram of symmetrical three-phase to ground short-circuit

There is a short-circuit current at point F and the circuit-breaker has to interrupt at current zero. Assume that the supply voltage is equal to $e(t) = E\cos\omega t$. The circuit voltage equation when the circuit-breaker is opened can be represented in the form

$$L\frac{di}{dt} + \frac{1}{C}\int i\,dt = E\cos\omega t \quad (2.1)$$

By using the Laplace transformation with the natural angular frequency $\omega_0 = 1/\sqrt{LC}$, the recovery voltage can be represented as

$$u(t) = E(-\cos\omega_0 t + \cos\omega t) \quad (2.2)$$

At the instant after short-circuit interruption, the time *t* is very short (*t* < 1 ms) and thus resulting in $\cos\omega t = 1$. The recovery voltage can be approximated in the form

$$u(t) = E(1 - \cos\omega_0 t) \quad (2.3)$$

The possible maximum recovery voltage without damping is 2E after time $\pi/\sqrt{LC}$. Practically, the maximum recovery voltage is less than 2E because of resistance and system losses.

The switching sequence depends on the neutral grounding. The example of an isolated neutral system with three-phase short-circuit interruption can be explained from Fig. 2.11. The arc interruption is first taking place at current zero of phase A, while phase B and C are still arcing. After 90^o from the first phase to clear (phase A), the other phases (B and C) are then simultaneously interrupted. The equivalent diagram of three-phase short circuit in an isolated neutral system is represented in Fig. 2.12. The first phase is going to be interrupted, then the reduced equivalent diagram can be expressed as in Fig. 2.13a and 2.13b.

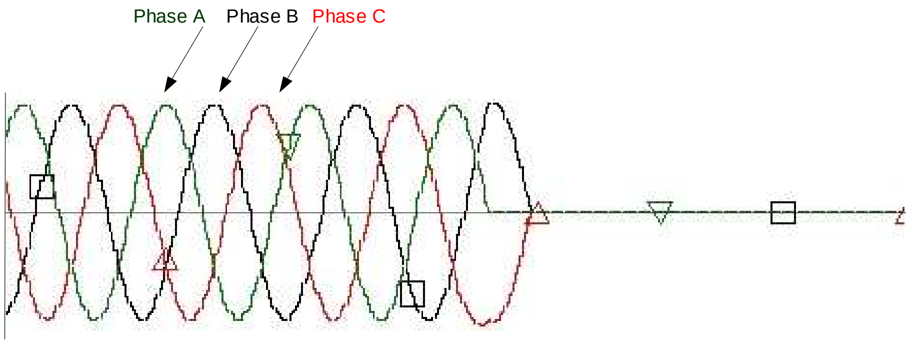


Figure 2.11: Currents of the three-phase short-circuit interruption

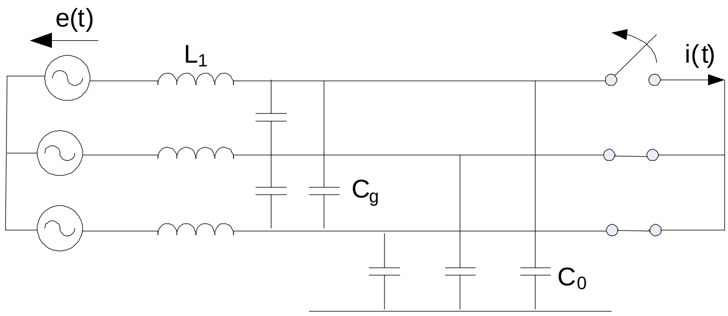


Figure 2.12: The equivalent diagram of three-phase short circuit

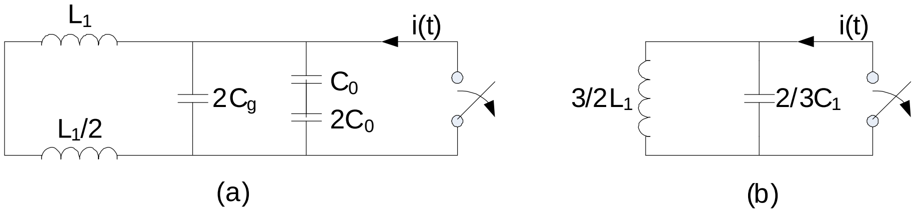


Figure 2.13: The reduced equivalent diagrams (a) and (b)

The coupling capacitance, C_g, can be represented in terms of positive and zero-sequence capacitance as $C_g = (C_1 - C_0)/3$. The Laplace equivalent impedance and voltage of the first-phase-to-clear can be expressed as

$$Z(p) = \frac{3}{2C_1}\frac{p}{p^2+\omega_0^2} \tag{2.4}$$

$$U(p) = \frac{3}{2C_1}\frac{p}{p^2+\omega_0^2}\frac{\hat{e}}{L_1}\frac{1}{p^2+\omega^2} \tag{2.5}$$

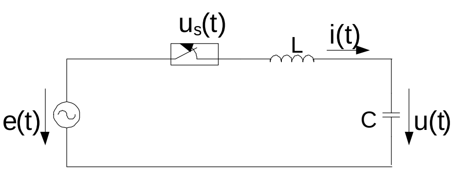
It is assumed that $\omega_0^2 >> \omega^2$, then the voltage of the first-phase-to-clear after transformation is

$$u(t) = \frac{3}{2}\hat{e}\left[-\cos\omega_0 t + \cos\omega t\right] \tag{2.6}$$

It can be seen from Eq. 2.6, that the first phase to clear factor, defined as the ratio between the voltage across the first clearing phase and the uninterrupted phase voltage, is 1.5. The first phase to clear factors in case of resonant earthed and solidly neutral are less than 1.5 depending on the ratio between positive and zero sequence impedances. When short-circuit occurs far from the terminal, the transient recovery voltage will have more than one frequency component. The frequency of source side and line side must be taken into account resulting in double frequency transient recovery voltage. In addition to transient recovery voltage, the rate of rise of recovery voltage (RRRV) must be considered. According to IEC standard 62271-100, circuit-breakers must be able to withstand RRRV up to 2 kV/µs. In some cases, for example, short-line faults (section 2.5.4) of which RRRVs are higher than 2 kV/µs, the protective capacitance must be implemented to reduce the steepness of recovery voltage.

2.5.2 Capacitive Current Interruption

Capacitive current interruption can generate overvoltages across circuit-breakers leading to dielectric breakdown of circuit-breakers. The reason for the overvoltages can be explained by the electrical charge effect at the capacitive loads such as capacitor banks, cables and unloaded transmission lines. The equivalent single-phase circuit diagram and waveforms of capacitive current interruption are depicted in Fig. 2.14.



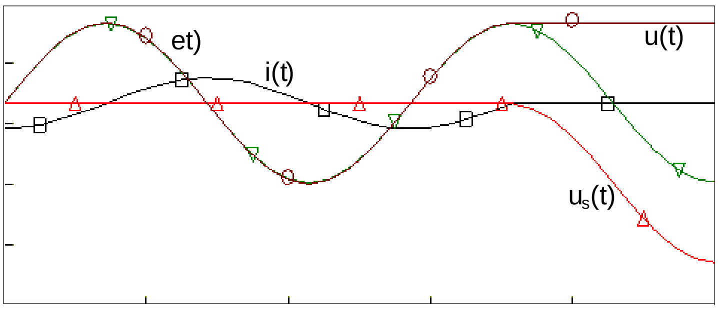


Figure 2.14: Equivalent circuit diagram of capacitive current interruption

Before the capacitive load is switched off, the capacitive load is fully charged equal to the peak supply voltage. After half a cycle, the supply voltage is reversed thus making the voltage across the circuit-breaker twice the peak value of the supply voltage. If the circuit-breaker cannot withstand this voltage, a restrike takes place across the circuit-breaker resulting in a high frequency current. The circuit-breaker is able to interrupt such current in a half cycle later. At this moment, the voltage at the capacitor reaches 3 times that of the supply voltage. If the circuit-breaker cannot withstand the voltage across itself, the restrike can take place again with the voltage at the capacitor 5 times that of the supply voltage. The details of capacitive current switching can be reviewed in [14].

Many applications of circuit-breaker interruption are considered as capacitive current interruption, for example, interruption of no-load transmission lines, interruption of no-load cables and switching-off capacitor banks. When the circuit-breaker is called upon to interrupt the capacitive current (for example, no-load transmission line interruption), the load voltage is higher than the supply voltage. This phenomenon is called Ferranti effect, leading to a voltage jump at the supply side of the circuit-breaker.

2.5.2.1 Interruption of no-load transmission lines

The transmission lines are first switched off at the line side resulting in no-load transmission lines. At this moment, only a charging current flows in the transmission lines and it charges the capacitance of the transmission lines. After that, the circuit-breaker at the sending end is called upon to switch off. The circuit-breaker is then stressed by the voltage rise at the supply side and the oscillation at the line side. The recovery voltage across the circuit-breaker varies from 2.0 to 3.0 p.u. depending on the ratio of positive-sequence to zero-sequence capacitance (C_1/C_0). The relation of C_1/C_0 and the recovery voltages are represented in [15]. The geometry of transmission lines and tower configurations affect the coupling capacitance between lines and earth, thus leading to different voltage stresses on circuit-breakers.

2.5.2.2 Interruption of no-load cables

Interruption of no-load cables is similar to interruption of no-load transmission lines which belongs to the case of capacitive current interruption. The difference is the interrupting current, which is larger than the interrupting current of no-load transmission lines but smaller than the interrupting current of capacitor banks. The configurations of cables must be taken into account. For example, the separate conductor with its own earth screen can be treated similar to capacitor banks with an earthed neutral in a grounded system, since there is only an effect of capacitance to ground.

2.5.2.3 Switching capacitor banks

Capacitor banks are used in power systems to improve voltage regulation and reduce losses through reduction in reactive current or filter higher harmonics. Energizing a single capacitor bank could generate inrush current with a high frequency. It is noted that the magnitude and frequency of inrush current in the case of switching back-to-back capacitor banks are higher [16]. Furthermore, energizing capacitor banks could lead to a pre-strike of the circuit-breaker when the supply voltage reaches its peak before the contacts touch. The switching off three-phase grounded capacitor banks in solidly grounded system can be treated as single phase circuit. The maximum voltage across the circuit-breakers is 2 p.u. In case of switching-off three-phase ungrounded capacitor banks, the trapped charge of the first-phase-to-clear must be taken into account. As a result, the maximum voltage across the circuit-breakers could reach 3 p.u.

2.5.3 Small Inductive Current Interruption

In case of a large short-circuit current interruption, the arc energy is high enough to keep the arc column ionized until the arc is interrupted at natural current zero. On the other hand, interrupting small inductive currents, such as unloaded currents of transformers and currents of shunt reactors, can produce overvoltages according to chopping current effects. It can be explained that the small inductive current is interrupted just before natural current zero, thus inducing the high transient voltages ($L \cdot di/dt$). Consequently, these transient voltages can cause flashover on the insulation, such as bushings. The equivalent single-phase circuit diagram and waveforms of small inductive current interruption are illustrated in Fig. 2.15.

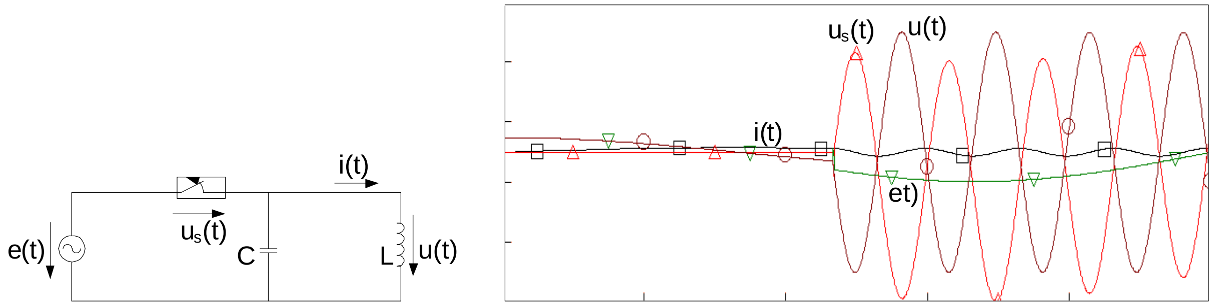


Figure 2.15: Equivalent circuit diagram of small inductive current interruption

The principle to calculate the voltages across circuit-breakers during current chopping is the energy conversion before and after arc interruption. When the circuit-breaker interrupts an arc current, the electromagnetic energy stored in the inductance L is transferred to electrical energy in the capacitance C. The balance energy equation is as follows [17]:

$$\frac{1}{2}Li_0^2 + \frac{1}{2}Cu_0^2 = E_0 \tag{2.7}$$

where L, C Inductance, Capacitance

i_0 Current at the time of interruption

u_0 Voltage at the time of interruption

E_0 Total energy

After the interruption, the total energy and maximum voltage can be represented as:

$$\frac{1}{2}Cu_{max}^2 = E_0 \tag{2.8}$$

$$u_{max} = \sqrt{\frac{L}{C}i_0^2 + u_0^2} \tag{2.9}$$

It can be seen from equation 1.6 that the maximum voltage depends on the characteristic impedance $Z_W = \sqrt{L/C}$ of equipment. The examples of transient overvoltages regarding switching shunt reactors and unloaded transformers can be reviewed in [18] and [19].

2.5.4 Short-Line Fault Interruption

It is found that short-circuit current interruption far from the circuit-breakers from hundreds of metres to a few kilometres could result in circuit-breaker breakdown. The very high steepness (3 to 10 kV/µs) of recovery voltages after circuit-breaker interruption could result in very high stress thus leading to thermal breakdown of the arc channel. The explanation of short-line fault is illustrated in Fig. 2.16.

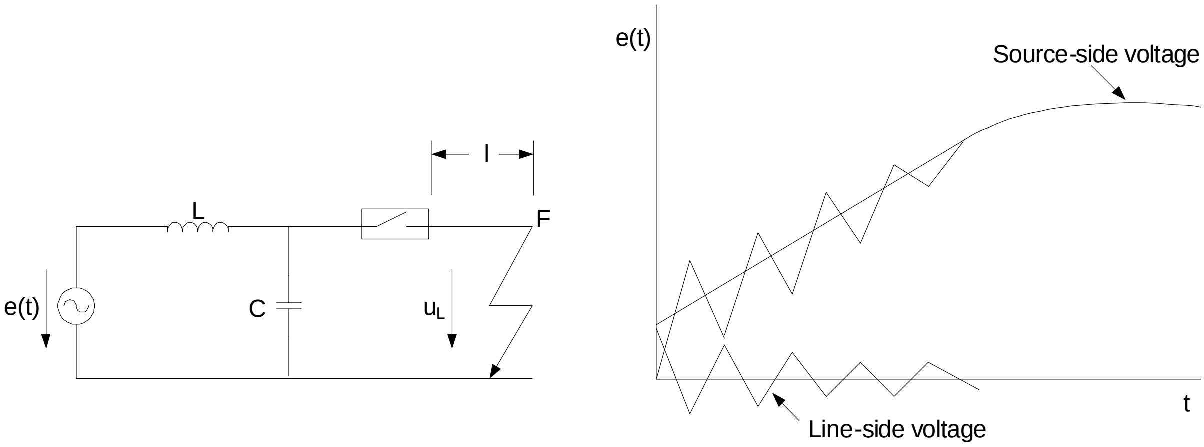


Figure 2.16: Equivalent circuit diagram of short line fault interruption

The transient recovery voltage after short-line fault interruption is composed of voltage generated by the source-side voltage and the line-side voltage. The source-side voltage is the gradually rising voltage with the (1-cosine) shape, whereas the line-side voltage has the saw-toothed voltage shape with very high frequency. The starting voltage of the recovery voltage and the line-side frequency can be represented as follows:

$$u_L = Z_W \frac{di}{dt} = Z_W \omega \sqrt{2} I_k'' \tag{2.10}$$

with I_k'' Short-circuit current

Z_W Characteristic impedance of the line

ω Operating frequency

$$f_L = \frac{1}{2\pi\sqrt{L_2 C_2}} \tag{2.11}$$

where L_2 and C_2 are the equivalent series impedance and shunt capacitance of the line from the circuit-breaker to the fault respectively. The saw-toothed voltage shape of the line-side is originated by the reflection of travelling wave at the short-circuit point.

The short-line fault test is considered as the most severe short-circuit test and has been included in the standard. The short-line fault tests are considered with respect to the short-circuit rating of circuit-breakers. 75% and 90% short-line faults have been applied by IEC standard.

2.5.5 Circuit-Breakers Installed for Generator Protection

Circuit-breakers for generator protection are installed between generators and step-up transformers. The characteristics of faults near generators can be as described below:

- The recovery voltage has a very high rate of rise due to the small capacitance, C.
- The effect of the d.c. component of short-circuit current must be taken into account.
- The decay of the a.c. component depends on subtransient and transient time constants of the generator.
- The d.c. component at the interrupting time could be higher than the peak value of the a.c. component depending on the generator rating.
- The short-circuit current might not cross the zero for a period of time depending on the load condition before interruption.

The generator circuit-breakers are designed to handle these conditions by introducing a high arc voltage. The high arc voltage generates an additional resistance resulting in reduction of the time constant of the fault. As a result, the fault can be interrupted with a reduced time delay.

At present, this type of circuit-breaker is widely used to protect generators having ratings from 100-1300 MVA. The interrupting capacities of SF_6 generator circuit-breakers are around 63 kA to more than 200 kA, while air-blast circuit-breakers are applied for higher interrupting capacities. The standard of the generator circuit-breakers can be found in [20]. The results of testing and influence of cable connection was studied in [21].

2.6 Summary of Reliability Surveys of HV Circuit-Breakers by CIGRE

The most important and internationally reliability surveys of HV circuit-breakers had been carried out by CIGRE. The first enquiry had been performed during 1974-1977 from 102 companies in 22 countries. This enquiry focused on all types of HV circuit-breakers with ratings of 63 kV and above. The total information of 77,892 breaker-years had been collected. The second enquiry, focused only on single-pressure SF_6 circuit-breakers, had been done during 1988-1991 from 132 companies in 22 countries. The second enquiry contains 70,708 breaker-years and also focused on circuit-breakers with ratings of 63 kV and above. The major and minor failures can be defined as follows:

- Major failure (MF): Complete failure of a circuit-breaker which causes the lack of one or more of its fundamental functions. A major failure will result in immediate change in the system operation conditions leading to removal from service for non-scheduled maintenance (intervention required within 30 minutes).
- Minor failure (mF): Failure of a circuit-breaker other than a major failure or any failure, even complete, of a constructional element or a subassembly which does not cause a major failure of the circuit-breaker.

The major and minor failures at different voltage levels from both enquiries can be summarized in Table 2.1 [22]. The short summary of the 2nd survey can be found in [23]. According to Table 2.1, the ratio between minor and major failures can be calculated and represented in Table 2.2.

It can be concluded from the 2nd enquiry compared with the 1st enquiry that:

- The major failure rate of the single-pressure SF_6 circuit-breakers is 60% lower than all types of circuit-breakers from the 1st survey.
- The minor failure rate of the SF_6 circuit-breakers is 30% higher than that of the first survey. It is because of more signals of the monitoring systems and because of SF_6 leakage problems
- The operating mechanism is subject to the most failures in the failure modes of “Does not open or close on command” and “Locked in open or closed position”.

Voltage (kV)	Major failure rate (Failures per year)		Minor failure rate (Failures per year)	
	1st Enquiry 1974-1977	2nd Enquiry 1988-1991	1st Enquiry 1974-1977	2nd Enquiry 1988-1991
All voltages	0.0158	0.0067	0.0355	0.0475
63-99	0.0041	0.0028	0.0165	0.0223
100-199	0.0163	0.0068	0.0417	0.0475
200-299	0.0258	0.0081	0.0639	0.0697
300-499	0.0455	0.0121	0.1635	0.0776
500 and above	0.1045	0.0197	0.0493	0.0837

Table 2.1: Summary of major and minor failure rates of the 1st and 2nd enquiries

Voltage (kV)	Ratio between minor and major failures	
	1st Enquiry 1974-1977	2nd Enquiry 1988-1991
All voltages	2.25	7.09
63-99	4.02	7.96
100-199	2.56	6.99
200-299	2.48	8.60
300-499	3.59	6.41
500 and above	0.47	4.25

Table 2.2: The ratio between minor and major failures

3 Switching Stresses of HV Circuit-Breakers

3.1 Switching Stress Parameters

Stresses of circuit-breakers can be divided into three groups: mechanical, thermal and electrical stresses. Mechanical stresses are composed of effects from winds, earthquakes and weather conditions. In some areas subject to such mechanical stresses, circuit-breakers with special insulation and very strong supporting structures must be implemented. Electrical stresses are composed of stresses from normal switching and clearing faults. For example, circuit-breakers are subject to stresses when they are requested to interrupt short-circuit, capacitive and small inductive currents. In other words, circuit-breakers are subject to stresses from interruption of no-load transmission lines, no-load cables, capacitor banks and chopping currents of reactors. In addition, the interruption of short-line faults results in very high stresses or high rate of rise of recovery voltages (RRRV) across circuit-breakers. Electrical stresses of circuit-breakers according to operating currents and short-circuit currents have been thoroughly studied in [24]. It is concluded that stresses of circuit-breakers according to operating currents and short-circuit currents are not severe, since circuit-breaker rating had been oversized to cope with the increment of energy consumption in the future.

In order to investigate electrical stresses of circuit-breakers according to effects of grounding and types of applications, interrupted currents, transient recovery voltages (TRV) across circuit-breakers and rate of rise of recovery voltages (RRRV) are taken into account in order to compare the stresses of circuit-breakers in any applications.

3.1.1 Interrupted Currents

Circuit-breakers are designed to be used as interrupting devices both in normal operations and during short-circuit circumstances.

The rated normal current (I_r) can be defined according to IEC standard [25] as follows:

"The rated normal current of switchgear and controlgear is the r.m.s. value of the current which switchgear and controlgear shall be able to carry continuously under specified conditions of use and behaviour"

The rated short-circuit withstand current is equal to the rated short-circuit breaking current (I_{rb}) in IEC standard and can be described as:

"The rated short-circuit breaking current is the highest short-circuit current which the circuit-breaker shall be capable of breaking under the conditions of use and behaviour prescribed in the standard"

For example, the stresses of HV circuit-breakers from the normal and short-circuit currents were thoroughly investigated and can be summarized in Table 3.1 and 3.2 [26] and [27].

Voltage (kV)	95 % Percentile I_{load}/I_r	Maximum value $I_{load,max}/I_r$
123	24 %	58 %
245	25 %	60 %
420	38 %	84 %

Table 3.1: Stresses of HV circuit-breakers according to load current compared to rated current (I_{load}: load current)

Voltage (kV)	95% Percentile		Maximum value	
	I_{k1TF}/I_{rb}	I_{k3TF}/I_{rb}	I_{k1TF}/I_{rb}	I_{k3TF}/I_{rb}
123	-	91 %	-	104 %
245	66 %	81 %	86 %	94 %
420	67 %	78 %	77 %	86 %

Table 3.2: Stresses of HV circuit-breakers according to short-circuit current compared to rated breaking current (I_{k1TF}: single-phase fault at terminal, I_{k3TF}: three-phase fault at terminal)

It can be seen from Table 3.1 that the stress of normal load current interruption is relatively low, since the 95 % percentiles of I_{load}/I_r are between 24-38 % and the 95 % percentiles of $I_{load,max}/I_r$ are around 58-84 %. The stresses of normal load current interruption are increased with increasing voltage levels. However, this is from the study of stresses in Germany where the energy consumption has been growing relatively slow compared with developing countries.

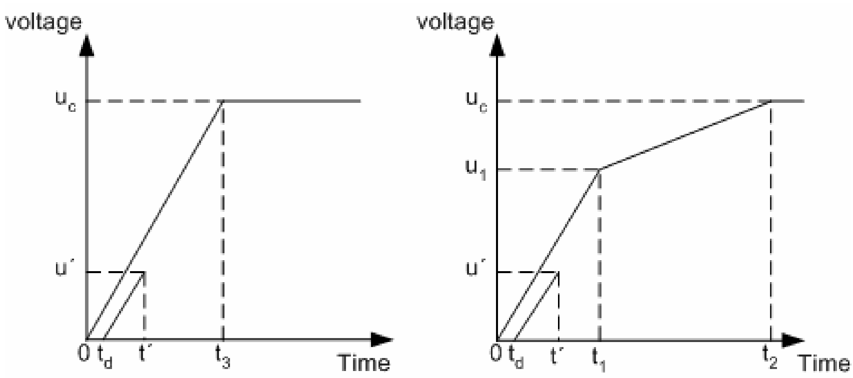
In comparison to stresses of normal load current interruption, the stresses of short-circuit current interruption are higher. Nevertheless, it is not a serious problem as long as the interrupted short-circuit current is still lower than the rated breaking current. It is shown in Table 3.2 that only in the case of a three-phase fault at the terminal (I_{k3TF}) of 123 kV system could the maximum short-circuit current of 104 % of rated breaking current be reached. It is obvious that the stresses of short-circuit current interruption are lower at the higher voltage levels.

3.1.2 Transient Recovery Voltages and Rate of Rise of Recovery Voltages

Transient recovery voltages are the voltages occurring across switching devices after the current interruption and their voltage waveforms are determined by power system configurations. It can be physically explained that this TRV oscillation results from the change of the energy before and after interruption and its duration is in the order of milliseconds. In the past, the TRV was first an unknown phenomenon and could not be explained until the development of the cathode-ray oscilloscope which is able to investigate high frequency oscillation.

The large investigation of TRV was started in 1959 by using the 245 kV networks. The tests focused on the first phase-to-clear after clearing three-phase ungrounded faults. As a result of this investigation, a large number of TRV waveforms in relation to short-circuit currents in the networks up to 45 kV were collected [28]. The results of investigation at 245 kV systems were then applied by IEC standard and the extension of investigation to 420 kV system were performed by CIGRE Study Committee 13. It was found that the RRRV should be 2 kV/µs with a first-phase-to-clear-factor of 1.3 [29].

According to IEC standard, the characteristics of TRV can be determined by two methods: two-parameter and four-parameter methods. These methods are based on the graphical analysis which can represent the magnitude of TRV and RRRV. The two and four-parameter methods are represented in Fig. 3.1 The detail of how to use these two methods to find the magnitude of TRV and RRRV is represented in the appendix of [7].



(a) (b)

Figure 3.1: (a): two-parameter method, (b): four-parameter method

Normally, the two-parameter method is applied in systems with voltages less than 100 kV or in systems with voltages greater than 100 kV where the short-circuit currents are relatively small. In other cases, the four-parameter method is applied in systems with voltages 100 kV and above. The TRV parameters in the IEC standard are classified with respect to proportion of maximum short-circuit current rating, for example, 10 %, 30 %, 60 % and 100 %. The characteristics of each test duty can be summarized as follows:

- *10% short-circuit current, IEC test duty 10*: The fault current is supplied from only one transformer and the TRV has very high steepness of 5.5 kV/µs at 100 kV to 12.6 kV/µs at 765 kV.
- *30% short-circuit current, IEC test duty T30*: The fault current is supplied from 1 or 2 transformers connected in parallel and the RRRV is 5 kV/µs for 100 kV and above.
- *60% short-circuit current, IEC test duty T60*: The fault current is supplied from transformers connected in parallel. The TRV has a steepness of 3 kV/µs for 100 kV and above.
- *100% short-circuit current, IEC test duty T100*: The RRRV is 2 kV/µs. The additional requirement of this test duty is ability to interrupt short-circuit current with operating sequence, for example, O-0.3s-CO-3min-CO. O represents opening operation and CO

represents closing operation followed immediately by an opening operation. The test duty T100 can be divided into two types: T100s (test with symmetrical short-circuit current) and T100a (test with asymmetrical short-circuit current).

3.2 Effects of Grounding and Types of Applications to Stresses of HV Circuit-Breakers

In order to investigate electrical stresses of circuit-breakers according to effects of grounding and types of applications, the 110 kV radial network model which has the short-circuit rating of 40 kA and 10 kA is established. This model is composed of five transmission line circuits and five cable circuits. The capacitor bank and the shunt reactor are also introduced in the network to simulate the stresses of interruption of capacitive current and chopping current respectively. Various types of grounding, isolated grounding, compensated grounding and solid grounding, at the main transformer have been applied. Interrupted currents, TRV and RRRV are taken into account in order to compare the stresses of circuit-breakers in any applications. The simulation of TRV and RRRV have been carried out by using PSCAD/EMTDC program, whereas short-circuit and load currents are simulated by ABB/NEPLAN program.

3.2.1 Test System Configurations, Specifications and Modelling of Equipment

The test system diagram is represented in Fig. 3.2. The ratings of 380/110 kV transformers, 300 MVA and 1200 MVA, are selected regarding the rated short-circuit currents of 10 kA and 40 kA respectively. The specifications and modelling of elements can be represented as follows:

- *Voltage source*: The voltage source of 380 kV with the rated short-circuit capacity of 63 kA is selected.
- *380/110 kV power transformers*: The transformer ratings of 300 MVA and 1200 MVA according to 10 kA and 40 kA respectively are applied. This 40 kA rating is considered as the maximum short-circuit rating for 110 kV circuit-breakers.

- *Transmission lines*: The length of transmission line of 25 km/circuit is modelled as distributed elements by using a frequency dependent model. The single conductor Al/St 240/40 and a double circuit have been used to model the transmission line circuit.
- *110 kV cables*: The single conductor per phase of the XLPE cable with the length of 15 km/circuit has been used.
- *20 kV cables*: The 20 kV cable with length of 80 km/circuit in the distribution network is modelled as lumped shunt capacitance.
- *110/20 kV distribution transformers*: The distribution transformers of 31.5 MVA are selected for supplying the loads of 13.5 MW/circuit.
- *Shunt reactor*: The shunt reactor of 100 MVar is installed at the receiving end of the 110 kV cable circuit to compensate the reactive power. Stray capacitance with the natural frequency of 2 kHz must be taken into account.
- *Capacitor banks*: Grounded and ungrounded capacitor banks of 10 MVar are installed behind the main circuit-breaker in order to study the stresses between different configurations.
- *Load*: In each circuit, the load of 15 MVA at 0.9 power factor is taken into consideration. The load model for medium voltage system is recommended in [30]. The parallel capacitance represents the capacitance of cable in distribution circuit.
- *System groundings*: The groundings of the system are composed of three types: isolated, compensated and solid grounding. The compensating coil in compensated grounding is introduced in order to compensate the earthed fault current.

3.2.2 Simulation Cases

Different circuit-breaker applications have been introduced in order to simulate stresses of circuit-breakers. In every application, the simulation is carried out by changing types of grounding and interrupting currents. The three main parameters: interrupted current, TRV and RRRV are taken into account. The applications of circuit-breakers in this study are composed of:

1. Switching-off no-load transmission line (Fig. 3.3a)
2. Switching-off no-load cable (Fig. 3.3b)
3. Interruption of single-phase 90 % short-line fault in transmission line (Fig. 3.3c)

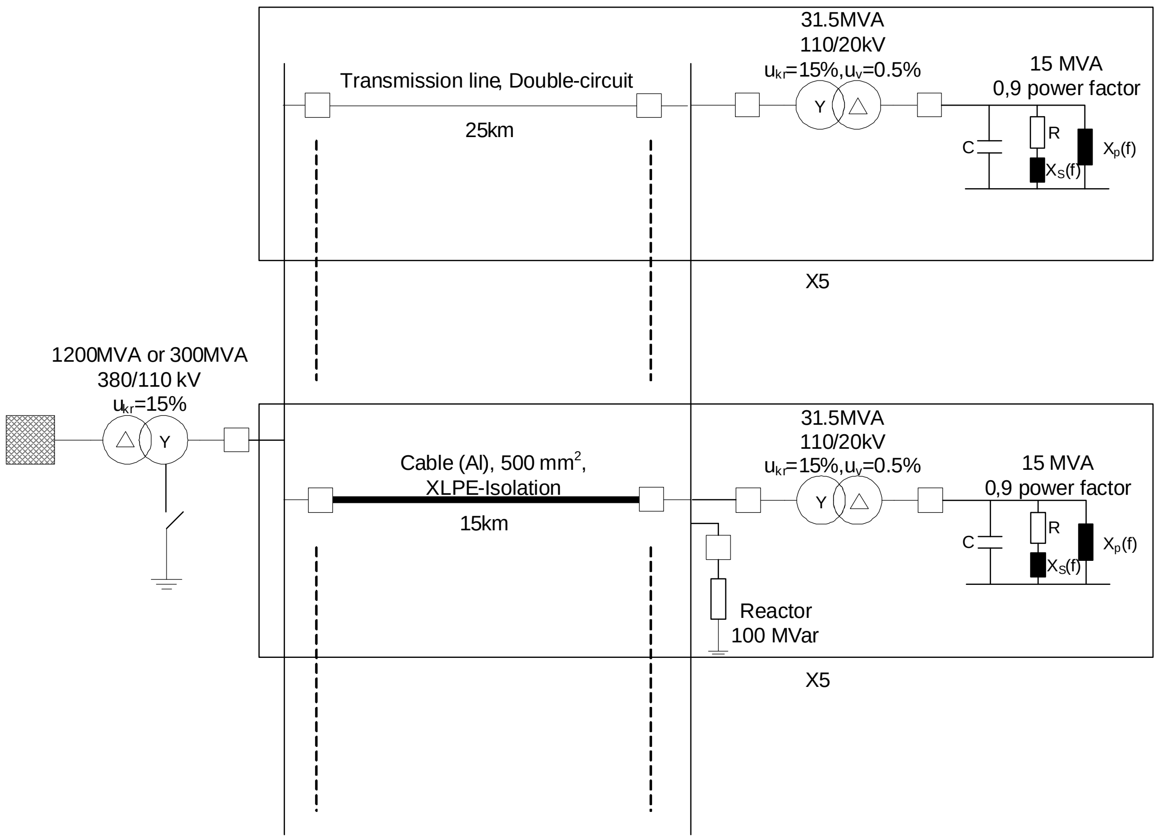


Figure 3.2: Simulation diagram of a test radial 110 kV system

4. Interruption of three-phase 90 % short-line fault in transmission line (Fig. 3.3d)
5. Interruption of single-phase 90 % short-line fault in cable (Fig. 3.3e)
6. Interruption of three-phase 90 % short-line fault in cable (Fig. 3.3f)
7. Switching-off ungrounded capacitor bank (Fig. 3.3g)
8. Switching-off grounded capacitor bank (Fig. 3.3h)
9. Switching-off shunt reactor (chopping current of 2.5 A, Fig. 3.3i)

TRV waveforms of the first-phase-to-clear of HV circuit-breakers in mentioned applications are illustrated in Fig. 3.3

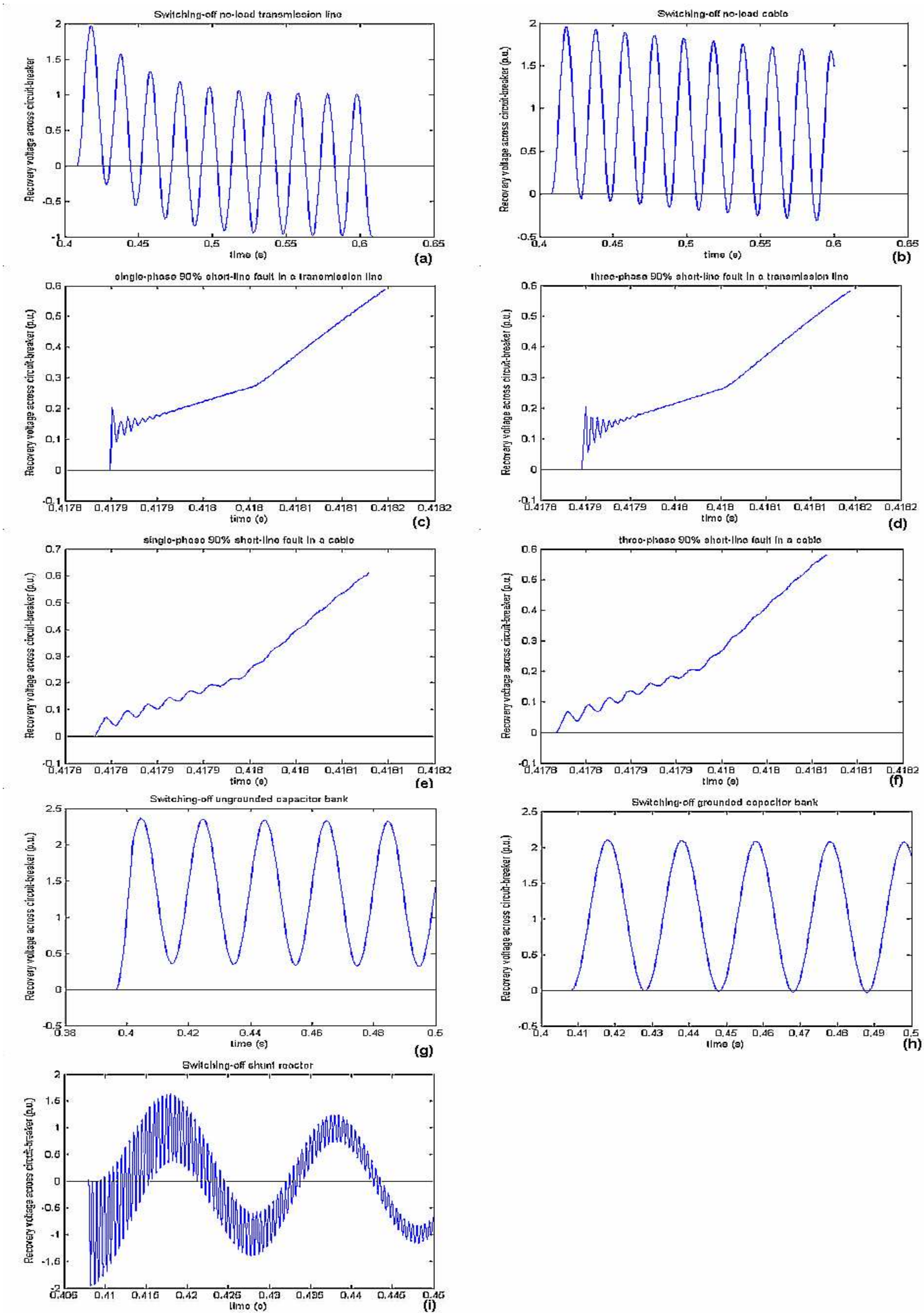


Figure 3.3: Transient recovery voltages across circuit-breakers in any applications

(a): Switching-off no-load transmission line

(b): Switching-off no-load cable

(c): Interruption of single-phase 90 % short-line fault in transmission line

(d): Interruption of three-phase 90 % short-line fault in transmission line

(e): Interruption of single-phase 90 % short-line fault in cable

(f): Interruption of three-phase 90 % short-line fault in cable

(g): Switching-off ungrounded capacitor bank

(h): Switching-off grounded capacitor bank

(i): Switching-off shunt reactor

3.2.3 Simulation Conditions

In order to simulate transients in power systems, the conditions of the simulation must be paid attention, for example, the simulation time step and applied models. The simulation conditions in this study are described as follows:

- *Simulation time step*: The simulation time step is determined by the maximum expected frequency (f_{max}) which is recommended in [30]. The simulation time step can be determined from:

$$\Delta t \le \frac{1}{10 \times f_{max}} \quad (3.1)$$

  The simulation time step of 1 μs is applied for the simulation cases of short-line faults (cases 3-6), since the maximum expected frequency of the beginning of the recovery voltage is very high. The time step of 5 μs is applied for the case 9, whereas the time step of 50 μs is sufficient for cases 1, 2, 7 and 8.
- *Opening of circuit-breaker*: Circuit-breakers are requested to open at current zero in cases 1-8 and at 2.5 A in case 9. The opening time after the initiation of faults is not less than 100 ms.
- *System grounding point*: In case of isolated grounding, there are no grounding points at any transformers. The grounding point in cases of compensated and solid grounding is employed at the 380/110 kV main transformer.
- *Transmission lines and cable models*: The configurations, for example, conductor configuration, tower configuration, sag distance and insulation configuration must be taken into account.

3.2.4 Results of Simulations

The considered parameters of the simulations are composed of recovery voltage across circuit-breaker (TRV), rate of rise of recovery voltage (RRRV), steady-state interrupted current (I_b) and types of system grounding. The results are represented in Table 3.3 and 3.4. It must be noted that the recovery voltages in case of short-line faults are considered by the first peaks of the voltage waveforms. In Table 3.3, there are some cases in which the RRRVs are over the IEC standard of 2 kV/µs. The values of the RRRV which are over IEC standard are then highlighted.

Simulation cases	System grounding								
	Isolated grounding			Compensated grounding			Solid grounding		
	I_b (kA)	TRV (p.u.)	RRRV kV/µs	I_b (kA)	TRV (p.u.)	RRRV kV/µs	I_b (kA)	TRV (p.u.)	RRRV kV/µs
1. Switching-off no-load transmission line	0.009	1.975	0.023	0.009	1.967	0.023	0.009	1.970	0.023
2. Switching-off no-load cable	0.051	2.022	0.022	0.051	1.920	0.021	0.051	1.956	0.021
3. Interruption of single-phase 90% short-line fault in transmission line	0.883	0.007	0.147	0.074	0.002	0.046	29.780	0.202	6.054
4. Interruption of three-phase 90% short-line fault in transmission line	31.073	0.204	6.127	31.073	0.204	6.130	31.073	0.205	6.13
5. Interruption of single-phase 90% short-line fault in cable	0.907	0.002	0.015	0.113	0.001	0.008	33.250	0.073	0.484
6. Interruption of three-phase 90% short-line fault in cable	31.406	0.068	0.506	31.406	0.068	0.508	31.406	0.068	0,509
7. Switching-off ungrounded capacitor bank	0.052	2.346	0.028	0.052	2.346	0.028	0.052	2.346	0.028
8. Switching-off grounded capacitor bank	0.052	2.044	0.022	0.052	1.962	0.021	0.052	1.985	0.021
9. Switching-off shunt reactor	0.505	1.952	0.862	0.505	1.951	0.862	0.505	1.951	0.862

Table 3.3: The results of simulations of circuit-breaker stresses with the short-circuit rating of 40 kA (the highlighted RRRVs are the values over IEC standard)

Simulation cases	System grounding								
	Isolated grounding			Compensated grounding			Solid grounding		
	I_b (kA)	TRV (p.u.)	RRRV kV/µs	I_b (kA)	TRV (p.u.)	RRRV kV/µs	I_b (kA)	TRV (p.u.)	RRRV kV/µs
1. Switching-off no-load transmission line	0.009	1.956	0.022	0.009	1.949	0.022	0.009	1.949	0.022
2. Switching-off no-load cable	0.050	2.002	0.021	0.050	1.902	0.021	0.050	1.937	0.021
3. Interruption of single-phase 90% short-line fault in transmission lines	0.956	0.017	0.113	0.090	0.004	0.029	8.251	0.210	1.568
4. Interruption of three-phase 90% short-line fault in transmission lines	8.8	0.218	1.631	8.8	0.218	1.63	8.8	0.218	1.631
5. Interruption of single-phase 90% short-line fault in cables	1.0	0.005	0.01	0.132	0.001	0.002	9.321	0.074	0.164
6. Interruption of three-phase 90% short-line fault in cables	9.09	0.074	0.164	9.09	0.074	0.164	9.09	0.074	0.164
7. Switching-off ungrounded capacitor bank	0.052	2.319	0.028	0.052	2.319	0.028	0.052	2.319	0.028
8. Switching-off grounded capacitor bank	0.052	2.025	0.022	0.052	1.944	0.021	0.052	1.965	0.021
9. Switching-off shunt reactor	0.479	1.860	0.808	0.479	1.860	0.808	0.479	1.860	0.808

Table 3.4: The results of simulations of circuit-breaker stresses with the short-circuit rating of 10 kA

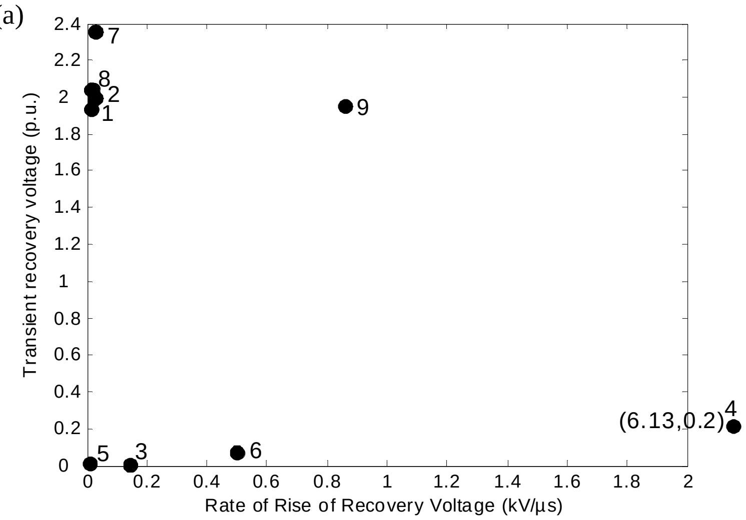
3.2.4.1 Transient recovery voltages (TRV) across circuit-breakers and rate of rise of recovery voltages (RRRV)

The stresses of circuit-breakers in the mentioned applications as a function of the TRV and the RRRV can be represented in Fig. 3.4a-c for the case of 40kA short-circuit capacity. It can be concluded from Table 3.3 and 3.4 that:

- In case of switching-off no-load transmission lines (case 1), the recovery voltages are between 1.949-1.975 p.u. and the RRRVs are around 0.023 kV/µs depending on the types of system grounding. It is obvious that the stress of TRV is relatively high, whereas the stress of RRRV is not the problem.

- The TRVs and the RRRVs in case of switching-off no-load cables (case 2) are 1.902-2.002 p.u. and 0.022 kV/µs respectively. In comparison to switching-off transmission lines, the stress of the TRV is slightly higher in the case of isolated system grounding, but the stress of the RRRV is fairly similar.
- The results from the short-line fault in transmission lines show that the RRRVs relate to the interrupted currents and characteristic impedances. It can be seen that the RRRVs in the case of single-phase short-line fault (case 3) with isolating grounding and compensated grounding are relatively low compared with the case of solid grounding and 3-phase short-line fault (case 4).
- The stresses of the RRRVs in case of short-line fault in cables are not so severe as in the case of the short-line fault in transmission lines because of the lower characteristic impedances of the cables. The RRRVs of single-phase and 3-phase short-line faults are not higher than 0.51 kV/µs.
- Switching-off ungrounded capacitor banks results in the highest TRVs (~2.3-2.35 p.u.) regardless of the types of system grounding. The stresses of RRRVs can be neglected due to very low RRRVs.
- The TRVs in the case of switching-off grounded capacitor banks lie between 1.94 p.u. and 2.04 p.u. corresponding to the system grounding and rating. It is shown that the TRVs are slightly higher when the ratings of the systems are higher. The stresses of the RRRVs play no important roles in this case.
- The stresses of switching-off the shunt reactor from the TRVs and RRRVs are moderately high. The TRVs are around 1.86-1.95 p.u. and the RRRVs are around 0.808-0.862 kV/µs.

(a)



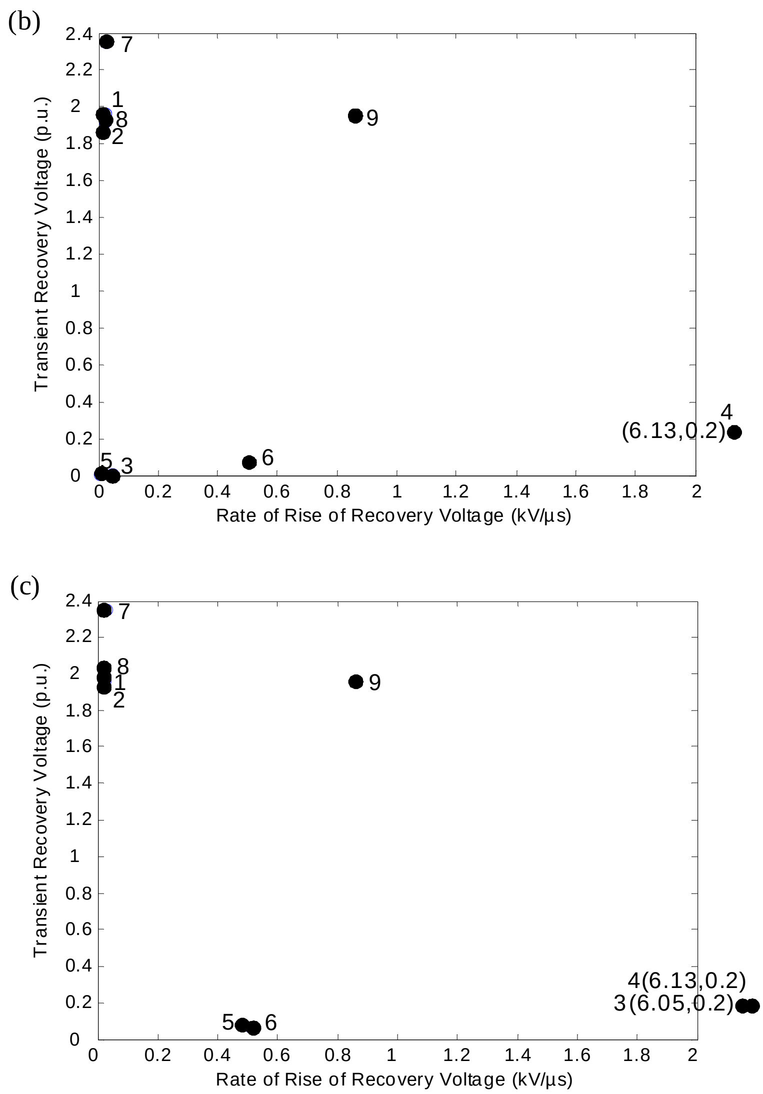


Figure. 3.4: Transient recovery voltages (TRVs) and rate of rise of recovery voltages (RRRVs) of different applications

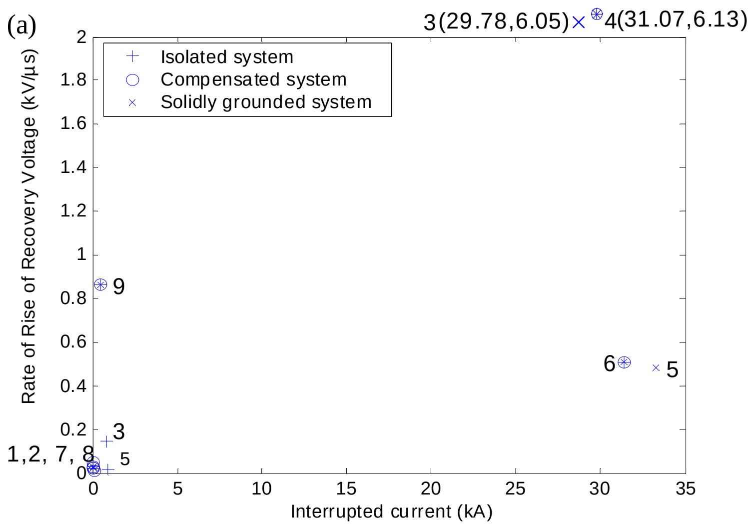
(a): Isolated grounding system

(b): Compensated grounding system

(c): Solidly grounded system

3.2.4.2 Interrupted currents and rate of rise of recovery voltages (RRRVs)

The relationship between interrupted currents and the RRRVs can be depicted in Fig. 3.5a and b. It can be concluded that:



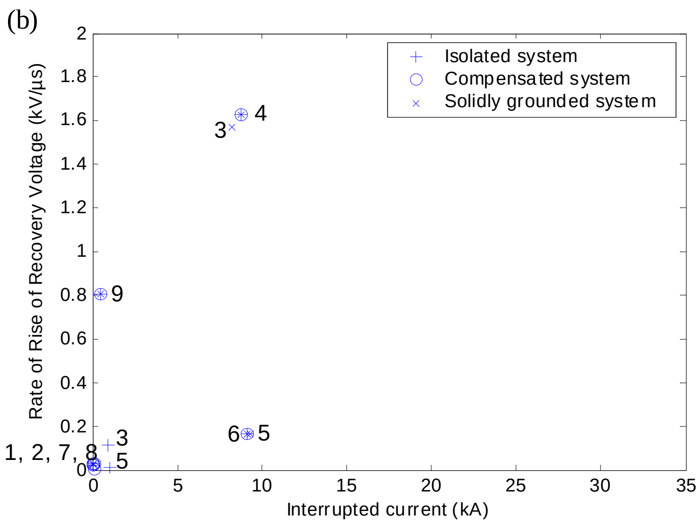


Figure 3.5: The stresses of circuit-breakers with respect to interrupted currents and rate of rise of recovery voltages (RRRVs)

(a): Short-circuit current of 40 kA

(b): Short-circuit current of 10 kA

- The RRRVs subject to the short-line faults in transmission lines are relatively high when the high short-circuit currents are interrupted. It can be seen from Fig. 3.5a that the RRRVs of such cases are around 6 kV/µs. However, the RRRVs of those cases are lower than 2 kV/µs, IEC standard value, when the interrupted currents are lower than 10 kA (Fig. 3.5b).
- In case of short-line faults in cables, the RRRVs are not so high as in transmission lines. The maximum value of the RRRV is less than 0.5 kV/µs when the interrupted currents are lower than 40 kA.

- Stresses of circuit-breakers in terms of the RRRVs in other cases are not so severe because they are lower than standard value of 2 kV/μs

3.2.5 Conclusions

Stresses of circuit-breakers in terms of the TRVs, the RRRVs and interrupted currents can be concluded from the simulations:

- Types of system grounding result in different TRVs, RRRVs and interrupted currents. For example, the interrupted currents of single-phase short-line faults are relatively low in case of isolated grounding and compensated grounding compared with solid grounding. However, types of grounding play no important role in case of 3-phase short-line faults and switching-off ungrounded capacitor banks.
- In the case of capacitive switching (except switching ungrounded capacitor banks), the TRVs in an isolated system are higher than those in a solidly grounded system and a compensated system respectively. These TRVs are dependent of the ratio of positive-sequence to zero-sequence capacitance (C_1/C_0).
- The interrupted currents of single-phase short line faults in a solidly grounded system are relatively high since the faults occur near the supply. In real distribution system, they would not be so high because of the impedances from the power plant to the faulted position are taken into account. Nevertheless, single-phase short line faults must be considered when the circuit-breakers are installed near power plants.
- It is obvious that 3-phase short-line faults result in very high RRRVs thus leading to the breakdown of circuit-breakers. In order to reduce the very high RRRVs, the resistance or capacitance will be applied in parallel with contact break.
- It could be concluded from the simulation that the circuit-breakers designed for interrupting capacitor banks can be also used for interrupting no-load transmission lines and no-load cables.
- It is evident that the RRRVs in case of short-line faults are related to the interrupted currents.
- The configuration of the whole system plays an important role in the TRVs and the RRRVs. For example, the zero-sequence capacitances of cable circuits affect the

transient recovery voltages. Without these cable circuits, transient recovery voltages are supposed to be higher.

- In comparison to IEC standard, the values of the RRRV in most cases are lower than the standard value (2 kV/µs) except in some cases of interruption due to a short-line fault in a cable and/or transmission line.

3.3 Stresses of HV Circuit-Breakers by Combined Statistical Method

The electrical stresses of circuit-breakers are mainly determined by operating currents, short-circuit currents and switching operation. In addition, the number of faults on overhead lines which circuit-breakers have to be interrupted is taken into account but considered separately from the electrical stresses. The aim of this study is to combine and investigate electrical stresses of circuit-breakers as a function of fault frequency and fault severity. The combination of fault density and fault severity of circuit-breakers are carried out by statistical method. Number of faults, short-circuit currents and length of transmission lines in 123 kV, 245 kV and 420 kV were collected from the utility during 10-year operation.

3.3.1 Concepts of Combined Statistical Method

The approach of combined statistical method is introduced by [31] and is mentioned as Chessboard method. This method can combine stresses of circuit-breakers as a function of fault density and fault severity. The result of the investigation indicates which areas are subject to the highest stress and which area the faults most frequently take place.

3.3.2 Investigation of HV Circuit-breaker Database

The population of circuit-breakers is taken from a utility in Germany. Only this utility is taken into account, since the utility provides the required information, such as number of faults, short-circuit currents and the length of transmission lines. Such information is necessary for the combined statistical method. Due to lack of complete information, other databases from other utilities cannot be applied in this study. The total population of circuit-breakers on different voltage levels is represented in Table 3.5.

	123 kV	245 kV	420 kV
no. of circuit-breakers	656	74	55

Table 3.5: The total population of HV circuit-breakers

Transmission lines in 123 kV, 245 kV and 420 kV are taken into consideration. However, not every transmission is subject to the faults. Table 3.6 represents the total number of transmission lines and the total lengths. It can be calculated from Table 3.6 that the proportions of faults in terms of the line length are 28.84 %, 66.33 % and 84.94 % in 123 kV, 245 kV and 420 kV respectively. In comparison with the proportions of faults (in terms of number of faulted lines), the proportions of faults are 22.40 %, 45.24 % and 48.39 % in 123 kV, 245 kV and 420 kV respectively. In conclusion, the faulted areas in higher voltage levels are larger than in lower voltage levels.

	123 kV	245 kV	420 kV
no. of lines	299	42	31
the length of lines (km)	3320	1417	963
no. of faulted lines	67	19	15
the length of faulted lines	951	940	818

Table 3.6: The population of transmission lines and the lengths of transmission lines

The maximum expected short-circuit currents in the substations had been recorded and divided by the rated short-circuit breaking currents (I_{rb}). Regardless of fault types, faults of each phase on faulted transmission lines were investigated. The numbers of faults per phase on different voltage levels are represented in Table 3.7

	123 kV	245 kV	420 kV
no. of faults per phase	352	307	260

Table 3.7: Investigated faults on transmission lines

In connection with Table 3.6, the average number of faults per phase per line on different voltage levels can be calculated. It is represented that the average number of faults per phase per line are 5.25, 16.16 and 17.33 in 123 kV, 245 kV and 245 kV respectively. It is obvious that the higher the voltage level, the higher the numbers of faults per phase per line.

3.3.3 Data Evaluation and Analysis

In order to apply the combined statistical method, the necessary information is collected and then investigated. The data evaluation steps are represented in Fig.3.6

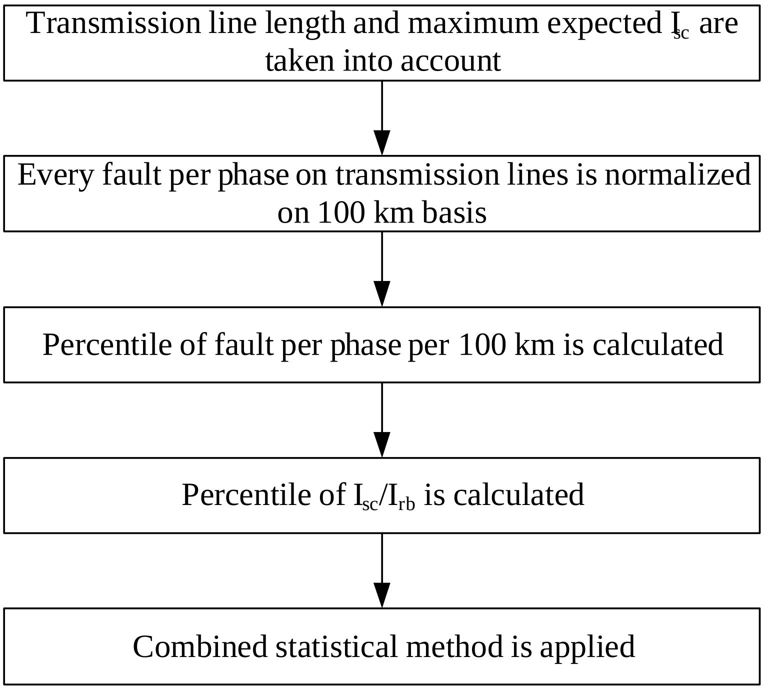


Figure 3.6: Steps of evaluation

The density of fault or frequency of fault can be calculated by using transmission line length and numbers of faults. After that the values are normalized on a 100 km basis. Every fault in every transmission line is separately considered. In other words, “faults per phase per 100 km” of each fault can be calculated by the following equation.

$$\text{Faults per phase per 100 km} = (1/\text{line length}) \times 100 \qquad (3.2)$$

The examples of fault determination from the database are given in Table 3.8. After faults per phase per 100 km are calculated, the percentile of them are then determined. Fault severity or the proportion of maximum expected short-circuit current to rated breaking current (I_{sc}/I_{rb}) can be obtained from the database. Afterwards, the percentile of it is determined

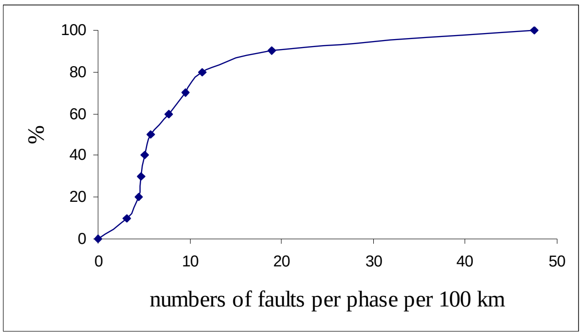
fault ID	Line length (km)	Faults/phase/100 km	I_{sc}/I_{rb}
1	4.5	22.22	0.71
2	4.5	22.22	0.71
3	10.4	9.62	0.53
4	10.4	9.62	0.53
5	10.4	9.62	0.53
6	10.4	9.62	0.53
7	17.5	5.72	0.23
8	17.5	5.72	0.23
9	17.5	5.72	0.23
10	23.02	4.34	0.31

Table 3.8: The examples of fault determination

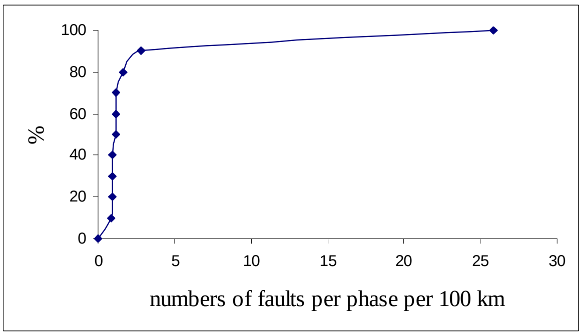
3.3.4 Implementation of Combined Statistical Method

The percentiles of faults per phase per 100 km and percentiles of I_{sc}/I_{rb} in 123 kV, 245 kV and 420 kV are carried out. Table 3.9 represents the percentiles of faults per phase per 100 km and percentiles of I_{sc}/I_{rb}. In 245 kV and 420 kV, there are only 19 and 15 faulted transmission lines respectively, thus resulting in repetitive “faults per phase per 100 km” values. As a result, the percentiles in 245 kV and 420 kV are not well distributed.

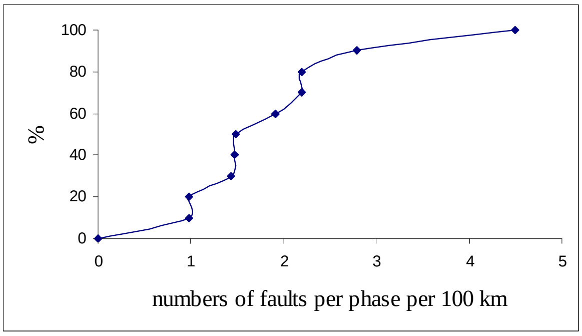
The percentiles of faults per phase per 100 km and percentiles of I_{sc}/I_{rb} can be represented in terms of graphs as shown in Fig. 3.7 and 3.8



(a)

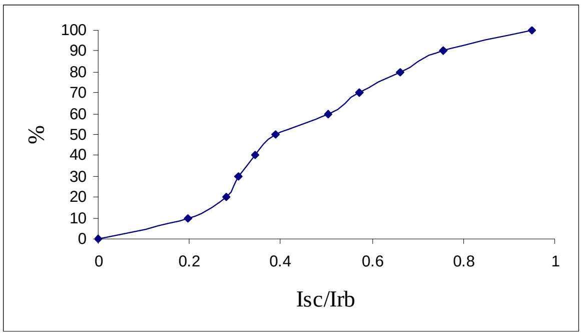


(b)

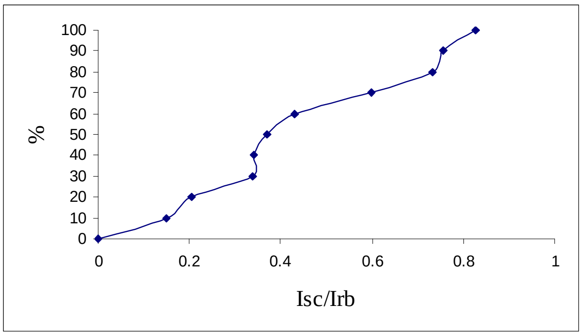


(c)

Figure 3.7:The Percentiles of faults per phase per 100 km
(a): 123 kV
(b): 245kV
(c): 420 kV



(a)



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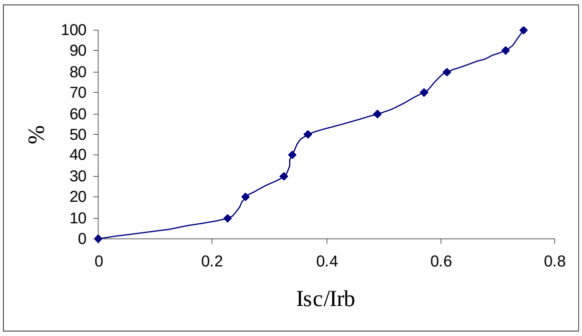


(c)

Figure 3.8:The percentiles of I_{sc}/I_{rb}
(a): 123 kV
(b): 245kV
(c): 420 kV

The percentiles of faults per phase per 100 km (Fig. 3.7) are calculated from the individual faults on different line lengths at different voltage levels. Therefore, it cannot be concluded that the number of faults are dependent on the voltage level. It is ascertained by CIGRE WG 13.08 that the number of faults is independent from the voltage level. It is shown in Fig. 3.8 that the 100% percentile of I_{sc}/I_{rb} in 123 kV system is higher than in 245 kV and 420 kV systems. In other words, circuit-breakers in 123 kV system have more stress from short circuit-current than those in 245 kV and 420 kV.

Percentiles	123 kV		245 kV		420 kV	
	faults/ phase/ 100 km	I_{sc}/I_{rb}	faults/ phase/ 100 km	I_{sc}/I_{rb}	faults/ phase/ 100 km	I_{sc}/I_{rb}
10%	3.154	0.198	0.840	0.149	0.988	0.226
20%	4.437	0.280	0.917	0.205	0.988	0.258
30%	4.669	0.307	0.917	0.338	1.428	0.325
40%	5.121	0.343	0.956	0.342	1.476	0.340
50%	5.716	0.389	1.1364	0.369	1.492	0.368
60%	7.703	0.503	1.1364	0.431	1.909	0.488
70%	9.507	0.571	1.1364	0.599	2.194	0.571
80%	11.342	0.661	1.637	0.732	2.194	0.612
90%	18.975	0.756	2.841	0.756	2.794	0.714
100%	47.551	0.950	25.873	0.826	4.495	0.746

Table 3.9: Percentiles of faults per phase per 100 km and percentiles of I_{sc}/I_{rb}

3.3.5 Results of Combined Statistical Method

Parameters of faults, faults per phase per 100 km and I_{sc}/I_{rb}, in 123 kV, 245 kV and 420kV are compared with the percentile values in Table 3.9 by using a counting program developed in MATLAB and then placed into the 10 x 10 squared boxes. Every square-box represents percentiles of faults per phase per 100 km and percentiles of I_{sc}/I_{rb} in a range of 10 %. The squared boxes of faults in 123 kV system are represented in Fig. 3.9a and the size of squared boxes can be reduced into 5 x 5 squared boxes as shown in Fig. 3.9b.

Percentiles of faults per phase per 100 km

90	0,0	0,0	2,8	0,0	1,4	1,4	0,6	2,6	1,1	0,0
	1,7	0,6	0,9	0,0	0,0	2,6	1,4	1,4	0,0	1,1
70	4,8	2,0	1,7	0,0	0,0	0,3	1,7	0,0	0,0	0,0
	0,0	0,9	0,6	0,0	1,7	0,6	0,0	2,3	0,6	3,4
50	2,0	0,6	1,4	0,0	0,6	0,6	0,0	0,6	2,3	1,1
	1,1	1,4	0,0	0,0	0,0	0,0	4,3	2,0	0,6	0,0
30	0,0	0,9	0,0	0,0	2,3	0,0	0,0	0,9	0,6	2,8
	0,0	4,8	0,0	4,8	1,4	1,4	0,0	0,0	0,0	0,0
10	0,6	1,1	0,9	1,1	2,6	1,4	0,0	0,0	2,3	1,4
	0,0	0,0	0,0	4,5	0,0	0,9	2,0	0,0	2,8	0,0
%	10		30		50		70		90	

Percentiles of Isc/Irb

(a)

Percentiles of faults per phase per 100 km

80	2.27	3.69	5.40	5.97	2.27
60	7.67	2.27	2.56	3.98	3.98
40	5.11	1.42	1.14	6.82	3.98
20	5.68	4.83	5.11	0.85	3.41
	1.70	6.53	4.83	1.99	6.53
%		20	40	60	80

Percentiles of Isc/Irb

(b)

Figure 3.9: Results of combined statistical method in 123 kV system
(a): Population distribution in % (10 x 10 squared boxes)
(b): Population distribution in % (5 x 5 squared boxes)

It is obvious that the highest density of faults (7.67%) lies between 0-20 % percentile of I_{sc}/I_{rb} and 60-80 % percentile of faults per phase per 100 km. In other words, at the highest density of faults, circuit-breakers are subject to 7.7-11.3 faults per phase per 100 km with the proportion of I_{sc}/I_{rb} up to 0.280. The second highest density (6.82 %) lies between 60-80 % percentile of I_{sc}/I_{rb} and 40-60 % percentile of faults per phase per 100 km. Circuit-breakers in this area are exposed to 5.1-7.7 faults per phase per 100 km with the proportion of I_{sc}/I_{rb} between 0.50-0.66.

The results of combined statistical method in 245 kV and 420 kV systems are distributed as shown in Fig. 3.10 and 3.11 respectively.

Percentiles of faults per phase per 100 km

80	0.00	0.65	0.00	11.73	1.95
60	0.98	12.70	1.30	0.00	0.00
40	12.05	0.00	11.40	0.00	0.00
20	7.49	0.00	0.00	0.00	7.49
	0.00	10.10	6.84	7.49	7.82
%		20	40	60	80

Percentiles of Isc/Irb

Figure 3.10: Results of combined statistical method in 245 kV system

Percentiles of faults per phase per 100 km					
80	2.31	0.77	4.23	3.46	0.77
60	0.00	2.31	10.38	3.85	8.46
40	5.77	4.23	0.00	9.23	0.00
20	2.69	0.00	2.31	5.77	8.46
	9.23	15.77	0.00	0.00	0.00
%		20	40	60	80

Percentiles of Isc/Irb

Figure 3.11: Results of combined statistical method in 420 kV system

In 245 kV system, the highest density of faults (12.70 %) is placed between 20-40 % percentile of I_{sc}/I_{rb} and 60-80 % percentile of faults per phase per 100 km. In other words, circuit-breakers are mostly subject to 1.1-1.6 faults per phase per 100 km with the proportion of I_{sc}/I_{rb} between 0.20-0.34.

In 420 kV system, the highest density of faults (15.77 %) lies between 20-40 % percentile of I_{sc}/I_{rb} and 0-20 % percentile of faults per phase per 100 km. This value corresponds to circuit-breakers subject to 0.99 faults per phase per 100 km and the proportion of I_{sc}/I_{rb} between 0.26-0.34.

When the 90 % percentile of faults per phase per 100 km and 90 % percentile of I_{sc}/I_{rb} are considered, the population in the area from 90 % to 100 % has to be aggregated. For example, the population of circuit-breakers in 123 kV system between 90 % to 100 % percentile of faults per phase per 100 km and I_{sc}/I_{rb} represents 19.88 % as shown in shaded area of Fig. 3.9a. This 90 % area in 245 kV and 420 kV systems represents 15.96 % and 15.77 % respectively. The highest density of faults at different voltage levels can be concluded in Table 3.10.

Voltage (kV)	Percentile of faults per phase per 100 km	Percentile of I_{sc}/I_{rb}
123	60 – 80 %	0 – 20 %
245	60 – 80 %	20 – 40 %
420	0 – 20 %	20 – 40 %

Table 3.10: The highest density of faults at different voltage levels

It is concluded that the combined statistical approach is a useful tool to investigate the stresses of circuit-breakers in terms of fault density and fault severity. The result of the investigation can highlight the areas subject to the highest stress and the areas the faults most frequently occur.

In order to have more reliable results, a large number of samples must be taken into account. It is recommended that utilities should provide the information related to the numbers of faults, faulted transmission line length and short circuit-current or maximum expected short-circuit current.

4 Failure Modes and Effects Analysis

4.1 Concepts and Definitions

The main principles of designing optimal diagnosis and maintenance programs depend on the basis of: which types and how often the failures occur, how severe the consequences are and which maintenance strategies are suitable to prevent such failures. Failure Modes and Effects Analysis (FMEA) is the systematic approach to investigate failures by identifying functions, failure modes and consequences of failures. In addition, the failure database such as the probability of failures must be integrated into the FMEA approach in order to assess the severity of failures.

FMEA can be considered as an important part of Reliability-Centred Maintenance (RCM) which is the method for achieving cost-effective programs. RCM was first applied in the civil aircraft industry in 1960s for the Boeing 747 series, which are more complicated than previous types. Concepts and fundamental principles of RCM can be defined in [32], [33] and [34]. It can be concluded from the first definition of RCM [33] that the aims of RCM method are: preservation of system functions, identification of failure modes, prioritizing of functions and selection of effective maintenance programs. The other definition and process of RCM method are based on seven questions [34]:

- What are the functions and associated performance standards?
- In what ways can the functions fail?
- What are the causes of each functional failure?
- What are the effects of each failure?
- What are the consequences of each failure?
- How to predict or prevent each failure?
- What can be done if there is no suitable preventive task?

The steps of an RCM analysis can be summarized as followed [35]:

- Study preparation
- System selection and definition
- Functional failure analysis
- Critical item selection
- Data collection and analysis
- Failure modes and effects analysis
- Selection of maintenance tasks
- Determination of maintenance intervals
- Preventive maintenance comparison analysis
- Treatment of non-critical items

The application of RCM to power systems was first introduced by EPRI in the area of the nuclear power industry. In the area of substation and HV circuit-breakers, the RCM methods and techniques can be reviewed in [36], [37] and [38]. The more detail and complete process of RCM applied to distribution systems is shown in [39]. In that study, the cable systems were selected from the RCM process to perform maintenance evaluation.

In the following evaluation, the application of FMEA to HV circuit-breakers had been studied and implemented in two aspects:

- Which components affect the functional failures of circuit-breakers
- How high are the risks to components in circuit-breakers

In order to conduct a FMEA process for HV circuit-breakers, the functions of circuit-breakers must be first defined. Afterwards, the types of damages from the functional failures are listed. The consequences of failures are then investigated by considering four main categories of consequences: personnel safety, environmental impact, operation availability and costs of repair. With the integration of the HV circuit-breaker database of Darmstadt University of Technology, it is possible to evaluate the severity of failures of each component of circuit-breakers resulting in risk assessment.

4.2 Patterns of Failures

The patterns of failures or failure characteristics represent the development of failures over time. The failures can occur suddenly or over a long period of time. The patterns of failures depend mainly on physical, on chemical mechanism and on types of equipment. The main patterns of failures as a function of failure rate can be represented in Fig. 4.1

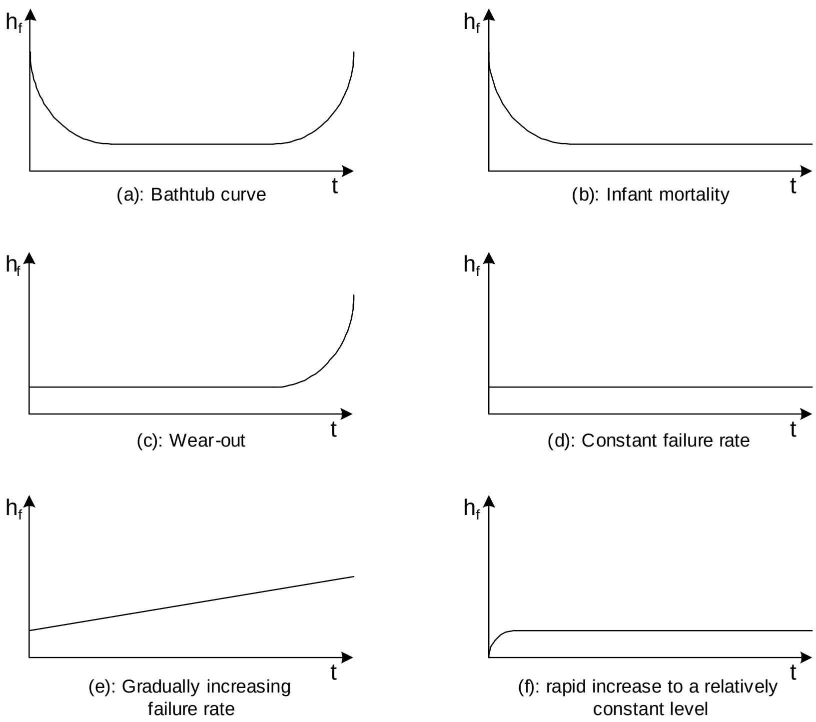


Figure 4.1: The patterns of failures

According to Fig. 4.1, the meanings of patterns of failures can be explained as followed:

- (a) Bathtub curve: This is the typical failure characteristic of power system equipment such as transformers and circuit-breakers. The failure rate is relatively high at the commissioning period and then reduced to the constant level during useful life. The failure rate is increased when the equipment starts to deteriorate.
- (b) Infant mortality: This type of failure characteristic is considered right after commissioning. The failure rate is relative high and then gradually reduced to the constant rate. The causes of high failure rate at the beginning result from manufacturing defects, defective parts, poor quality control, contamination and poor workmanship.

- (c) Wear-out: This pattern of failure is recognized during the deterioration process resulting from corrosion, aging and friction. The failure rate is gradually increased with increasing ages of equipment.
- (d) Constant failure rate: This failure characteristic is mentioned as “Acts of God” or random error, since the failure rate remains constant for a period of time. It is the pattern of failure during useful life.
- (e) Gradually increasing failure rate: This is the aging pattern without identifiable wear-out age.
- (f) Rapid increase to a relatively constant level: This pattern of failure represents very low failure rate at the beginning because of new status of the equipment. The failure rate is then increased until it is constant.

The failures related to the operating time, as shown on the left-side of Fig. 4.1, can be prevented by using preventive maintenance programs such as scheduled maintenance, inspection and overhaul. In this circumstance, the specific period to perform preventive maintenance is defined to keep failure probability within the acceptable level. This maintenance program is carried out without consideration of equipment status.

The other type of failure, which is not relevant to the operating time, as shown on the right-side of Fig. 4.1, can be prevented by using predictive maintenance or condition-based maintenance. The maintenance programs of HV circuit-breakers can be categorized as follows:

- Corrective maintenance: This maintenance program is mentioned as a replacement program when the components fail. It is usually applied for components of which failures have small consequences to the operation or when the failures rarely occur.
- Condition-based maintenance: This maintenance program is applied on the basis of status of components by using diagnosis methods. However, the technical and economical aspects must be taken into account.
- Time-based maintenance: It can be referred to scheduled maintenance which is carried out according to specific interval. This type of maintenance is still the most widely used maintenance program nowadays.
- Reliability-centered maintenance: This is a systematic maintenance program which is based on the status and failure consequences of equipment to the whole system.

4.3 Steps of Failure Modes and Effects Analysis for HV Circuit-Breakers

The reference FMEA table and its example can be represented in Table 4.1 and steps of FMEA of HV circuit-breakers can be explained in order as follows:

Failure mode	Failure cause			Prob. of failure	Consequences of failures	Failure detection	Criticality	Ranking	Maintenance
	level 1	level 2	level 3						
1. Does not close on command	1. Operating mecha-nism fails	1.1 Drive fails	1.1.1 Motor fails	0.0058	O- / C-	Easy	12.63	42	Condition-based
			1.1.2 N2 Storage fails	0.037	O / C-	Easy	90.79	20	Condition-based

Table 4.1: The reference of FMEA table and its example

4.3.1 Failure Database and Investigation

The failure database must be provided before the FMEA process begins. The failure database, collected from utilities from 1960s to 2003, has been divided into five main components: operating mechanism, HV insulation, life-parts, control/auxiliary and others. Each main component can be further subdivided into many subcomponents. The detailed treeing diagram of every component can be found in Appendix D of [40]. The subcomponents with the number of failures can be found by using the web-based failure database developed by the Institute of Power Systems, Darmstadt University of Technology. As a result, a complete treeing diagram of HV circuit-breakers composed of subcomponents and number of failures is achieved. The subcomponents with the failure statistics play a very important role for failure modes and effects analysis, since the functional failures are directly related to those subcomponents.

In this study, only SF6 circuit-breakers are of interest because they are predominant in the high voltage levels. The number of 4275 failures from 4357 SF6 circuit-breakers has been arranged regarding the subcomponents. It must be noted that the distinction between minor and major failures is not defined in this database.

4.3.2 Functions of HV Circuit-Breakers

This is the first step to start the FMEA of HV circuit-breakers. The functions of HV circuit-breakers can be defined as follows:

- Switching-off operating current
- Switching-on operating current
- Short-circuit current interruption
- Secure open and closed position

The next step is to consider the failures where HV circuit-breakers cannot fulfil the functional requirements.

4.3.3 Functional Failure Modes of HV Circuit-Breakers

When HV circuit-breakers cannot fulfil the functional requirements as stated in section 4.3.2, the types of functional failure modes must be defined. Normally, the failures can be divided into two types of failures: major and minor failures. The minor failures can be prevented by using scheduled maintenance. In order to do such maintenance, two questions must be answered:

- What are the causes of failures?
- Which events generate the failures?

The possible functional failure modes of HV circuit-breakers according to CIGRE surveys can be listed as followed:

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

These functional failure modes are listed in the “failure mode” column of FMEA Table as represented in Table 4.1.

4.3.4 Causes of Failures

This is the process after the functional failures are set up (section 4.3.3). The causes of functional failures regarding components are considered and categorized. Furthermore, the detail of the component failures must be investigated with the knowledge from experts and guidance of IEEE [41]. For example, the failure of an operating mechanism results in the functional failure modes “Does not close on command”, “Does not open on command”, “Close without command”, “Open without command” and “Does not break the current”. The possible causes of failures of an operating mechanism must be figured out. They are then compared with the failure database; thereby the number of failures can be arranged regarding components. It must be noted that the failure database is based on the failures of components without the records of failure modes. Therefore, the proportion of failures from CIGRE, Table 4.2, which occurred in any failure modes, must be applied.

For example, the causes of hydraulic operating mechanism failure in the functional failure mode “Does not close on command” are composed of: 20 failures of motors, 160 failures of N2 Storage, 230 failures of connection, 33 failures of values and others. The failure causes in FMEA Table are subdivided in 3 levels as represented in Table 4.1.

4.3.5 Consequences of Failures

After the causes of failures are classified, the next step of the FMEA is to evaluate the consequences of failures. The evaluation of the consequences of failures is significant to figure out the importance of failures. In this study, the consequences of failures are categorized into four groups:

- Personnel safety
- Environmental impact
- Operation availability/Duration of repair
- Costs of repair

Characteristic	Proportion of failures 2nd Enquiry
Does not close on command	24.6 %
Does not open on command	8.3 %
Closes without command	1.1 %
Opens without command	7.0 %
Does not make the current	1.7 %
Does not break the current	3.0 %
Fails to carry the current	1.5 %
Breakdown to earth	3.2 %
Breakdown between poles	1.5 %
Breakdown across open pole (Internal)	3.6 %
Breakdown across open pole (External)	1.5 %
Locking in open or closed position	28.5 %
Others	14.6 %

Table 4.2: The proportions of functional failure modes from the CIGRE's 2nd enquiry

Moreover, these four main groups are subdivided into 10 levels of consequences with the application of a score system as shown in Table. 4.3 The total consequences of failures can be represented as:

$$\text{Consequences of failures} = \text{Personnel safety} + \text{Environmental impact} + \text{Duration of repair} + \text{Costs of repair} \quad (4.1)$$

The consequences of failures of FMEA Table (Table 4.1) are represented in the column of "Consequences of failures".

Consequence		Description of consequences	Score
P:	Personnel safety	Injury or death of personnel	10
E+:	Environmental impact	Release of SF_6 and oil insulating medium	9
E:	Environmental impact	Occurrence of fire	8
E-:	Environmental impact	No release of SF_6 and oil insulating medium	7
O+:	Duration of repair	> 5 days	6
O:	Duration of repair	2-5 days	5
O-:	Duration of repair	2 days	4
C+:	Costs of repair	> 10000 Euro	3
C:	Costs of repair	1000-10000 Euro	2
C-:	Costs of repair	< 1000 Euro	1

Table 4.3: Consequences of failures and their descriptions

4.3.6 Failure Detection

In order to evaluate the consequences of failures in section 4.3.5 conservatively, the criterion of “Failure detection” must be considered. In other words, it is very important to determine if the failures can be detected by the diagnosis or observation methods. For instance, the consequence of SF_6 leakage is severe, but it is easy to detect this circumstance by a monitoring technique, thus reducing the probability of occurrence. The process of failure detection analysis is carried out by introduction of a score system as represented in Table 4.4

Failure detection	Score
Impossible to detect	3
Difficult to detect	2
Easy to detect	1

Table 4.4: Failure detection

The descriptions of different levels of failure detection can be explained as followed:

- Impossible to detect: The failure cannot be discovered by the maintenance method.
- Difficult to detect: The failure is not be able to be diagnosed or the additional diagnose must be required.
- Easy to detect: The failure can be detected by the maintenance method.

4.4 Failure Modes and Effects Analysis Evaluation Process

The process of the FMEA, after assembling the required information in section 4.3, can be represented in Fig. 4.2

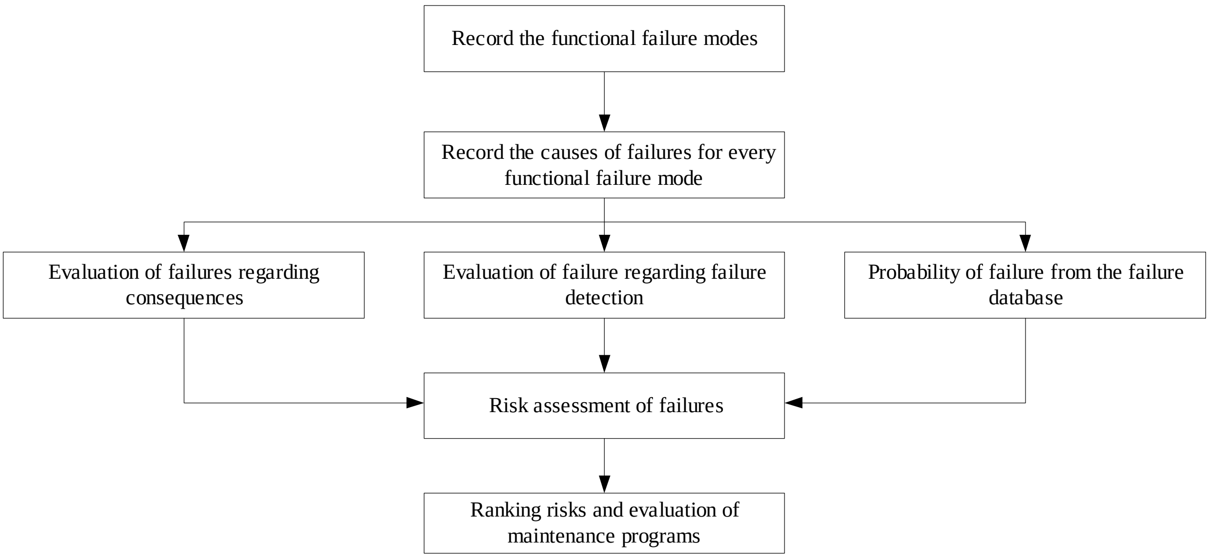


Figure 4.2: The flowchart of FMEA evaluation process

It can be seen from Fig. 4.2 that the risk assessment of failures are comprised of the product of three parameters: consequences, failure detection and probability of failure. The product of first two parameters, consequences and failure detection, are mentioned as the entire consequences. The consequence damage with the highest score represents the highest risk of the considered component. Therefore, the appropriate maintenance program must be applied to reduce this high risk. Due to the application of the score system for different parameters, the results of the evaluation are largely dependent on the range of the score scales. In order to reduce this effect, the decision matrix approach as shown in Fig. 4.3 must be implemented [42]. With this method, every 2 parameters are compared with each other, in this case providing an indication of the risk.

Criteria	A: Consequence of failure	B: Failure detection	C: Probability of failure	Σ	**WF/%**
A: Consequence of failure	0	1	1	2	16.7
B: Failure detection	3	0	3	6	50.0
C: Probability of failure	3	1	0	4	33.3
				12	100.0

Figure 4.3: The decision matrix

The weighting factors with respect to the decision criteria can be defined as follows: (example)

- The effect of parameter A is smaller than B: 1
- The effect of parameter A is similar to B: 2
- The effect of parameter A is larger than B: 3

The summation of each parameter on the horizontal axis is compared with the total summation on the vertical axis, resulting in the proportion of each parameter to the total effect. The evaluation with this method represents the maximum weighting factors that should be applied for each parameter. The maximum weighting factors for each parameter can be concluded as followed:

- Consequence of failure 16.7%
- Failure detection 50.0%
- Probability of failure 33.3%

The weighting factors of the three parameters show that the effect of failure detection plays a higher significant role for risk assessment than the other two parameters. The equation of risk assessment composed of three mentioned parameters can be expressed as:

$$\text{Risk} = \text{Consequence of failure} \times \text{Failure detection} \times \text{Probability of failure} \qquad (4.2)$$

It must be noted that the maximum values of the mentioned parameters from section 4.3.1, 4.3.5 and 4.3.6 must be transformed to match with the maximum weighting factors from the decision matrix. The transformation method and the related equations are represented in Appendix A.

4.5 Results of Failure Modes and Effects Analysis

With the FMEA evaluation process, the risk of failure of every component can be investigated. The damage of one component can lead to many functional failures. For example, the failure of a motor could result in the functional failures “Does not close on command” and “Does not open on command”. The priority of risk in relation to functional failures and damage of components from the FMEA process in section 4.3 is shown in Table 4.5. It is obvious from Table 4.5 which functional failures, from which components, must be carefully taken into account. The full analysis of FMEA is found in Appendix B1.

In addition, it is very useful to assess the risk with respect to only components, since the typical maintenance program is designed to maintain the components. The evaluation of risk based only on components can be represented in Table 4.6. The details of the evaluation can be found in Appendix B2.

Priority	Score	Functional failure	Damaged component
1	4011	Does not break the current	Controlled capacitor
2	3482	Does not close on command	Linkage
3	1530	Does not open on command	Linkage
4	1455	Breakdown to earth	Porcelain
5	1216	Does not make the current	Switching contacts
6	1196	Breakdown to earth	Arcing chamber housing
7	1140	Does not close on command	SF_6 heating equipment
8	1124	Fails to carry current	Switching contacts
9	928	Breakdown along open pole (external)	Porcelain
10	830	Does not break the current	Linkage
11	806	Breakdown across open pole (external)	Arcing chamber housing
12	451	Does not open on command	SF_6 heating equipment
13	187	Does not close on command	SF_6 leakage/Sealing
14	182	Does not close on command	Damping equipment
15	155	Opens without command	Trip latch

Table 4.5: The priority of risk in relation to functional failures and damage of components

Priority	Score	Damaged component	Maintenance strategy
1	3659	Linkage	Corrective
2	2999	Controlled capacitor	Time-based
3	1421	Porcelain	Time-based
4	1414	Switching contacts	Time-based
5	1134	Arcing chamber housing	Time-based
6	1120	SF_6 heating equipment	Condition-based
7	222	SF_6 leakage/Sealing	Condition-based
8	165	Damping equipment	Time-based
9	132	Trip latch	Corrective
10	111	Sensors	Corrective

Table 4.6: The priority of risk with respect to damaged components

4.6 Risk Assessment of HV Circuit-Breakers

The risk assessment in this section is carried out by using the a diagram with the different classes of risk. In Fig. 4.4, the risk diagram is represented by 2 parameters: total consequence and probability of failure. The total consequence of failure, in this case, is the product of consequence of failure (Table 4.3) and failure detection (Table 4.4). In addition, the decision matrix approach as explained in Section 4.4 must be taken into account. It is found that failure detection plays a more significant role than the consequence of failure in the ratio of 75:25.

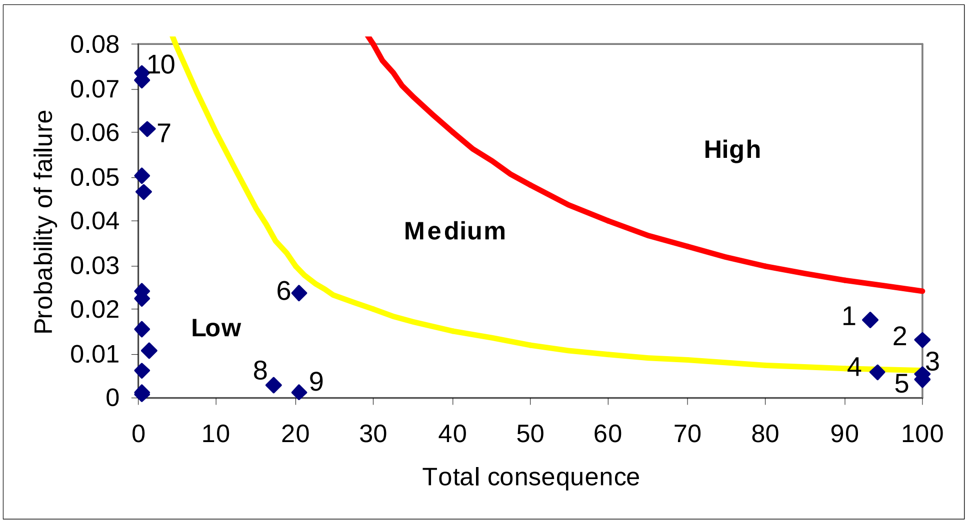


Figure 4.4: The risk diagram of SF_6 circuit-breakers (The numbers on the diagram are related to the priority of risk in Table 4.6)

In order to evaluate the levels of risk, the classification of risk with respect to probability and total consequence must be defined as followed:

The probability of failure:

- 0.00 – 0.02: Low
- 0.02 – 0.04: Medium
- 0.04 – 0.08: High

The total consequence:

- 0 – 30%:Low
- 30 – 60%: Medium
- 60 – 100%: High

From these criteria, the iso-risk curves can be calculated and plotted as shown in Fig. 4.4. These iso-risk curves illustrate the identical degrees of risk along the iso-risk curve lines. It can be concluded from Fig. 4.4 that:

- The components 1 and 2 corresponding "linkage" and "controlled capacitor" are in the region of "Medium" level of risk. In order to reduce the degree of risk, an improved maintenance program is recommended. For example, the typical corrective maintenance of linkage and time-based maintenance of controlled capacitor could be changed to online condition-based maintenance.
- The components 3, 4 and 5 regarding "porcelain", "switching contacts" and "arcing chamber" housing are on the low-medium iso-risk curve. In this case, it is possible to reduce the risk by introducing the more effective maintenance program. However, it is not necessary to change the maintenance technique, since the probabilities of failures are relatively low.
- The component 6, "SF_6 heating equipment", is close to the low-medium boundary. In order to reduce the risk to the secure position (low region), the condition-based maintenance should be more frequently carried out. The more frequent condition-based maintenance can be also applied to component 7, "SF_6 sealing", to reduce the probability of failure. However, those components are already in the low risk region. It might not be cost-effective to improve the maintenance program.
- The probabilities of failures from components 8 and 9, "damping equipment" and "trip latch", are considerably low. Therefore, it is not necessary to change the maintenance programs.
- The component 10, "sensors", has the highest probability of failures but very small consequence of failure. It is possible to improve or change the maintenance method from corrective to time-based or condition-based method. However, it is unreasonable to use the additional monitoring methods for the monitoring devices such as sensors.

It can be concluded in this chapter that the Failure Modes and Effects Analysis (FMEA) method is very useful method to evaluate the risk of components of HV circuit-breakers. Consequently, the improved maintenance programs for determined components can be introduced.

5 Probability and Reliability Models

5.1 Probability Distributions in Reliability Evaluation

Probability distributions are considered as the main parameters in order to evaluate the reliability of components and systems. These probability distributions correspond to the time-to-failure of components which are variable due to different types, structures, manufactures and operating conditions. Practically, the time-to-failure cannot be obtained directly from the components or systems but must be determined from the sample testing or from the data collection.

The main types of distributions are divided into two groups: discrete and continuous distributions. Discrete distributions represent random variables as discrete values which are normally nonnegative integer values, whereas continuous distributions represent random variables as real numbers. The two most important discrete distributions are binomial and Poisson distributions. The frequently-used continuous distributions comprise normal, exponential, Weibull, gamma and Rayleigh distributions.

The four main probability functions: the reliability function, the cumulative distribution function, the probability density function and the hazard rate function are introduced in this chapter. In addition, mean time to failure and mean time to repair are taken into account. The fundamentals of reliability engineering can be reviewed in [43] and [44]. The focus of reliability engineering on power systems can be found in [45].

5.1.1 The Reliability Function

The cumulative distribution function, designated by Q(t), is the distribution function increasing from zero to unity. At time $t = 0$, the component is just in operation, then $Q(t = 0)$ is equal to zero. In other words, there is no failure at the beginning of the operation. When the time reaches infinity ($t \rightarrow \infty$), the probability of failure is likely to be unity, since the component will fail when the time is long enough. In the area of reliability, it is often to mention the cumulative distribution function in terms of the reliability function, R(t), which is the complementary value of the cumulative distribution function as represented in Eq. 5.1.

$$R(t) = 1 - Q(t) \tag{5.1}$$

In case of a continuous random variable, the probability density function (PDF) can be obtained by the derivative of the cumulative distribution function. The probability density function can be mentioned as a failure density function, $f(t)$.

$$f(t) = \frac{dQ(t)}{dt} = -\frac{dR(t)}{dt} \tag{5.2}$$

or

$$Q(t) = \int_0^t f(t)\, dt \tag{5.3}$$

and

$$R(t) = 1 - \int_0^t f(t)\, dt = \int_t^\infty f(t)\, dt \tag{5.4}$$

For the discrete random variable, the integrals in Eq. 5.3 and 5.4 are replaced by summations. The shapes of cumulative distribution function, reliability function and probability density function are depicted in Fig. 5.1

5.1.2 Failure Rate Function

The failure rate or hazard rate function, λ(t), is one of the most important functions in reliability analysis. It is described as a transition rate of failure over a period of time. This function is dependent on the number of failures in a specified period of time and the number of components subject to failure.

$$\lambda(t) = \frac{\text{number of failure per unit time}}{\text{number of components exposed to failure}} \tag{5.5}$$

The general reliability functions can be represented and explained by simple equations as follows:

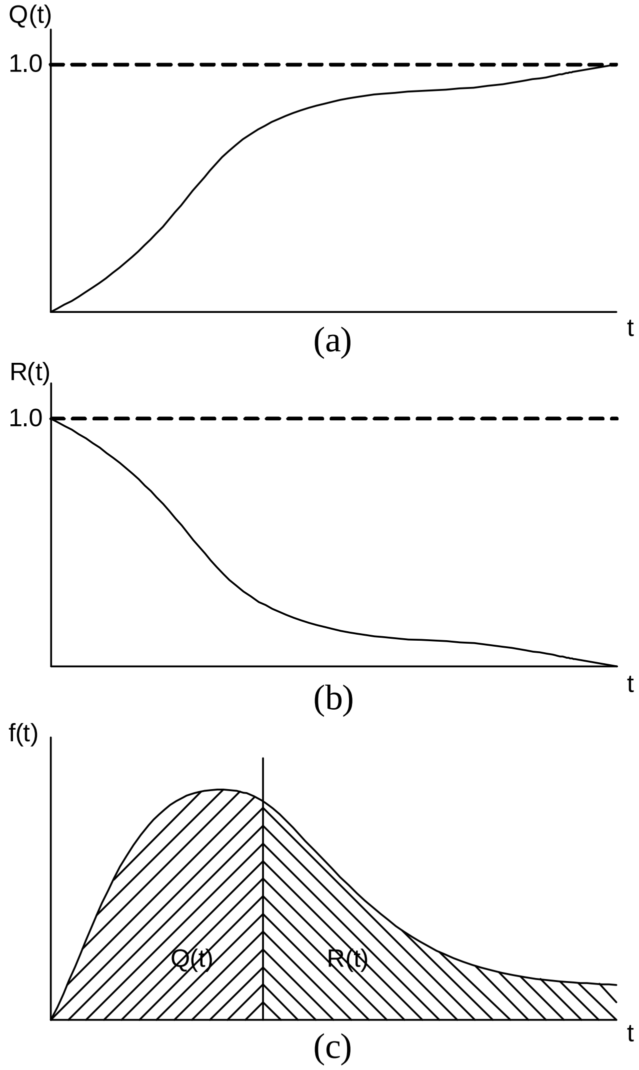


Figure 5.1: (a) The cumulative distribution function, Q(t)
(b) The reliability function, R(t)
(c) The probability density function, f(t)

Assume that a number of identical components N_0 are under test.

$N_s(t)$ = number of components surviving at time t

$N_f(t)$ = number of components failed at time t

$$N_0 = N_s(t) + N_f(t)$$

The reliability function, R(t), at any time t, is represented as

$$R(t) = \frac{N_s(t)}{N_0} \tag{5.6}$$

$$= \frac{N_0 - N_f(t)}{N_0} \qquad = 1 - \frac{N_f(t)}{N_0} \tag{5.7}$$

Likewise, the cumulative distribution function Q(t) is

$$Q(t) = \frac{N_f(t)}{N_0} \tag{5.8}$$

From Eq. 5.2, the probability density function can be calculated as

$$f(t) = \frac{dQ(t)}{dt} = \frac{-dR(t)}{dt}$$

$$f(t) = \frac{1}{N_0} \cdot \frac{dN_f(t)}{dt}, \text{ when } dt \to 0 \tag{5.9}$$

Comparing the equations 5.5 and 5.9, the failure rate and the probability density function are identical at time t = 0. The general equation of failure rate at time t can be expressed as

$$\lambda(t) = \frac{1}{N_s(t)} \cdot \frac{dN_f(t)}{dt} \qquad = \frac{N_0}{N_0} \cdot \frac{1}{N_s(t)} \cdot \frac{dN_f(t)}{dt}$$

$$= \frac{N_0}{N_s(t)} \cdot \frac{1}{N_0} \cdot \frac{dN_f(t)}{dt} \qquad = \frac{1}{R(t)} \cdot f(t) \tag{5.10}$$

or

$$= \frac{-1}{R(t)} \cdot \frac{dR(t)}{dt} \tag{5.11}$$

The reliability function R(t) can be derived from failure rate function as follows:

$$\lambda(t) = \frac{-1}{R(t)} \cdot \frac{dR(t)}{dt} \qquad \lambda(t)dt = \frac{-dR(t)}{R(t)}$$

Integrating,

$$\int_0^t -\lambda(t)dt = \int_1^{R(t)} \frac{1}{R(t)} \cdot dR(t) \qquad \int_0^t -\lambda(t)dt = \ln R(t)$$

$$R(t) = \exp\left[-\int_0^t \lambda(t)dt\right] \tag{5.12}$$

5.1.3 Mean Time to Failure

The mean time to failure (MTTF) or expected value can be defined as

$$MTTF = E(T) = \int_0^\infty t \cdot f(t)dt : \text{ continuous distribution} \tag{5.13}$$

or $$MTTF = E(X) = \sum_{x=0}^\infty x \cdot P_x : \text{ discrete distribution} \tag{5.14}$$

Substituting the Eq. 5.2 into Eq. 5.13 results in

$$MTTF = \int_0^\infty -\frac{dR(t)}{dt} \cdot tdt$$

$$MTTF = -t \cdot R(t)\Big|_0^\infty + \int_0^\infty R(t)dt \qquad MTTF = \int_0^\infty R(t)dt \tag{5.15}$$

The mean time to failure is one of several measures to represent the central tendency of the failure distribution. The other important parameters are the median time to failure, t_{med}, and the mode, t_{mode}. The median time to failure divides the failure distribution into two halves (50:50), while the mode represents the maximum value of the failure distribution.

$$R(t_{med}) = 0.5 \tag{5.16}$$

$$f(t_{mode}) = \max_{0 \le t < \infty} f(t) \tag{5.17}$$

The example of MTTF, the median and the mode are shown in Fig. 5.2

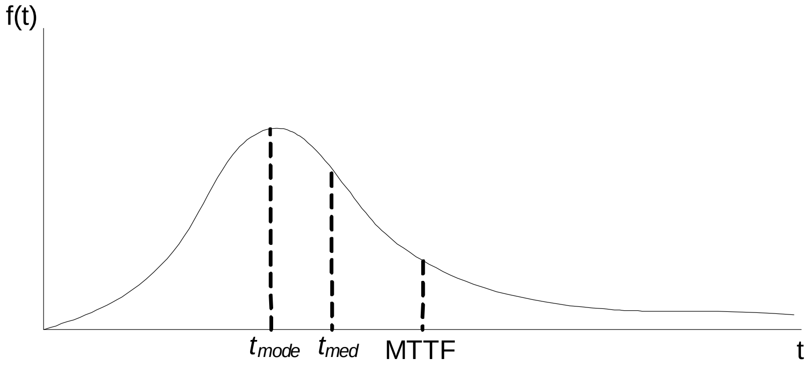


Figure 5.2: The example of MTTF, the median and the mode

It is obvious from Fig. 5.2 that only the MTTF cannot represent the shape of failure distribution. The other measure which can be used to describe the shape of failure distribution is variance, σ^2, expressed by

$$\sigma^2 = \int_0^\infty (t - MTTF)^2 \cdot f(t)dt$$

$$\sigma^2 = \int_0^\infty t^2 \cdot f(t) \cdot dt - (MTTF)^2 \qquad (5.18)$$

5.1.4 The Exponential Distribution

The exponential distribution is one of the most important distributions in a reliability evaluation. It has a constant failure rate (λ) which is the characteristic of the components in the useful life region of bathtub curve. The meaning behind the constant failure rate is that the failures occur randomly. In other words, the time-to-failure of a component is independent to the period of time that a component has been operated. For example, the probability of failure of a component in the next 10 years is the same as the probability in the first few years. This characteristic of the exponential distribution is mentioned as memoryless property.

According to Eq. 5.12, the reliability function R(t) with the constant failure rate, $\lambda(t) = \lambda$, can be represented as

$$R(t) = \exp\left[-\int_0^t \lambda dt\right] = e^{-\lambda t} \tag{5.19}$$

and $Q(t) = 1-e^{-\lambda t}$

Therefore, the probability density function, mean time to failure and variance are represented as

$$f(t) = -\frac{dR(t)}{dt} = \lambda e^{-\lambda t} \tag{5.20}$$

$$MTTF = \int_0^\infty R(t)dt = \int_0^\infty e^{-\lambda t}dt \qquad MTTF = \left.\frac{e^{-\lambda t}}{-\lambda}\right|_0^\infty = \frac{1}{\lambda} \tag{5.21}$$

$$\sigma^2 = \int_0^\infty \left(1 - \frac{1}{\lambda}\right)^2 \lambda e^{-\lambda t}dt = \frac{1}{\lambda^2} \tag{5.22}$$

In order to prove the memoryless property of the exponential distribution, the conditional probability and Fig. 5.3 are applied.

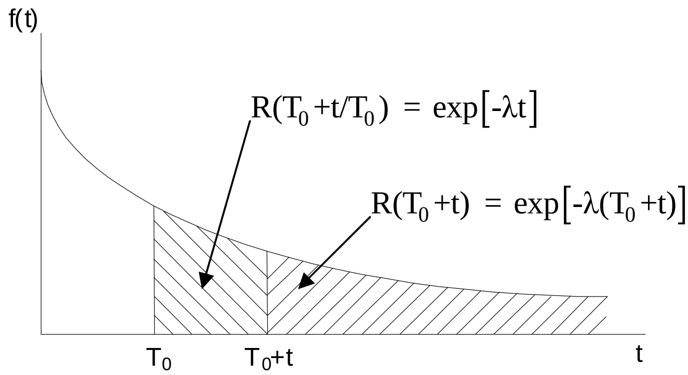


Figure 5.3: The memoryless property of exponential distribution

$$R(T_0 + t|T_0) = \frac{R(T_0 + t)}{R(T_o)} = \frac{\exp[-\lambda(T_0 + t)]}{\exp[-\lambda T_0]}$$

$$= \frac{\exp(-\lambda T_0)\cdot \exp(-\lambda t)}{\exp(-\lambda T_0)} = \exp(-\lambda t) = e^{-\lambda t} = R(t) \tag{5.23}$$

5.1.5 The Weibull Distribution

The Weibull distribution is the most important distribution to analyse and predict failures of components. According to the bathtub curve, Fig. 5.4, it can identify the distributions of infant mortality (region 1), constant failure (region 2) and wear-out (region 3). The Weibull distribution was found by Waloddi Weibull (1887-1979) who defined the model of a product life as a function of

$$f(t) = \frac{\beta}{\alpha}\left[\frac{t}{\alpha}\right]^{\beta-1} \exp\left[-\left(\frac{t}{\alpha}\right)^{\beta}\right] \tag{5.24}$$

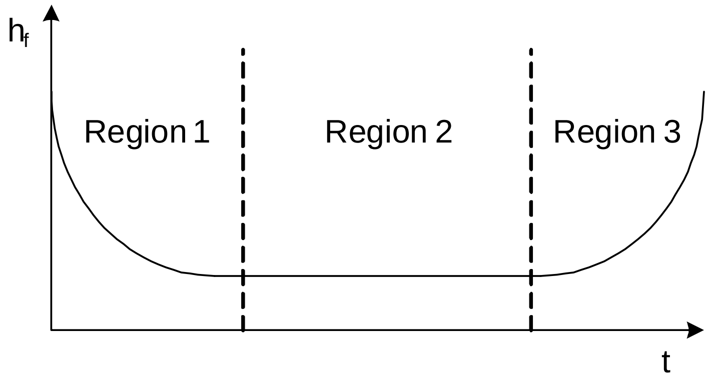


Figure 5.4: Bathtub curve

The relevant equations of Weibull distribution are

$$R(t) = \int_t^{\infty} f(t)dt$$

$$R(t) = \exp\left[-\left(\frac{t}{\alpha}\right)^{\beta}\right] \tag{5.25}$$

$$\lambda(t) = \frac{\beta}{\alpha}\left(\frac{t}{\alpha}\right)^{\beta-1} \tag{5.26}$$

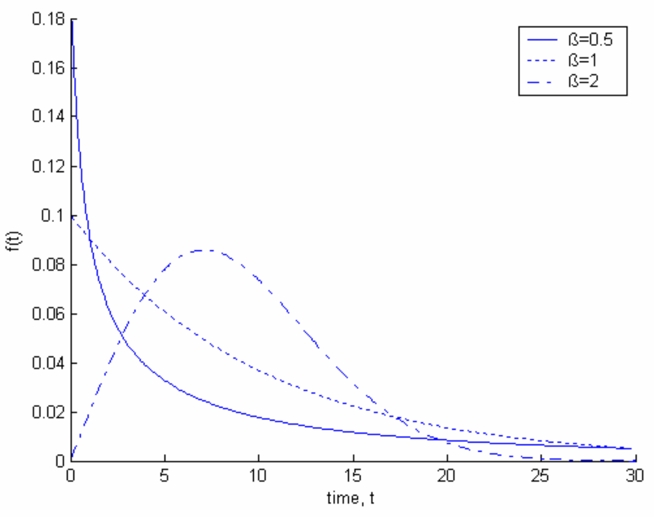
The β is referred to the shape parameter of the distribution. The different values of β represent the different shapes of distribution as follows:

- $\beta < 1$: the Weibull distribution has a hyperbolic shape and $f(0) = \infty$. The distribution represents the infant mortality or debugging period.

- β = 1: the failure rate is constant ($\lambda = 1/\alpha$) and the distribution is similar to the exponential distribution representing the useful life period.
- β > 1: the distribution is skewed from left to right. It corresponds to the wear out period.

The illustration of the Weibull distribution with different shape parameters can be represented in Fig. 5.5a – 5.5d. The α is referred to the scale parameter which influences the mean and the spread of the distribution. It is also mentioned as the characteristic life.

(a)



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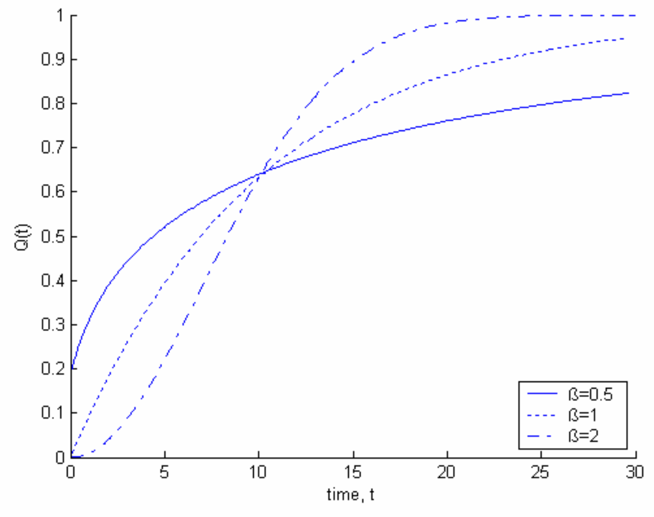

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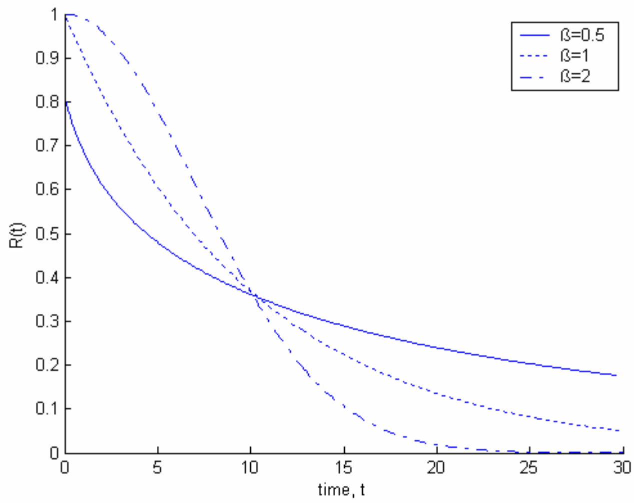


(d)

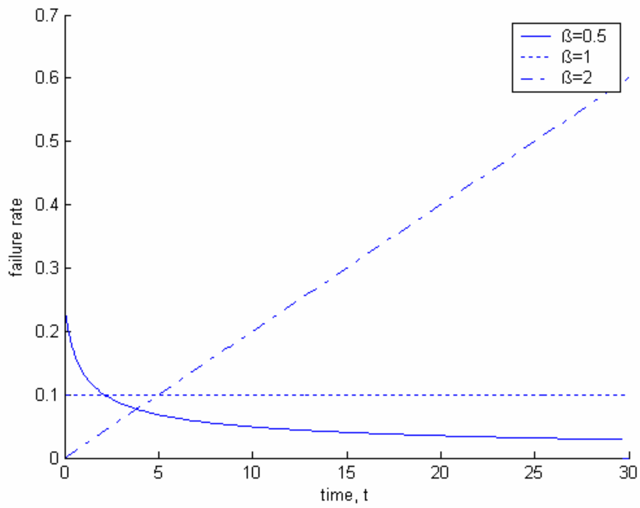


Figure 5.5: The Weibull distribution with different shape parameters, β

(a): The probability density function, f(t)

(b): The cumulative distribution function, Q(t)

(c): The reliability function, R(t)

(d): The failure rate, λ

5.2 Treeing Model

The treeing Model of HV circuit-breakers is the reliability model which is composed of the distribution of consecutive failures. The aim of this model is to investigate when the failures occur and what probabilities are during the lifetime. The conditional probability method is applied to investigate the probabilities of failures from a new status to the first and second failure in subsequent years. As a result, the critical years of which the failures frequently occur can be figured out.

5.2.1 Concepts and Diagram

The failures of HV circuit-breakers up to their second failures are taken into account. The failures of each circuit-breaker can be represented with respect to time, for example, as shown in Fig. 5.6.

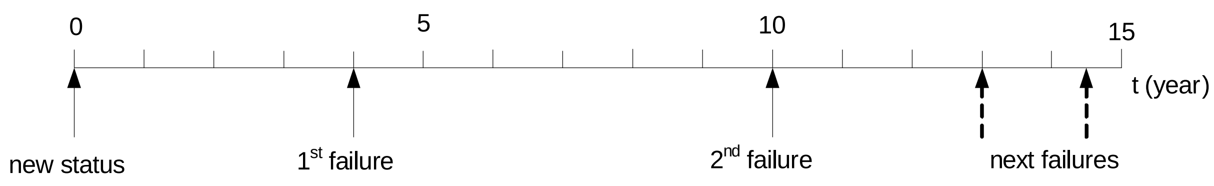


Figure 5.6: The occurrence of failures with respect to time

It can be concluded from Fig. 5.6 that the first failure occurs at the fourth year and the second failure on the tenth year. Such information is taken for every HV circuit-breaker. The steps of establishing the treeing diagram can be explained as follows:

1. The failure-free durations of HV circuit-breakers are extracted from the database. For instance, the failure-free durations of the circuit-breaker in Fig. 5.6 are 4 years from the new status to the first failure and 6 years from the first to the second failure.
2. The numbers of failures with respect to the failure-free durations are arranged. Therefore, the numbers of failures in any years are made available.
3. The counting program developed in MATLAB is applied to count the number of circuit-breakers under specified time conditions. For example, there are 11 HV circuit-breakers having the first failure in the first year and the second failure in the third year.
4. With the conditional probability method, the treeing diagram of failures is established.
5. The two-dimensional diagram of HV circuit-breakers in relation to the number of failures is applied.

The formula of conditional probability is

$$P(A|B) = \frac{P(A \cap B)}{P(B)} \tag{5.27}$$

where P(A|B) is the probability of A given B. The treeing diagram of all types of HV circuit-breakers is represented in Fig 5.7. In this figure, the number of circuit-breakers subject to failures and their conditional probabilities in any years are written. For example, there are 190 from the total of 9305 circuit-breakers exposed to the first failure in the first year. From those 190 circuit-breakers, there are 36 subject to the second failure within the next 6 months. This treeing diagram can be illustrated as a two-dimensional diagram in Fig. 5.8. It shows how many circuit-breakers exposed to the second failures and at which years. For example, it can be read from Fig. 5.8 that the highest number of circuit-breakers subject to the second failures is 36. Those 36 circuit-breakers had the first failures in the first year and the second failures in the next 6 months. More detail as to the number of circuit-breakers subject to the second failures can be read from Table 5.1.

Using Fig. 5.7 and Table 5.1, the critical paths of the development of failures can be figured out. When only the first failures are considered, it is obvious that the failures most frequently occur in the sixth year (252 out of 9305 CBs). The second highest failure amount takes place in the first year (190 out of 9305 CBs). After that, the second failures are taken into consideration. It is seen that the most critical path represents the first failure in the first year and the second failure in the same year (36 out of 9305 CBs). The second most critical path shows the first failure in the sixth year and the second failure in the same year (28 out of 9305 CBs). In order to make this information easy to be compared with information from other types of circuit-breakers, the years of the second failures must be transformed with respect to the starting point. The first five critical paths are listed in Table 5.2.

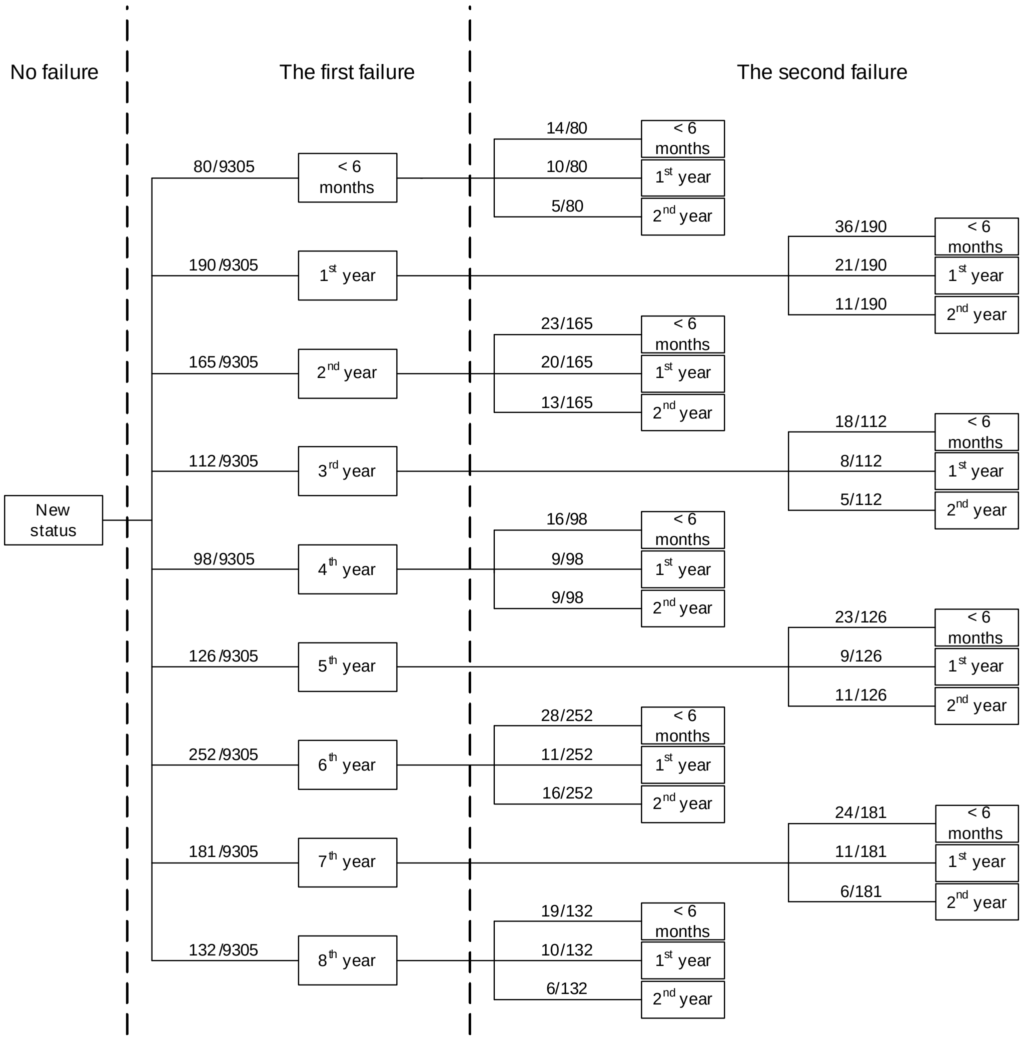


Figure 5.7: Treeing diagram of all types of HV circuit-breakers

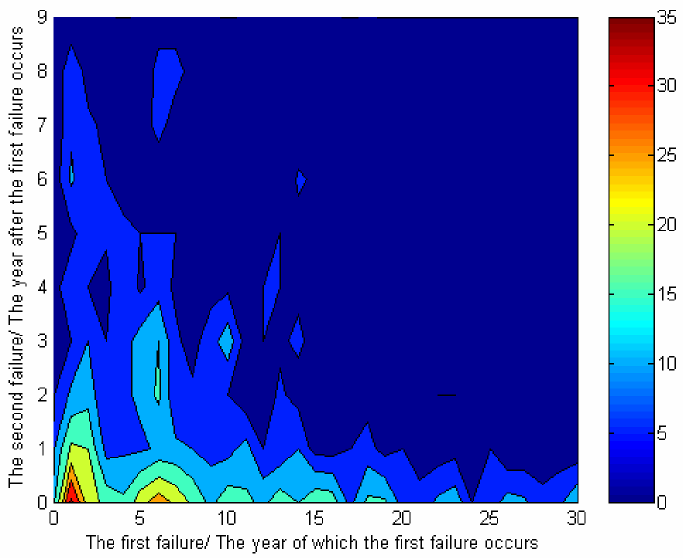


Figure 5.8: Two-dimensional diagram representing the number of failures with respect to time

year		The first failure/ The year of which the first failure occurs																		
		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
The second failure/ The year after the first failure	0	14	36	23	18	16	23	28	24	19	14	18	16	14	18	15	19	18	9	16
	1	10	21	20	8	9	9	11	11	10	8	8	12	5	6	10	3	3	5	7
	2	5	11	13	5	9	11	16	6	6	8	5	1	2	6	3	2	5	4	3
	3	2	5	10	5	8	12	15	6	3	8	13	3	5	4	6	3	4	2	1
	4	4	7	5	3	10	4	8	4	2	3	4	2	5	5	4	3	3	0	2
	5	3	4	7	6	7	5	5	5	3	3	0	2	4	5	3	4	3	1	1
	6	1	11	5	5	1	1	1	2	2	4	4	1	3	0	6	4	0	1	3
	7	1	9	6	4	2	2	7	2	1	0	3	2	1	2	0	3	0	4	0
	8	1	9	3	5	2	0	7	7	3	4	2	1	2	5	2	2	1	0	0
	9	1	1	3	1	0	1	2	2	2	2	0	3	2	1	2	1	1	0	1
	10	1	3	2	2	1	4	4	1	0	3	0	1	0	1	1	2	1	0	0
	11	1	2	1	0	0	1	2	1	4	0	1	2	2	0	0	0	2	0	2
	12	1	0	3	0	1	0	2	2	0	0	2	0	0	1	1	1	0	0	0
	13	1	0	3	3	1	1	2	0	1	1	1	2	0	1	0	0	0	0	0
	14	1	3	2	1	0	2	1	1	2	0	0	0	0	0	0	0	1	0	1
	15	0	3	3	1	0	4	0	0	2	1	1	0	0	1	1	0	0	1	0
	16	0	0	0	2	0	0	1	0	0	0	0	2	0	0	0	0	0	0	0
	17	0	1	0	0	2	0	0	3	0	0	2	0	1	0	0	0	0	0	0
	18	0	0	0	2	1	0	0	1	2	2	0	0	0	0	0	0	0	0	0

Table 5.1: The table representing the number of failures under specified time conditions

The probabilities shown in Table 5.2 are the absolute probabilities with respect to the total number of circuit-breakers (9305 CBs). For example, the probability of the circuit-breakers having the first failure in the first year and the second failure in the same year is 0.0038 (36/9305). In connection with the treeing diagram, Fig. 5.7 and the conditional probability method, it is possible to consider the probabilities step by step. For instance, the probability of the circuit-breakers having the first failure in the first year is 0.02 (190/9305). The conditional probability of those 190 circuit-breakers having the second failure in the same year is 0.19 (36/190).

Critical path	The first failure/ year of which the fist failure occurs	The second failure/ year of which the second failure occurs	Probability under specified conditions
1	1st year	1st year	0.0038 (36/9305)
2	6th year	6th year	0.0030 (28/9305)
3	7th year	7th year	0.0026 (24/9305)
4	2nd year	2nd year	0.0025 (23/9305)
5	5th year	5th year	0.0025 (23/9305)

Table 5.2: The critical paths of the failures

5.2.2 Results of Treeing Diagram

In addition to the investigation of all types of HV circuit-breakers, the treeing models of four specified types of HV circuit-breakers, SF_6 with hydraulic drive, SF_6 with mechanical drive, minimum oil with hydraulic drive and with mechanical drive, are established and investigated. The first five critical paths of different types of HV circuit-breakers are listed in Table 5.3. The two-dimensional diagrams of these types of circuit-breakers are represented in Appendix C.

Critical path	SF_6 with hydraulic drive (3168 CBs)			SF_6 with mechanical drive (1220 CBs)			Min. oil with hydraulic drive (1076 CBs)			Min. oil with mechanical drive (1674 CBs)		
	1st failure (year)	2nd failure (year)	Prob.	1st failure (year)	2nd failure (year)	Prob.	1st failure (year)	2nd failure (year)	Prob.	1st failure (year)	2nd failure (year)	Prob.
1	1st	1st	0.010	16th	16th	0.007	26th	26th	0.006	23rd	23rd	0.003
2	6th	6th	0.009	10th	10th	0.002	6th	14th	0.006	27th	27th	0.003
3	7th	7th	0.007	1st	1st	0.002	14th	20th	0.005	29th	29th	0.003
4	2nd	2nd	0.006	2nd	4th	0.002	19th	19th	0.005	5th	8th	0.002
5	2nd	3rd	0.006	10th	13th	0.002	22nd	22nd	0.005	17th	24th	0.002

Table 5.3: The comparison of critical paths of different types of circuit-breakers

It must be noted that the probabilities in Table. 5.3 are the absolute probabilities related to the total population of each respective type. It can be concluded from the treeing models that:

- The second failures which occur in the same year as the first failures are probably considered as the failures from human error or imperfect repair.
- It is obvious that the probabilities of failures of SF_6 circuit-breakers with hydraulic drives are higher than other types of circuit-breakers.
- It is likely that, the first failures occurring in the first 2-3 years are failures in infant mortality or in the debugging period.
- When failures in the debugging period are neglected, the failures of SF_6 circuit-breakers with hydraulic drives most frequently occur at the sixth year, whereas those for SF_6 circuit-breakers with mechanical drives take place at the sixteenth year. It is obvious that the reliability of circuit-breakers with mechanical drives is higher than ones with hydraulic drives.
- Most of the failures of minimum oil circuit-breakers frequently occur after the 20^{th} year. It is because of the aging phenomena. However, there are some failures found in the first ten years.
- The probabilities of failures of SF_6 circuit-breakers over 20 years are lower than the first 20 years due to the fact that a great number of SF_6 circuit-breakers have not reached the aging period. It might be very interesting to further collect the failure database in the next 20 years and use this treeing diagram to investigate the critical paths again.

The advantages of treeing diagram can be concluded as followed:

- With the conditional probability method, it is possible to determine the probability of failures at any specified time condition.
- The treeing model can be used to establish the adaptive maintenance programs or at least to provide valuable information for asset managers and maintenance personnel as to when "the following failures" are likely to occur. The adaptive maintenance program can be explained by using the example of SF_6 circuit-breakers with hydraulic drives. It is clear that the first failures frequently occur in the 6^{th}-7^{th} year. The maintenance program should be introduced before this time to reduce the probability of failures. Afterwards, it can be found in the treeing diagram that the second failures frequently occur within 1-3 year after the first failures. This is the information for the asset managers and maintenance personnel to be aware of the following failures coming in the near future.
- The treeing diagram can be expanded to study the third and fourth failures but it requires required a more complicated filter and counting program.

5.3 Cascading Reliability Model

A cascading reliability model can be considered as the extension of treeing model. The main difference is the reliability point of view. The cascading reliability model determines the reliability of consecutive failures in terms of the mean time to failure (MTTF), state and transition probabilities. In this model, the failure database of different types of HV circuit-breakers from the 1960s is applied in order to investigate reliability. With the cascading reliability model, the durations between failures or mean time to failure (MTTF) between consecutive failures are investigated. Consequently, the failure development trend from the first to the second and the third failure can be determined. The exponential reliability distributions of the first, second, and third failures are introduced in terms of the cascading reliability model. As a result, the probabilities and availabilities of HV circuit-breakers subject to consecutive failures can be investigated. For example, with this cascading reliability model, the probability that circuit-breakers are subject to the first failure within 10 years, the second failure within the next 5 years and the third failure within the next 3 years can be discovered.

Other probabilistic models applied to HV circuit-breakers can be found in [46] and [47]. The aging probability with an effect of maintenance on reliability and costs is discussed in [48].

5.3.1 Investigation of Failure Database

In this section, the preparation of failure data and investigation of reliability parameters are described. It must be noted that five different groups (all types, SF_6 with hydraulic drive, SF_6 with mechanical drive, minimum oil with hydraulic drive and with mechanical drive) had been studied. According to small samples of air blast circuit-breakers, they were not separately considered.

5.3.1.1 Investigation of failure-free time of HV circuit-breakers

Since the 1960s, every failure regardless of major and minor failures had been recorded in the database. Accordingly, failures are considered without the distinction between major and minor failures. The structure of the failure database can be reviewed from [49] and [50]. The durations between failures of HV circuit-breakers are extracted from the database, thus forming the failure-free times. As a result, the distribution between numbers of failures and failure-free times can be established. For example, the HV circuit-breaker has 3 failures in the 10^{th}, 17^{th}, and 24^{th} year. It can be seen that the first failure occurs in the 10^{th} year, the second failure in the next 7 years and the third failure in the following 7 years. From the whole population, the failure-free times of the first failures are then collected and the distribution is formed. The second and the third failure-free times can be carried out in the same way. Finally, the distributions of the first, second, and third failures are connected in series, thus forming the cascading reliability model. The average failure-free time can be represented as follows.

$$E(x)=\sum_{i=1}^{n} X_i \cdot P_i \qquad (5.28)$$

where X_i: the failure-free time i (year)

P_i: the probability of failures at failure-free time i

5.3.1.2 Reliability parameters

This average failure-free time can be represented as the mean time to failure (MTTF). For example, the MTTF1, MTTF2, and MTTF3 represent the average failure-free times from no failure to the first failure, the first to the second failure, and the second to the third failure respectively. These MTTFs and their distributions are then connected in series to form the cascading reliability model. When the distribution of failures can be represented by an exponential distribution, the failure rate (λ) is then calculated by inverse of MTTF. In conclusion, the exponential reliability distributions, MTTFs and failure rates of different types of HV circuit-breakers are investigated and the failure developments are then compared.

5.3.1.3 Precautions of evaluation of reliability parameters

Precautions in the evaluation of reliability parameters must be taken into account in order to reduce inaccuracy of reliability parameters; for example:

- Due to lack of commissioning date information, the manufacturing date is then applied as the starting time. For the first failures, ones occurring in the first 3 years can be considered as the failures in the burn-in period. MTTFs with and without consideration of this period are compared.
- For the second failures, ones occurring on the same day or in the next few months after the first failures are considered as repetitive failures resulting from human error and incomplete repair/inspection. Consequently, the expected values or MTTFs are reduced. The third and following failures can be treated by the same assumption.

5.3.2 Principle of Cascading Reliability Model

The cascading reliability model of HV circuit-breakers can be described as the connection of reliability distributions of the first, second and following failures in series. The probabilities of each state, between states and the reliability distributions can be investigated. The cascading reliability model of HV circuit-breakers can be represented in Fig. 5.9.

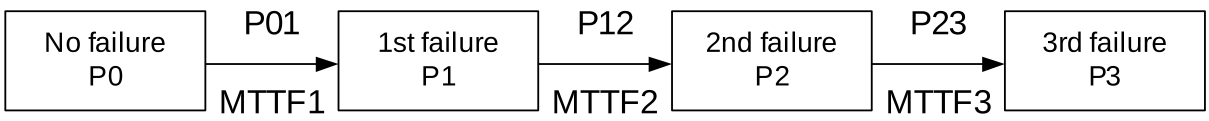


Figure 5.9: The cascading reliability model of HV circuit-breakers

The probabilities P0, P1, P2 and P3 represent the state probabilities, whereas the probabilities P01, P12, P23 show the transition probabilities between states. The state probabilities are the probabilities of residing in any states. For example, the state probability P0 is the probability of circuit-breakers staying in failure-free state. The transition probabilities are the probabilities between states. For example, the transition probability P12 is the probability of failure development from the first to the second failure. MTTFs and their exponential reliability distributions represent the development of failures between states. In other words, the durations between failures and their probabilities can be investigated by using this cascading reliability model. It must be noted that, MTTFs are investigated from the database in which the general maintenance programs are already included. It means that, the influence of general maintenance programs to MTTFs is already included.

5.3.2.1 Reliability and availability of cascading reliability model

The reliability and availability of the cascading reliability model can be classified into two categories: the real case and the approximated case by using an exponential distribution. The real reliability can be investigated from the real distribution of failures, whereas the approximate reliability can be derived from the exponential reliability distribution. The exponential reliability distribution and its related equations are represented in Section 5.1.4.

The survivor function, R(t), for the HV circuit-breakers having many failures can be examined by connecting the exponential functions of every failure in series leading to the cascading reliability model. In this study, HV circuit-breakers having up to 3 failures are considered. The survivor function, R(t), of HV circuit-breakers subject to 3 failures can be represented as

$$R(t) = e^{-\lambda_1 t_1} \cdot e^{-\lambda_2 (t_2 - t_1)} \cdot e^{-\lambda_3 (t_3 - t_2)} \tag{5.29}$$

$$R(t) = e^{-t_1/MTTF1} \cdot e^{-(t_2 - t_1)/MTTF2} \cdot e^{-(t_3 - t_2)/MTTF3} \tag{5.30}$$

λ_1, λ_2, λ_3:	failure rate of the first, second, and third failure
t_1,t_2,t_3:	The time of the first, second, and third failure
MTTF1, 2, and 3:	Mean time to failure of the first, second, and third failure

For example, the survivor function, R(t), of HV circuit-breakers having the first failure within 10 years, the second failure within the next 5 years, and the third failure within the next 3 years can be calculated as $R(t) = e^{-\lambda_1 (10)} \cdot e^{-\lambda_2 (5)} \cdot e^{-\lambda_3 (3)}$.

5.3.3 Results of Investigation

The results of investigation can be divided into two parts. The first part represents the failure development from the beginning to the last failures. Due to small numbers of HV circuit-breakers having more than 3 failures, only the cascading model up to 3 failures is illustrated. The state probabilities and transition probabilities can be examined from the model. The second part represents the exponential reliability distributions of the cascading reliability model.

5.3.3.1 State and transition probabilities of cascading reliability model

The state and transition probabilities of the cascading reliability model with respect to Fig. 5.9 can be summarized in Table 5.4. This table shows the different types of circuit-breakers subject to failures and how those failures transit from state to state. For example, SF_6 circuit-breakers with mechanical drive stay in the failure-free state, P0, 83 % and the transition probability from the failure-free to the first failure state, P01, is 17%. The MTTFs with and without the consideration of burn-in period and repetitive failures (according to the section 5.3.1.3) are represented in Table 5.5. These MTTFs represent how fast the failures occur from state to state. For instance, SF_6 circuit-breakers with mechanical drive stay 10.74 years (MTTF1) until the first failures occur. After that, the second failures occur 2.09 years (MTTF2) later.

Type of CB	State probability				Transition probability		
	P0	P1	P2	P3	P01	P12	P23
All types	0.66	0.18	0.07	0.03	0.34	0.47	0.56
SF_6 with hydraulic drive	0.47	0.25	0.12	0.06	0.53	0.53	0.59
SF_6 with mechanical drive	0.83	0.13	0.03	0.01	0.17	0.23	0.28
Min. oil with hydraulic drive	0.45	0.27	0.12	0.07	0.55	0.51	0.59
Min. oil with mechanical drive	0.83	0.10	0.03	0.01	0.17	0.42	0.51

Table 5.4 State and transition probabilities of different types of HV circuit-breakers

Type of CB	with burn-in period and repetitive failures			without burn-in period and repetitive failures		
	MTTF1 (year)	MTTF2 (year)	MTTF3 (year)	MTTF1 (year)	MTTF2 (year)	MTTF3 (year)
All types	12.35	3.43	2.25	14.62	5.11	4.09
SF_6 with hydraulic drive	7.79	3.30	2.35	10.10	4.84	4.00
SF_6 with mechanical drive	10.74	2.09	2.85	14.06	3.5	4.63
Min. oil with hydraulic drive	16.96	4.68	2.30	17.68	6.44	4.44
Min. oil with mechanical drive	18.99	3.14	2.45	19.23	5.69	5.25

Table 5.5 Mean time to failures of different types of HV circuit-breakers

It can be seen from Table 5.5 that MTTF3s are shorter than MTTF2s and MTTF1s respectively. In other words, the following failures occur faster than the previous ones. The state probabilities and MTTFs can be illustrated in Fig. 5.10 and 5.11 respectively. The summation of state probabilities of each type of circuit-breaker is equal to unity, but only the summation to state P3 is represented in Fig. 5.10. It is apparent that more than 90 % of HV circuit-breakers are not exposed to more than 3 failures. It can be seen that more than 80 % of HV circuit-breakers with mechanical drives stay in failure-free state, P0. It could be concluded that HV circuit-breakers with mechanical drives have higher reliability than HV circuit-breakers with hydraulic drives.

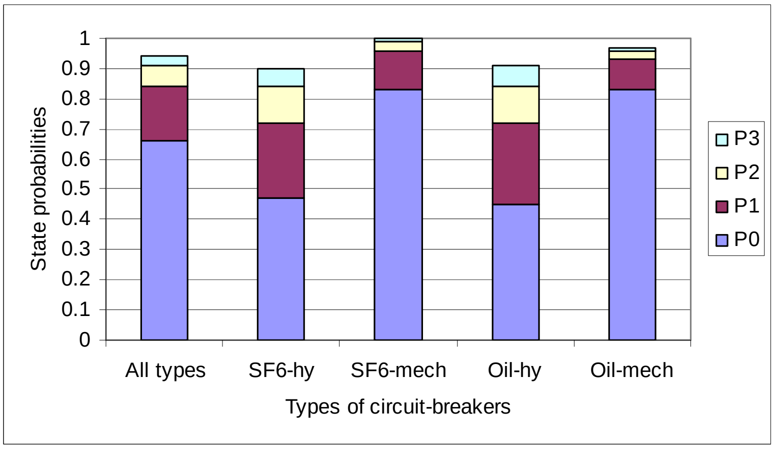


Figure 5.10: State probabilities of different types of HV circuit-breakers

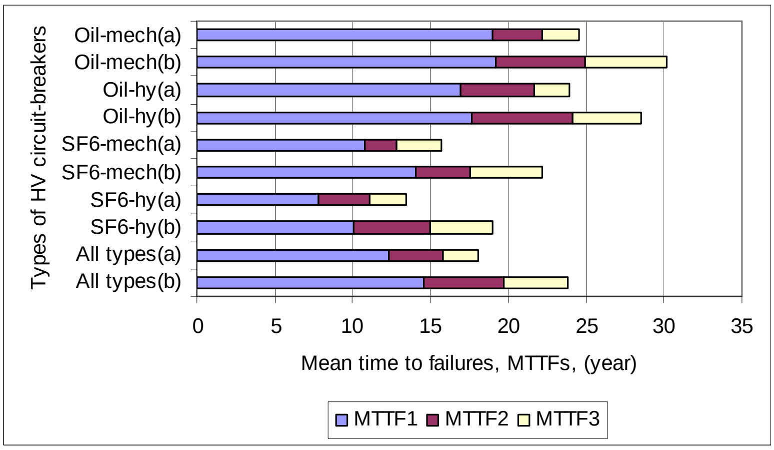


Figure 5.11: Mean time to failures of different types of circuit-breakers
(a): with consideration of burn-in period and repetitive failures
(b): without consideration of burn-in period and repetitive failures

The failure development in terms of MTTFs can be explained from Fig. 5.11. It is obvious that without the consideration of burn-in period and repetitive failures, the cascading MTTF (MTTF1, MTTF2, and MTTF3) is extended up to around 6 years. The effect of human error and incomplete repair/inspection can be derived from Table 5.5 and Fig. 5.11. For example, in case of all types of HV circuit-breakers, MTTF2 can be extended up to 49 % without the consideration of repetitive failures. In other words, a perfect repair/inspection is able to extend MTTF2 up to 1.68 years or 49% in case of all types of HV circuit-breakers.

5.3.3.2 The exponential reliability distributions of the cascading reliability model

The exponential reliability distributions of the cascading reliability model are composed of three distributions of failures connected in series. Examples of the exponential reliability distributions of SF_6 circuit-breakers with hydraulic drives are depicted in Fig. 5.12. It is obvious that the failure development of the third failure is faster than the second and the first failure respectively. The cumulative distribution function or probability of failure, Q(t), and the survivor function, R(t), can be calculated by using Eq. (5.1), (5.29) and (5.30).

For instance, the survivor function, R(t), of the SF_6 circuit-breakers with hydraulic drives having the first failure within 10 years, the second failure within the next 5 years, and the third failure within the next 3 years, can be calculated by using MTTFs from Table 5.5 as follows:

$$R(t) = e^{-10/MTTF1} \cdot e^{-(15-10)/MTTF2} \cdot e^{-(18-15)/MTTF3}$$

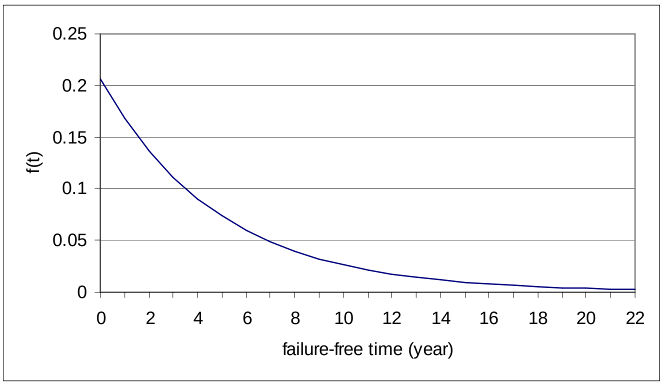
$$R(t) = e^{-10/10.1} \cdot e^{-5/4.84} \cdot e^{-3/4.0} = 0.0625$$

$$Q(t) = 1-R(t) = 1-0.0625 = 0.9375$$

The interpretation of the calculation must be carefully paid attention. For the above example, it can be concluded that SF_6 circuit-breakers with hydraulic drives having exactly 3 failures will have the survivor function of 6.25 % when the above time conditions are taken into account. In other words, the probability of failure of SF_6 circuit-breakers in these conditions is 93.75 %. However, the population of the SF_6 circuit-breakers with hydraulic drives having exactly 3 failures, state P3, represents only 6 % of the total population of this type.

(a)

(b)



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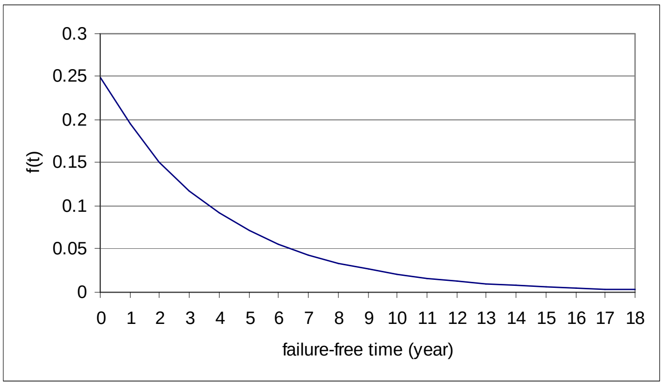


Fig. 5.12: The exponential reliability distributions of SF_6 circuit-breakers with hydraulic drives (without consideration of burn-in period and repetitive failures)
(a): The first failure (b): The second failure (c): The third failure

When the survivor function up to the second failure (the first failure within 10 years and the second failure within the next 5 years) is considered, the calculation is then carried out as follows:

$$R(t) = e^{-10/MTTF1} \cdot e^{-(15-10)/MTTF2}$$

$$R(t) = e^{-10/10.1} \cdot e^{-5/4.84} = 0.1323$$

$$Q(t) = 1\text{-}R(t) = 1\text{-}0.0625 = 0.8677$$

It can be concluded in the same way that SF_6 circuit-breakers with hydraulic drives having exactly 2 failures will have the survivor function of 13.23 % when the above time conditions are given. The probability of failure in this case is 86.77 %. The population of this type of circuit-breakers having exactly 2 failures, state P2, corresponds to 12 % of the total population. The survivor function of SF_6 circuit-breakers with hydraulic drives having only one failure within 10 years is 0.37 %. The population of this type of circuit-breaker having only one failure, state P1, is 25 % of the total population.

In order to compare the survivor functions of different types of HV circuit-breakers, the identical time conditions must be taken into account. On the other hand, the time conditions can be compared when a similar survivor function is considered. For example, the time conditions of HV circuit-breakers having exactly 3 failures (the first failure within 10 years, the second failure within the next 5 years, and the third failure within the next 3 years) are set, and the survivor functions of different types of HV circuit-breakers are then compared.

- SF_6 with hydraulic drives: R(t) = 0.0625
- SF_6 with mechanical drives: R(t) = 0.0616
- Minimum oil with hydraulic drives: R(t) = 0.133
- Minimum oil with mechanical drives: R(t) = 0.139

It is obvious in the comparison that minimum oil circuit-breakers have approximately 2 times higher survivor function than SF_6 circuit-breakers under a similar condition. Furthermore, the state probability P3 must be taken into consideration to compare the percentage of the population at this state. It can be seen from Table 5.4 that the population of HV circuit-breakers with mechanical drives (SF_6 and minimum oil circuit-breakers) at state P3 represents only 1 % of the total population of its type, whereas the circuit-breakers with hydraulic drives show 6-7 %. It is then concluded that the HV circuit-breakers with mechanical drives have higher reliability than HV circuit-breakers with hydraulic drives.

5.3.4 Conclusions

The following can be concluded from the investigation of the cascading reliability model of HV circuit-breakers:

- The cascading reliability model of HV circuit-breakers is composed of state probabilities, transition probabilities, and reliability distributions. This model is very useful to study the probability of failures and availability of circuit-breakers in any states. It is also beneficial for maintenance personnel to be aware of the first and following failures.
- State probabilities represent the probabilities of circuit-breakers residing in any states. For instance, state P0 shows the probability of HV circuit-breakers having no failure and state P1 represents the probability of HV circuit-breakers having only one failure.
- Transition probabilities show probabilities between states. As a result, the development of failures from state to state can be investigated.
- The probability of failure, Q(t), and survivor function, R(t), can be examined by using the exponential reliability distributions. These Q(t) and R(t) can be considered separately regarding only interested failure or many failures in combination. For example, it is possible to calculate the survivor function of HV circuit-breakers having exactly 3 failures under specified time conditions or calculate only the survivor function of the second failure.
- It can be seen from the investigation that HV circuit-breakers with mechanical drives are subject to failures less than ones with hydraulic drives.
- It is obvious that minimum oil circuit-breakers have longer MTTFs than SF_6 circuit-breakers. This result is ascertained by circuit-breaker international surveys that SF_6 circuit-breakers are prone to gas leakage.
- It can be concluded that the repetitive failures resulting from human error and incomplete repair/inspection reduce the MTTFs (MTTF1, MTTF2, and MTTF3) of HV circuit-breakers up to 6 years.
- MTTF3 is shorter than MTTF2 and MTTF1 respectively. It is implied that the upcoming failures occur in shorter periods of time than the previous ones. In other words, it is likely that HV circuit-breakers subject to many failures are prone to the upcoming failures faster than ones with only few failures.

6 The Application of Markov Model

In this study, the Markov model with the combination of a failure database is applied to HV-circuit-breakers. In the Markov model, the HV circuit-breaker is composed of five components in parallel: drive, HV insulation, life-parts, control/auxiliary, and others. The different types of HV circuit-breakers, i.e. all types, SF_6 with hydraulic drive, SF_6 with mechanical drive, minimum oil with hydraulic drive and minimum oil with mechanical drive, are taken into account in order to compare the reliability. The mean time to failure (MTTF) of mentioned components are investigated by using the failure database, whereas the mean time to repair (MTTR) is obtained from the manufacture.

6.1 Principles of Markov Model

The Markov model is used to describe the process of the system, i.e. how the system changes from state to state. It can be described as a state-space model which is composed of state probabilities and transition probabilities between states. The system states represent the conditions of their states, for example, working states, down states and repair states. The examples of illustrations of state-space models can be given in Fig. 6.1a and 6.1b.

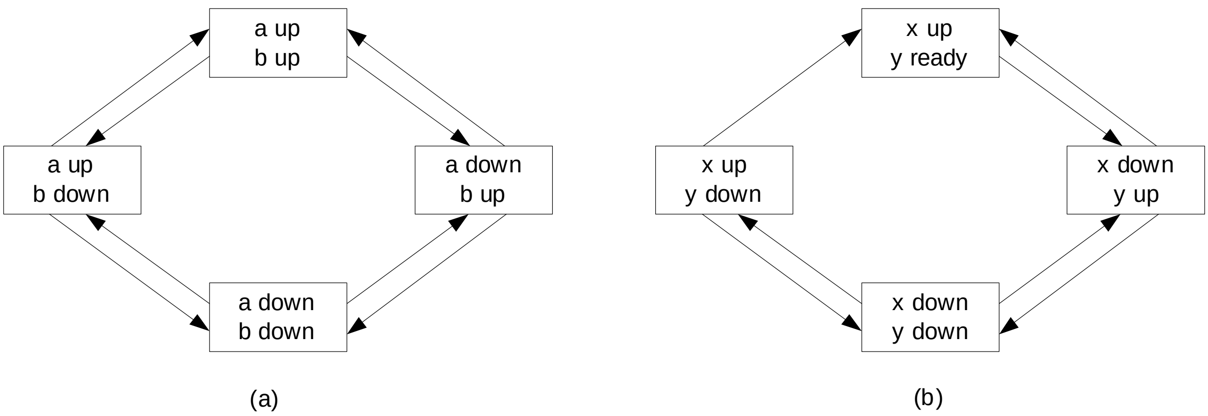


Figure 6.1: The examples of state space models
(a): the system with two independent components
(b): the system with a main unit (x) and a standby unit (y)

The state-space model is very applicable for reliability evaluation of repairable systems. It can be applied to HV circuit-breakers in order to determine the steady-state probability, the mean time to failure and the interval of residing in each state. It must be noted that the Markov model can be implemented only when the system states do not depend on the earlier states. In other words, the Markov model can be applied to the exponential distribution corresponding constant failure rate. In some cases when the systems do not represent the exponential distribution, the Markov model is still applicable for studying the long term circumstances [51]. The general principle and arrangement can be explained from Fig. 6.2 representing a single component with repair.

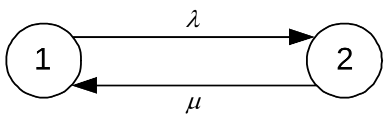


Figure 6.2: A diagram of a single component with repair

The system has a constant failure rate, λ, and a constant repair rate, μ. It is assumed that the system will be in one of two states: in operation (state 1) or under repair (state 2). With the application of Markov process, the following equations are:

$$\frac{dP_1(t)}{dt} = -\lambda P_1(t) + \mu P_2(t) \tag{6.1}$$

$$P_1(t) + P_2(t) = 1 \tag{6.2}$$

The state space equations can be generally expressed in terms of matrix as follows:

$$\frac{dP}{dt} = a \cdot P$$

$$\begin{bmatrix} \frac{dP_1}{dt} \\ \frac{dP_2}{dt} \\ \vdots \\ \frac{dP_n}{dt} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \cdot \begin{bmatrix} P_1 \\ P_2 \\ \vdots \\ P_n \end{bmatrix} \tag{6.3}$$

where $\frac{dP}{dt}$ is the changing of state *P* represented in column matrix consisting of $\frac{dP_1}{dt}, \frac{dP_2}{dt}, ..., \frac{dP_n}{dt}$ and a is the transition matrix.

P is the column matrix representing the state probabilities of P_1, P_2, …P_n. It can be concluded from Eq. (6.1) and (6.3) that the changing of P_1 is equal to the minus of the number of transitions to other states and the plus of the number of transitions from other states. In order to form the transition matrix (a), the following rules must be taken into account.

- The primary diagonal elements are negative, whereas the other elements are positive.
- The primary diagonal elements are the negative summation of the transition rates from state i to state j.
- The secondary elements are equal to the transition rates from state j to the state i.
- The secondary elements are: $a_{ij} \neq a_{ji}$
- The summation of the elements in the same column is zero.

At steady state condition, $\frac{dP_n}{dt}$ is zero and then the Eq. (6.3) can be represented as

$$\begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} . \begin{bmatrix} P_1 \\ P_2 \\ \vdots \\ P_n \end{bmatrix} \tag{6.4}$$

Likewise the Eq. (6.2), the summation of every state must be unity.

$$1 = P_1 + P_2 + ...P_n \tag{6.5}$$

Since the Eq. (6.4) is linear, any row can be substituted by Eq. (6.5) as shown.

$$\begin{bmatrix} 0 \\ 0 \\ \vdots \\ 1 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ 1 & 1 & \cdots & 1 \end{bmatrix} . \begin{bmatrix} P_1 \\ P_2 \\ \vdots \\ P_n \end{bmatrix} \tag{6.6}$$

The state probabilities, P_1, P_2, … P_n can be calculated from Eq. (6.6) by multiplying the inverse of the transition matrix at both sides. The frequency that the equipment changes from state to state can be calculated by the product of the state probability and the sum of transition rates of this state to other states.

$$H_n = -P_n a_{nn}$$

The mean duration of residing in each state can be expressed as:

$$T_n = -\frac{1}{a_{nn}} \tag{6.7}$$

6.2 Reliability Parameters

The average failure-free time can be represented as the mean time to failure (MTTF). When the distribution of failures is represented by an exponential distribution, the failure rate (λ) is then calculated by the inverse of the MTTF. The failure rates (λ) of five main components of different types of HV circuit-breakers can be obtained from the database (shown in section 6.5). Afterwards, MTTFs and failure rates of five main components of different types of HV circuit-breakers are investigated and then compared. Moreover, the mean time to repair (MTTR) of each component, obtained from the manufacture, must be taken into account. It is assumed that the MTTR as shown in Table 6.1 has the exponential distribution corresponding the constant repair rate (μ).

Component	MTTR (day)	Repair rate, μ (1/a)
1. Drive	3	121.67
2. HV Insulation	4	91.25
3. Life-Parts	10	36.5
4. Control/Auxiliary	2	182.5
5. Others	2	182.5

Table 6.1: MTTRs and repair rates of components of HV circuit-breakers

The failure-free time must be carefully considered since there are many failures recorded on the same day or in the next few months. It can be explained that these failures resulted from human error and incomplete repair/inspection. Consequently, the expected value or MTTF is reduced. The effects of human error and incomplete repair/inspection on MTTF will be discussed in the upcoming section.

6.3 Parallel Markov Model for HV Circuit-Breakers

The possible states of HV circuit-breakers having 5 components in parallel are 32 states. However, it is assumed from the physical characteristics of an HV circuit-breaker that only a failure from one component results in the interruption of operation. Afterwards, the action must be called upon to repair or replace such a component. Consequently, the numbers of states are reduced to 6 states. The parallel Markov model of HV circuit-breakers can be represented in Fig. 6.3. It can be explained from Fig. 6.3 that at state Z0 every component of HV circuit-breakers is in operation. When there is a failure in a component (state Z1-Z5), the repair or replace program must be taken into action. After that, HV circuit-breakers return to the normal operation (state Z0).

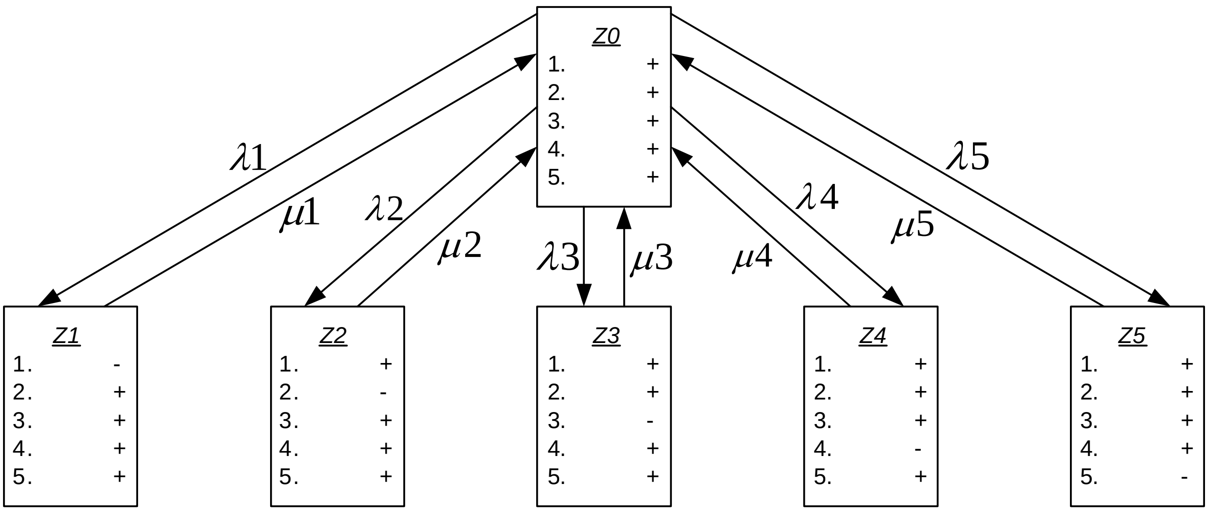


Figure 6.3: Parallel Markov model of HV circuit-breakers

In Fig. 6.3, the + sign represents that there is no failure on the component, whereas the - sign represents the failure on the component. The assigned numbers of the components (1-5) correspond to the different components as represented in Table 6.1.

6.4 Matrix Approach

The transition rates of the multi-component systems can be easily expressed in the form of a transition matrix. The primary diagonal elements (i = j) of the matrix are the negative of the summation of outgoing transition rates of state i. For the secondary diagonal elements, the element i, j is the transition rate into state i from state j where i $\neq$ j. The transition matrix of the parallel Markov model (Fig. 6.3) can be represented as:

$$\begin{bmatrix} \frac{dP_0}{dt} \\ \frac{dP_1}{dt} \\ \frac{dP_2}{dt} \\ \frac{dP_3}{dt} \\ \frac{dP_4}{dt} \\ \frac{dP_5}{dt} \end{bmatrix} = \begin{bmatrix} -(\lambda 1+\lambda 2+\lambda 3+\lambda 4+\lambda 5) & \mu 1 & \mu 2 & \mu 3 & \mu 4 & \mu 5 \\ \lambda 1 & -\mu 1 & 0 & 0 & 0 & 0 \\ \lambda 2 & 0 & -\mu 2 & 0 & 0 & 0 \\ \lambda 3 & 0 & 0 & -\mu 3 & 0 & 0 \\ \lambda 4 & 0 & 0 & 0 & -\mu 4 & 0 \\ \lambda 5 & 0 & 0 & 0 & 0 & -\mu 5 \end{bmatrix} . \begin{bmatrix} P_0 \\ P_1 \\ P_2 \\ P_3 \\ P_4 \\ P_5 \end{bmatrix} \tag{6.8}$$

$$P_0 + P_1 + P_2 + P_3 + P_4 + P_5 = 1 \tag{6.9}$$

The Eq. (6.9) will be replaced in the Eq. (6.8), thus resulting in the transition matrix, a.

$$\begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} = \begin{bmatrix} -(\lambda 1+\lambda 2+\lambda 3+\lambda 4+\lambda 5) & \mu 1 & \mu 2 & \mu 3 & \mu 4 & \mu 5 \\ \lambda 1 & -\mu 1 & 0 & 0 & 0 & 0 \\ \lambda 2 & 0 & -\mu 2 & 0 & 0 & 0 \\ \lambda 3 & 0 & 0 & -\mu 3 & 0 & 0 \\ \lambda 4 & 0 & 0 & 0 & -\mu 4 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 \end{bmatrix} . \begin{bmatrix} P_0 \\ P_1 \\ P_2 \\ P_3 \\ P_4 \\ P_5 \end{bmatrix} \tag{6.10}$$

The probabilities P0 to P5 of states Z0 to Z5 can be calculated by using Cramer's rule. The steady-state availability of HV circuit-breakers is considered as the probability of state Z0. In addition, the duration of residing in each state can be calculated as follows:

$$T_0 = \frac{1}{\lambda 1 + \lambda 2 + \lambda 3 + \lambda 4 + \lambda 5} \quad (6.11)$$

$$T_1 = \frac{1}{\mu 1},\ T_2 = \frac{1}{\mu 2},\ T_3 = \frac{1}{\mu 3},\ T_4 = \frac{1}{\mu 4},\ T_5 = \frac{1}{\mu 5} \quad (6.12)$$

The residing duration of T_0 represents the most important parameter. It represents the duration of HV circuit-breakers being in operation without any failures.

6.5 Results of Markov Model

As mentioned earlier, the expected value of failure-free time or mean time to failure (MTTF) of different components on different types of HV circuit-breakers must be first investigated. The investigation of MTTFs of different components and types of HV circuit-breakers is shown in Table 6.2 and 6.3. MTTF1, MTTF2, …, MTTF5 correspond to the components 1-5 stated in Table 6.1

	All Types	SF6 with hydraulic drive	SF6 with mechanical drive	Min. oil with hydraulic drive	Min. oil with mechanical drive
No. of faulted CB	3153	1678	203	589	280
No. of total CB	9305	3168	1220	1076	1674
No. of failures	6858	3994	265	1263	658
MTTF1(yrs)/λ1	9.015 / 0.111	6.172 / 0.162	4.577 / 0.218	11.427 / 0.087	16.787 /0.060
MTTF2(yrs)/λ2	11.763 / 0.085	7.804 / 0.128	6.181 / 0.162	14.364 / 0.070	16.510 / 0.061
MTTF3(yrs)/λ3	10.068 / 0.099	9.302 / 0.108	13.691 / 0.073	17.542 / 0.057	5.479 / 0.183
MTTF4(yrs)/λ4	8.821 / 0.113	7.079 / 0.141	6.730 / 0.149	12.707 / 0.079	17.025 / 0.059
MTTF5(yrs)/λ5	10.23 / 0.098	7.434 / 0.135	7.962 / 0.126	18.494 / 0.054	14.194 / 0.070

Table 6.2: MTTFs and failure rates of different components and types of circuit-breakers (every failure is taken into account)

	All Type	SF6 with hydraulic drive	SF6 with mechanical drive	Min. oil with hydraulic drive	Min. oil with mechanical drive
No. of failures	5207	2968	207	1021	439
MTTF1(yrs)/λ1	12.046 / 0.083	8.773 / 0.114	7.176 / 0.139	14.203 / 0.070	19.823 /0.050
MTTF2(yrs)/λ2	15.084 / 0.066	11.076 / 0.090	12.5 / 0.080	17.006 / 0.059	18.250 / 0.055
MTTF3(yrs)/λ3	14.930 / 0.067	12.051 / 0.083	15.880 / 0.063	23.830 / 0.042	12.275 / 0.081
MTTF4(yrs)/λ4	10.582 / 0.094	8.569 / 0.117	8.926 / 0.112	15.281 / 0.065	18.427 / 0.054
MTTF5(yrs)/λ5	13.664 / 0.073	10.197 / 0.098	9.545 / 0.105	22.75 / 0.044	18.590 / 0.054

Table 6.3: MTTFs and failure rates of different components and types of circuit-breakers (failures occurring within the first year are not taken into account)

It can be concluded from Table 6.2 and 6.3 that the human error and incomplete repair/inspection occurring within the first year reduce the MTTFs, thus leading to reduced availability of HV circuit-breakers. In case of all types of circuit-breakers, the comparison of failure density functions of components is represented in Fig. 6.4

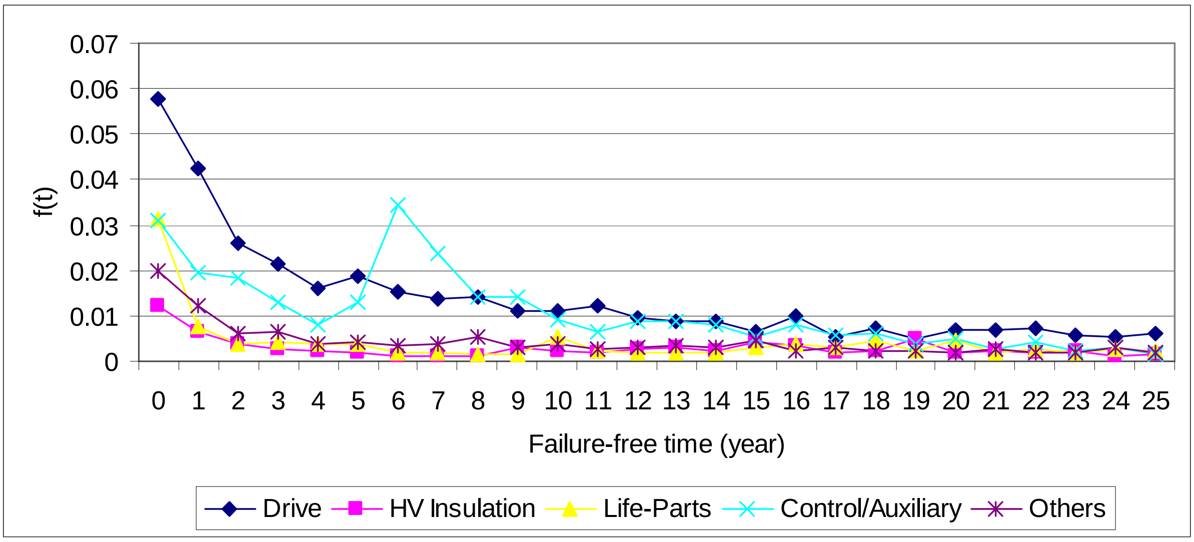


Figure 6.4: Comparison of failure density functions of components of all types of HV circuit-breakers

It can be seen from Fig. 6.4 that the functions are not perfectly exponentially distributed. However, the error between the real failure function and exponential function is relatively small and will not be discussed in this study. The exponential function can be represented as follows:

$$f(t) = \lambda \cdot e^{-\lambda t}$$

The investigation of availability of HV circuit-breakers has been carried out by replacing the values from Table 6.2 and 6.3 into the Eq. 6.10-6.12. As a result, the probability and duration of residing at every state can be found. The results of the investigation are represented in Table 6.4 and 6.5.

	All Types	SF_6 with hydraulic drive	SF_6 with mechanical drive	Min. oil with hydraulic drive	Min. oil with mechanical drive
P0	0.9943	0.9928	0.9930	0.9962	0.9932
P1	0.0009	0.0013	0.0018	0.0007	0.0005
P2	0.0009	0.0014	0.0018	0.0008	0.0007
P3	0.0027	0.0029	0.0020	0.0016	0.0050
P4	0.0006	0.0008	0.0008	0.0004	0.0003
P5	0.0005	0.0007	0.0007	0.0003	0.0004
T0 (year)	1.9763	1.4837	1.3736	2.8818	2.3095
T1 (year)	0.0082	0.0082	0.0082	0.0082	0.0082
T2 (year)	0.0110	0.0110	0.0110	0.0110	0.0110
T3 (year)	0.0274	0.0274	0.0274	0.0274	0.0274
T4 (year)	0.0055	0.0055	0.0055	0.0055	0.0055
T5 (year)	0.0055	0.0055	0.0055	0.0055	0.0055

Table 6.4: Probabilities and durations of residing in each state of different types of HV circuit-breakers (every failure is taken into account)

	All Types	SF_6 with hydraulic drive	SF_6 with mechanical drive	Min. oil with hydraulic drive	Min. oil with mechanical drive
P0	0.9959	0.9947	0.9951	0.9970	0.9962
P1	0.0007	0.0009	0.0011	0.0006	0.0004
P2	0.0007	0.0010	0.0009	0.0006	0.0006
P3	0.0018	0.0023	0.0017	0.0011	0.0022
P4	0.0005	0.0006	0.0006	0.0004	0.0003
P5	0.0004	0.0005	0.0006	0.0002	0.0003
T0 (year)	2.611	1.992	2.004	3.571	3.401
T1 (year)	0.0082	0.0082	0.0082	0.0082	0.0082
T2 (year)	0.0110	0.0110	0.0110	0.0110	0.0110
T3 (year)	0.0274	0.0274	0.0274	0.0274	0.0274
T4 (year)	0.0055	0.0055	0.0055	0.0055	0.0055
T5 (year)	0.0055	0.0055	0.0055	0.0055	0.0055

Table 6.5: Probabilities and durations of residing in each state of different types of HV circuit-breakers (failures occurring within the first year are not taken into account)

The duration of residing in state Z0 or the duration that HV circuit-breakers are in operation without failures can be plotted as bar graph as shown in Fig. 6.5.

It is obvious in Fig. 6.5 that without the consideration of the first-year failures (T02), HV circuit-breakers stay in operation 32%, 24%, 45%, 24%, and 47% longer in all types, SF6 with hydraulic drive, SF_6 with mechanical drive, minimum oil with hydraulic drive and minimum oil with mechanical drive respectively. It could be implied that the duration of operation can be prolonged when the effects of human error and incomplete repair/inspection are reduced. It is obvious from the proportion of increasing duration that HV circuit-breakers with mechanical drives are subject to human error and incomplete repair/inspection more than ones with hydraulic drives.

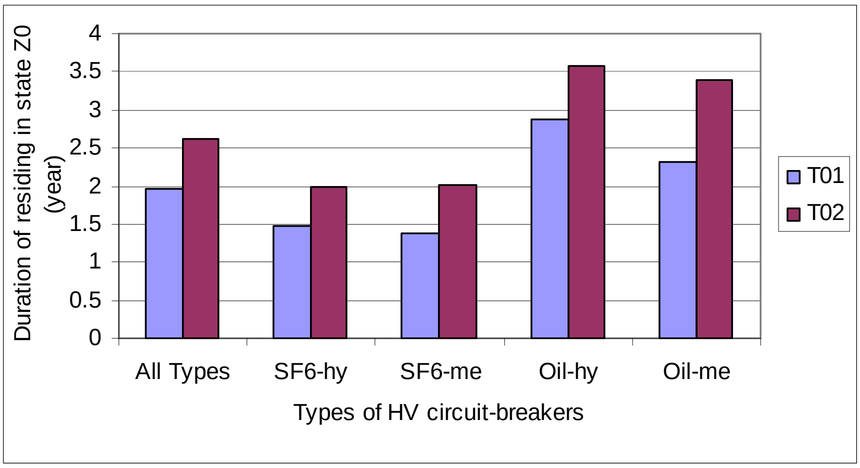


Figure 6.5: The durations of residing in state Z0
T01: every failure is considered
T02: failures in the first year are not considered

The steady-state availabilities of different types of HV circuit-breakers are all over 0.99 since the repair times of components are considerably shorter than their MTTFs. It could be concluded that as long as the action to repair is as short as mentioned, the availability of HV circuit-breakers remains high.

As mentioned earlier that there is no distinction between minor and major failures in the database, state Z0, represented the duration without failures, appears to be shorter than expectation. Practically, it is beneficial to consider the state Z0 with only the effects of major failures. Therefore, the relationship between minor and major failures [2] is applied. The average ratio of minor and major failure is 7.3 mf/MF. This factor is then applied in Eq. (6.11) to find the durations of residing in state Z0. The durations of residing in state Z0 calculated from only major failures can be represented in Table 6.6 and Fig. 6.6.

	All Types	SF_6 with hydraulic drive	SF_6 with mechanical drive	Min. oil with hydraulic drive	Min. oil with mechanical drive
T01 (year)	14.427	10.831	10.027	21.037	16.860
T02 (year)	19.060	14.542	14.630	26.068	24.827

Table 6.6: The durations of residing in state Z0 calculated from only major failures
T01: every failure is considered
T02: failures in the first year are not considered

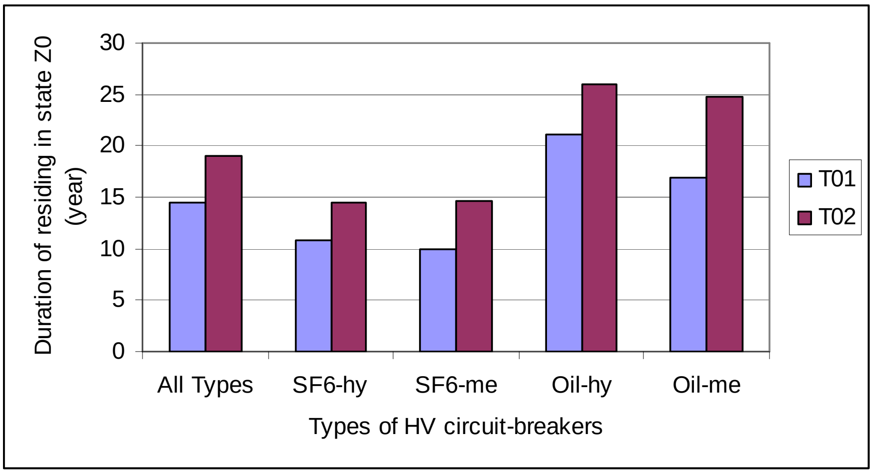


Figure 6.6: The durations of residing in state Z0 calculated from only major failures
T01: every failure is considered
T02: failures in the first year are not considered

It can be seen from Fig. 6.6 that the durations of uninterrupted state Z0 are around 14 years for the SF_6 circuit-breakers and 24-26 years for minimum oil circuit-breakers.

6.6 Conclusions

It can be concluded from the MTTF investigation and availability of HV circuit-breakers by the Markov model:

- The investigation of all types of HV circuit-breakers, representing the largest studied population, shows that HV insulation has the longest MTTF, whereas the control/auxiliary component has the shortest MTTF.
- The populations of SF_6 circuit-breakers with hydraulic drives and SF_6 circuit-breakers with mechanical drives are very different. Therefore, it is difficult to make conclusions as to the MTTF. However, it is obvious from Table 6.2 that the proportion of faulted circuit-breakers to total circuit-breakers in the same category represents the overall reliability. More than half of the population of SF_6 circuit-breakers with hydraulic drives had been exposed to failures, whereas only 16 % of the population of SF_6 circuit-breakers with mechanical drives had experienced failures.
- The mechanical drive has longer MTTF than the hydraulic drive which is in accordance with practical experience.
- The control/auxiliary components of minimum oil circuit-breakers have longer MTTF than control/auxiliary components of SF_6 circuit-breakers due to less complicated control/auxiliary in minimum oil circuit-breakers.
- It can be seen from Table 6.2 and 6.3 that without the consideration of failures in the first year, the MTTFs of components can be increased up to 47 %. It is recommended that repair/inspection must be carefully carried out in order to prevent the following failures occurring in the same year.
- Components of minimum oil circuit-breakers have longer MTTFs than components of SF_6 circuit-breakers. However, it must be paid attention that the database of minimum oil circuit-breakers is longer than SF_6 circuit-breakers. The record time of minimum oil circuit-breakers is around 50 years, whereas the record time of SF_6 circuit-breakers is only 30 years.
- The failure density functions of components are roughly exponentially distributed. In other words, this exponential distribution corresponds to random failures. Hence, the preventive or time-based maintenance cannot extend MTTF or reduce the failure rate. In order to extend MTTF, the predictive or condition-based maintenance must be introduced.

7 Cost Structure and Maintenance Optimization

The first part of this chapter is to investigate the influence of circuit-breaker specifications on the costs of circuit-breakers. By using the decision matrix approach, it is possible to figure out the cost structure of the main components related to the specifications. The second part of this chapter deals with the maintenance optimization. The optimal maintenance frequency during useful life is carried out by using the optimal maintenance frequency model [52] in order to minimize the downtime. The last part represents how to improve the reliability of HV circuit-breakers during the wear-out period. The reliability during the wear-out period can be investigated by the use of probability distribution and improved by using the preventive maintenance. The Weibull distribution model is therefore applied to design the improved preventive maintenance model.

7.1 Cost Structure Determination

The specifications of HV circuit-breakers according to IEC 62271-100 and additional specifications are determined in order to study the influence of each specification on the cost of the circuit-breaker. The steps of cost determination are described as followed:

1. The table is composed of considered specifications and five main components:
   - quenching unit
   - insulation
   - supporting structure
   - drive
   - control system
2. The influence of every specification to each component is discussed with the manufacture and the results are then fulfilled into the table (Table 7.1)
3. The specifications having the same properties are grouped and the reduced table is formed (Table 7.2). For example, “rated lightning” and “switching impulse” withstand voltage has the same influences on quenching unit, insulation and supporting structure.

4. The cost proportion of main components is taken into consideration by using a decision matrix approach (Fig. 7.1). In other words, the relationship of five main components to the costs of an HV circuit-breaker can be explored.
5. The specifications in each related main component are investigated by using the decision matrix approach to find the significance of each specification (Appendix D).
6. Finally, the influence of each specification to HV circuit-breakers can be determined.

It can be seen from Table 7.1 and 7.2 that the specifications play no important role on the cost of control systems.

Specification \ Component	Quenching Unit	Insulation	Supporting structure	Drive	Control system
1. Rated voltage	X	X	X	X	
2. Rated lightning impulse withstand voltage	X	X	X		
3. Rated switching impulse withstand voltage	X	X	X		
4. Rated operating current	X	X	X	X	
5. Power factor	X			X	
6. Rated duration of short circuit (1 s)	X				
7. Rated short circuit breaking current	X	X	X	X	
8. DC component of the rated short-circuit breaking current (20 %)	X	X	X	X	
9. First pole-to-clear factor	X			X	
10. Rated out-of-phase breaking current (optional)	X				
11. Rated line-charging breaking current	X		X	X	
12. Rated cable-charging breaking current	X		X	X	
13. Rated single capacitor bank-breaking current	X		X	X	
14. Rated back-to-back capacitor bank-breaking current	X				
15. Rated capacitor bank inrush making current	X				
16. Rated back-to-back capacitor bank inrush making current (optional)	X				
17. Rated operating sequence	X			X	
18. Temperature class	X			X	
19. Classification: number of operation	X			X	

Specification \ Component	Quenching Unit	Insulation	Supporting structure	Drive	Control system
20. Earthquake level		X	X	X	
21. Bending strength		X	X		
22. Pollution level		X			
23. Overvoltage across CB	X	X			
24. Rate of Rise of Recovery Voltage (RRRV)	X			X	
25. Short-line faults	X				

Table 7.1: The influence of specifications to the components

Specification \ Component	Quenching Unit	Insulation	Supporting structure	Drive	Control system
1. Rated voltage	X	X	X	X	
2. Rated lightning and switching impulse withstand voltage	X	X	X		
3. Rated operating current	X	X	X	X	
4. Rated duration of short circuit (1 s)	X				
5. Rated short circuit breaking current and DC component	X	X	X	X	
6. First pole-to-clear factor	X			X	
7. Rated out-of-phase breaking current (optional)	X				
8. Rated line-charging breaking current	X		X	X	
9. Rated capacitor bank inrush making current	X				
10. Rated operating sequence	X			X	
11. Temperature class	X			X	
12. Classification: number of operation	X			X	
13. Earthquake level		X	X	X	
14. Bending strength		X	X		
15. Pollution level		X			
16. Rate of Rise of Recovery Voltage (RRRV)	X			X	

Table 7.2: The influence of specifications to the components (reduced version)

Nr.	Criteria	1	2	3	4	5	Sum	WF/%
1	Quenching unit	0	4	5	2	5	16	26.7
2	Insulation	2	0	5	3	5	15	25.0
3	Supporting structure	1	1	0	1	4	7	11.7
4	Drive	4	3	5	0	5	17	28.3
5	Control System	1	1	2	1	0	5	8.3
							60	100.0

Figure 7.1: The decision matrix of five main components

Influence evaluation: 1: very small 4: strong

2: small 5: very strong

3: similar

By using this decision matrix approach, Fig. 7.1, every parameter is compared with each other with different degrees of significance. For example, the quenching unit compared with the insulation has stronger influence on the costs. Therefore, the number 4 is placed in the first row and the second column. On the other hand, the quenching unit compared with drive has smaller influence on the costs. The number 2 is then placed in the first row and the fourth column. The upper triangle of the matrix (above the primary diagonal axis) must be considered. The lower triangle of the matrix (below the primary diagonal axis) is justified by reversion of the investigation of the above triangle. For example, the insulation compared with the quenching unit has smaller influence on the costs. The number 2 is then placed in the second row and the first column. After the whole decision matrix is completed, the proportion of every main component can be found. The proportion distribution of main components to the costs of HV circuit-breakers is represented in Fig. 7.2

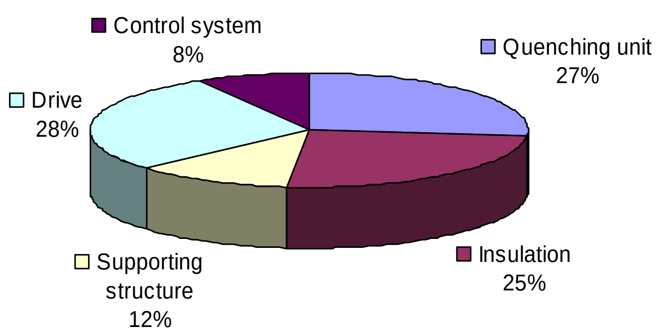
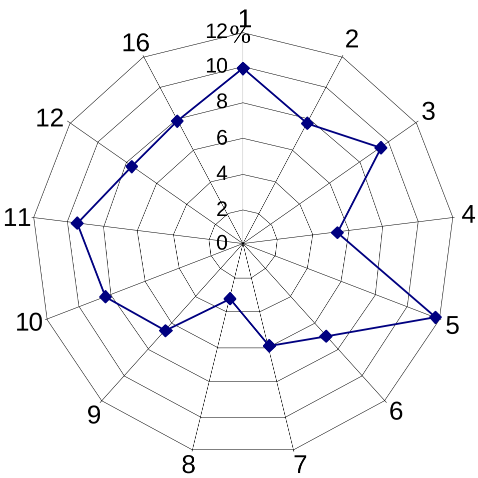


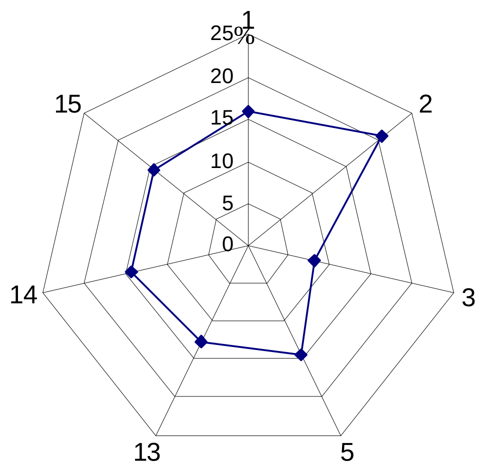
Figure 7.2: The proportion distribution of five main components to the cost of HV circuit-breakers

It is seen from Fig. 7.2 that the drive or the operating mechanism plays the most important role on the total cost followed by the quenching unit, the insulation and the supporting structure.

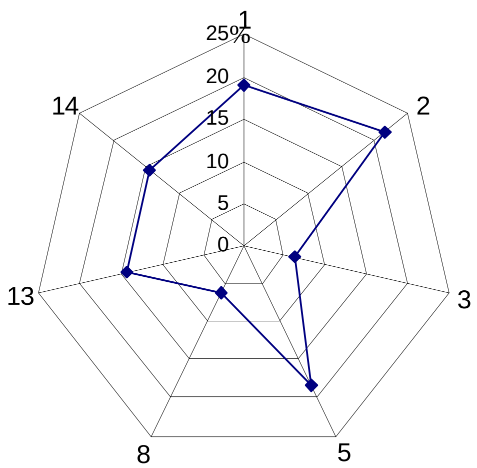
The specifications of each component represented in Table 7.2 are considered one by one by using the decision matrix in order to find the proportions of specifications (Appendix D). The proportions of specifications with respect to each component can be represented as web diagrams in Fig. 7.3.



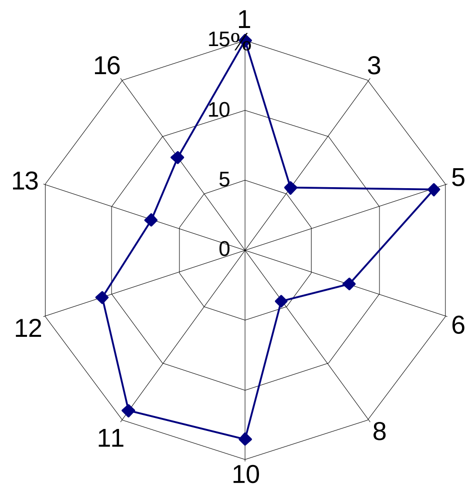
(a) Quenching unit



(b) Insulation



(c) Supporting structure



(d) Drive

Figure 7.3: Web diagrams of the circuit-breaker specifications with respect to each component (The numbers at the perimeter of the circle correspond to specifications represented in Table. 7.2)

For instance, the proportion of rated voltage (no. 1) to the cost of the quenching unit is 10%, while the proportion of rated line charging (no. 8) to the cost of the quenching unit is only 3.3%. In case of the insulation, rated lightning and switching impulse withstand voltage (no. 2) accounts for the highest proportion (20 %).

Specification \ Component	Quenching Unit	Insulation	Supporting structure	Drive	Total
1. Rated voltage	2.7 %	4.0 %	2.3 %	4.1 %	13.1 %
2. Rated lightning and switching impulse withstand voltage	2.1 %	5.0 %	2.6 %		9.7 %
3. Rated operating current	2.5 %	2.0 %	0.8 %	1.6 %	6.9 %
4. Rated duration of short circuit (1 s)	1.4 %				1.4 %
5. Rated short circuit breaking current and DC component	3.1 %	3.6 %	2.2 %	3.9 %	12.8 %
6. First pole-to-clear factor	1.9 %			2.2 %	4.1 %
7. Rated out-of-phase breaking current (optional)	1.6 %				1.6 %
8. Rated line-charging , cable-charging and capacitor bank breaking current	0.9 %		0.7 %	1.2 %	2.8 %
9. Rated capacitor bank inrush making current	1.8 %				1.8 %
10. Rated operating sequence	2.3 %			3.7 %	6.0 %
11. Temperature class	2.5 %			3.9 %	6.4 %
12. Classification: number of operation	2.1 %			3.0 %	5.1 %
13. Earthquake level		3.2 %	1.7 %	2.0 %	6.9 %
14. Bending strength		3.6 %	1.7 %		5.3 %
15. Pollution level		3.6 %			3.6 %
16. Rate of Rise of Recovery Voltage (RRRV)	2.1 %			2.4 %	4.5 %
Total	27 %	25 %	12 %	28 %	92 %

Table 7.3: The proportions of specifications to the main components (without control system)

The proportions of specifications related to the circuit-breaker are shown in Table 7.3. The whole table of which the control system (8 %) is not included represents 92 %. It can be expressed in terms of pie chart in Fig. 7.4. The influence of specifications on the cost of the circuit-breaker is as shown in Fig. 7.4 is valuable for the circuit-breaker designers to design the optimal and cost-effective HV circuit-breakers.

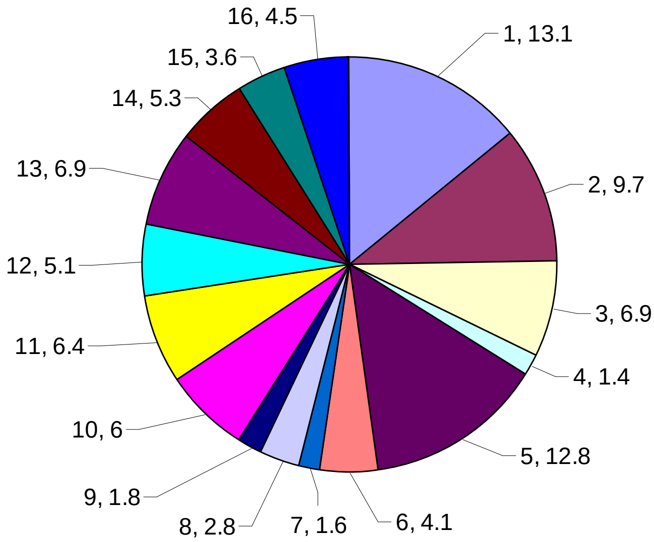


Figure 7.4: The proportions of specifications to the cost of HV circuit-breaker

The most and least important specifications to the cost of circuit-breakers can be summarized in Table 7.4

	The most important specifications	%	The least important specifications	%
1.	Rated voltage	13.1	Rated duration of short-circuit	1.4
2.	Rated short-circuit breaking current	12.8	Rated out-of-phase breaking current	1.6
3.	Rated lightning and switching impulse withstand voltage	9.7	Rated capacitor bank inrush making current	1.8

Table 7.4 The most and least important influences on the cost of circuit-breakers

7.2 Maintenance Optimization

In the first part of this section, the optimal maintenance frequency during the useful lifetime is calculated by using the optimal maintenance frequency model and failure statistics during 1991-2000 [37]. The optimal maintenance frequency of different types of HV circuit-breakers at different voltage levels had been investigated. The second part of this section concerns with the improvement of maintenance strategy during the wear-out period. The wear-out behaviour of HV circuit-breakers is simulated by a Weibull distribution. The integration of different preventive maintenance models represents the improvement of reliability of HV circuit-breakers.

7.2.1 Optimal Maintenance Frequency

The equipment of HV circuit-breakers breaks down from time to time. In order to reduce the breakdowns, periodic maintenance must be implemented. However, the maintenance might result in the system downtime. More frequent maintenance could reduce the downtime due to system failures but increase the downtime due to maintenance. The principle of optimal maintenance frequency in order to minimize the downtime can be expressed in Fig. 7.5.

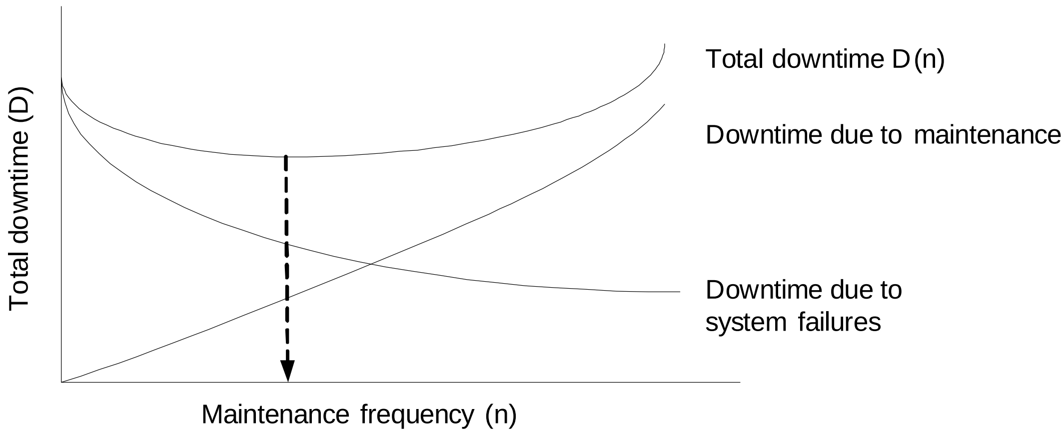


Figure 7.5: Optimal maintenance frequency: Minimization of downtime

It is obvious from Fig. 7.5 that the total downtime, D(n), is the summation of downtime due to maintenance (D_M) and downtime due to system failures. The downtime due to system failures can be mentioned as downtime due to repairs (D_R).

$$D(n) = D_R + D_M = \frac{\lambda(n)}{\mu} + \frac{n}{i} \quad (7.1)$$

where:

Parameter	Equation	Remark
$\lambda(n)$	1/mean time to failure (MTTF)	Failure rate or number of repairs per unit time
μ	1/mean time to repair (MTTR)	Repair rate
n		Number of periodic maintenance per unit time
i	1/mean time to maintenance (MTTM)	Maintenance rate
D_R	$\lambda(n)/\mu$	Downtime due to repair
D_M	n/i	Downtime due to maintenance

In order to find the optimal maintenance frequency, the derivative of downtime is applied as followed.

$$\frac{dD(n)}{dn} = \frac{\lambda'(n)}{\mu} + \frac{1}{i} = 0 \tag{7.2}$$

It is assumed that the failure rate varies inversely with the number of periodical maintenance. k is the arrival rate of failure per unit time when one periodical maintenance is made per unit time.

$$\lambda(n) = \frac{k}{n} \qquad \lambda'(n) = -\frac{k}{n^2} \tag{7.3}$$

From Eq. (7.2) and (7.3), the optimal maintenance frequency, n, can be found. The value n is the number of optimal maintenance frequency per year.

$$n = \sqrt{\frac{i \cdot k}{\mu}} = \sqrt{\frac{MTTR \cdot k}{MTTM}} \tag{7.4}$$

From the database, it is estimated that the periodical minor and major maintenance of HV circuit-breakers are carried out every 4 and 7 years respectively. It is assumed that the minor maintenance is related to the minor failures and the major maintenance is related to major failures. Accordingly, the failure rates in the Table 7.5 represent the major failure rates when major maintenance tasks are carried out. Likewise, Table 7.5 represents the minor failure rates when minor maintenance programs are introduced. With these assumptions, the two optimal maintenance models are then introduced:

- the optimal major maintenance of HV circuit-breakers in relation to major failures
- the optimal minor maintenance of HV circuit-breakers in relation to minor failures

According to the statistics [37], the major failure rates of HV circuit-breakers in Germany at different voltage levels are represented in Table 7.5. The minor failure rates are calculated by using the relationship between the major and minor failure rates according to CIGRE. They are represented in Table 7.6.

Type	123kV	245kV	420kV
minimum oil	0.0021	0.0104	0.0203
air-blast	0.0039	0.0114	0.0319
SF_6	0.0024	0.0144	0.0260

Table 7.5: Failure rates of major failures, λ_{MF}

Type	123kV	245kV	420kV
minimum oil	0.0147	0.08944	0.12992
air-blast	0.0273	0.09804	0.20416
SF_6	0.0168	0.12384	0.1664

Table 7.6: Failure rates of minor failures, λ_{mf}

7.2.1.1 The optimal major maintenance of HV circuit-breakers in relation to major failures

The assumptions in this case can be concluded as follows:

- It is estimated that the actual major maintenance had been carried out every 7 years
- Number of failures per year, k, when 1 major maintenance is made per year = λ_{MF} / 7
- Mean time to repair (MTTR) = 3 days

- Mean time to major maintenance (MTTM) = 1 day

The optimal major maintenance, $$n = \sqrt{\frac{i \cdot k}{\mu}} = \sqrt{\frac{MTTR \cdot k}{MTTM}} = \sqrt{\frac{MTTR \cdot \lambda_{MF}}{MTTM \cdot 7}} \quad (7.5)$$

Substitute the values from Table 7.5 into the Eq. (7.5) thus resulting in the optimal major maintenance per year, n. The inversion of n corresponds to the optimal major maintenance interval which can be represented in Table 7.7

Type	123kV	245kV	420kV
minimum oil	33.3	15.0	10.7
air-blast	24.5	14.3	8.6
SF_6	31.2	12.7	9.5

Table 7.7: Optimal major maintenance interval (years)

In order to study the influence and deviation of the actual major maintenance to the optimal major maintenance interval, the relationship between them must be investigated as followed:

- The actual maintenance interval is varied from 6 to 12 years while keeping the major failure rate, λ_{MF}, constant.
- The actual maintenance interval is varied while the major failure rate, λ_{MF}, is changed proportionally. The longer the actual maintenance interval, the higher the failure rates. As a result, the optimal major maintenance interval is constant.

The example of SF_6 circuit-breakers is represented in Fig. 7.6. It shows the varied optimal major maintenance interval when the actual major maintenance interval is changed. The shaded area is the deviation between the constant optimal maintenance interval and the variable one. For instance, in case of 123 kV, the optimal major maintenance interval is increased from 31 to 41 years when the actual major maintenance interval is changed from 7 to 12 years. The deviation of 245 and 420 kV cases is relatively small when the actual major maintenance is varied.

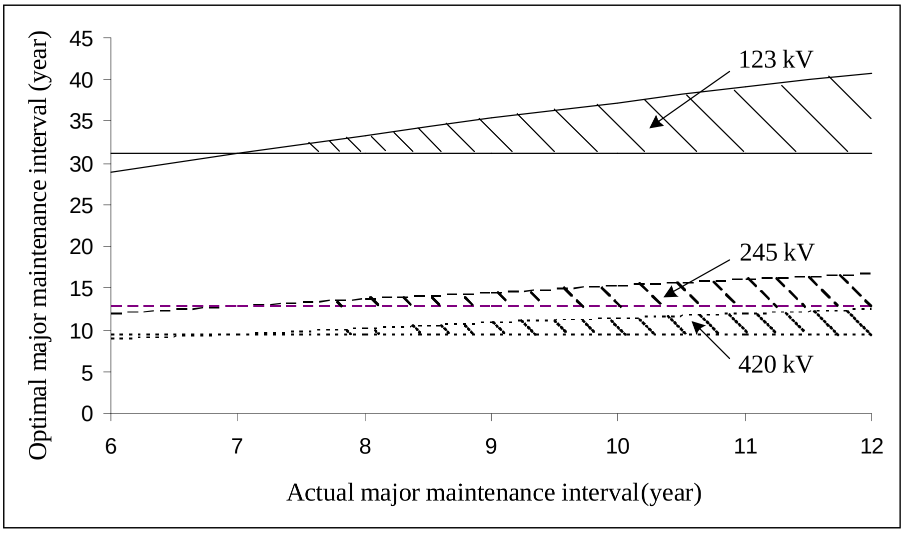


Figure 7.6: The deviation of optimal major maintenance interval with respect to major maintenance interval (SF_6 circuit-breakers)

7.2.1.2 The optimal minor maintenance of HV circuit-breakers in relation to minor failures

The assumptions in this case can be summarized as follows:

- It is estimated that the actual minor maintenance is carried out every 4 years
- Number of failures per year, k, when 1 minor maintenance is made per year = $\lambda_{mf} / 4$
- Mean time to repair (MTTR) = 1 day
- Mean time to minor maintenance (MTTm) = 0.5 day

The optimal minor maintenance, $$n = \sqrt{\frac{i \cdot k}{\mu}} = \sqrt{\frac{MTTR \cdot k}{MTTm}} = \sqrt{\frac{MTTR \cdot \lambda_{mf}}{MTTm \cdot 4}} \quad (7.6)$$

Substitute the values from Table 7.6 into the Eq. (7.6) thus resulting in the optimal minor maintenance per year, n. The inversion of n corresponds to the optimal minor maintenance interval which can be represented in Table 7.8

Type	123kV	245kV	420kV
minimum oil	11.7	4.7	3.9
air-blast	8.6	4.5	3.1
SF_6	10.9	4.0	3.5

Table 7.8: Optimal minor maintenance interval (years)

The influence and deviation of actual minor maintenance interval to the optimal minor maintenance interval can be performed in the same way as major maintenance. The actual minor maintenance interval is varied from 3 to 9 years.

Fig. 7.7 represents the example of SF_6 circuit-breakers. The deviation between the constant optimal maintenance interval and the variable one is shown in the shaded area. In case of 123 kV, it can be seen that the optimal minor maintenance interval is varied from around 11 to 16 years when the actual minor maintenance is changed from 4 to 9 years. The deviation in case of 245 and 420 kV is smaller than 123 kV.

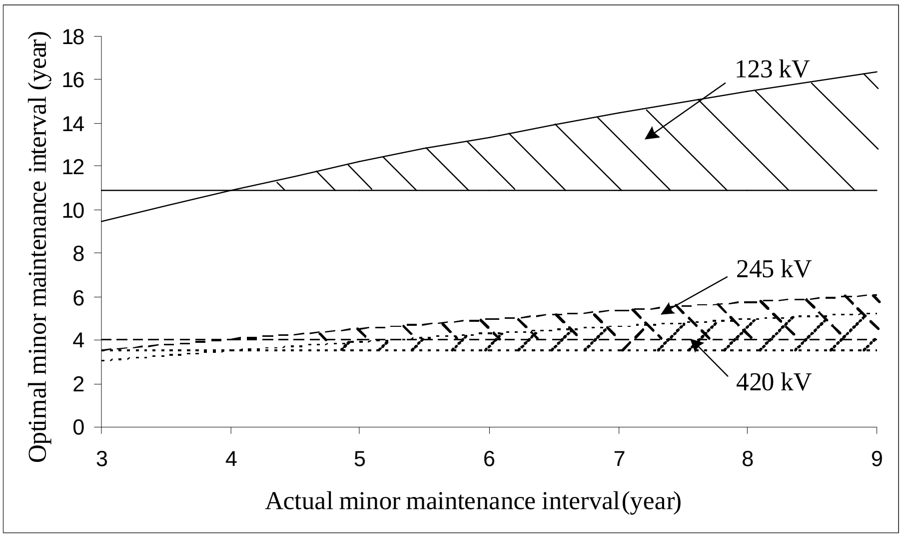


Figure 7.7: The deviation of optimal minor maintenance interval with respect to minor maintenance interval (SF_6 circuit-breakers)

The optimal minor and major maintenance of different types of HV circuit-breakers at different voltage levels can be concluded in Table 7.9.

	123 kV		245 kV		420 kV	
	minor maintenance (years)	major maintenance (years)	minor maintenance (years)	major maintenance (years)	minor maintenance (years)	major maintenance (years)
minimum oil	11.7	33.3	4.7	15.0	3.9	10.7
air-blast	8.6	24.5	4.5	14.3	3.1	8.6
SF_6	10.9	31.2	4.0	12.7	3.5	9.5

Table 7.9: The optimal minor and major maintenance intervals of HV circuit-breakers

It can be concluded from Table 7.9 that:

- Since 123 kV-HV circuit-breakers had been subject to relatively small failures, the actual minor and major maintenance intervals of 4 and 7 years respectively are too frequent. The optimal minor maintenance interval should be around 8 – 12 years depending on types of circuit-breakers. The optimal major maintenance programs of 123kV-HV circuit-breakers should be performed every 24 – 33 years.
- The minor failure rates of 245 kV-HV circuit-breakers are relatively high. The optimal minor maintenance intervals in this case are around 4-5 years. The optimal major maintenance interval should be extended from 7 years to 14 years in this voltage level.
- In case of 420 kV-HV circuit-breakers, the optimal minor maintenance interval should be performed every 3-4 years, whereas the optimal major maintenance programs should be carried out every 8-10 years.
- It can be seen from the calculation that with the optimal minor and major maintenance programs, the numbers of maintenance are reduced and the systems operate at the minimum downtime.

7.3 Reliability under Preventive Maintenance

7.3.1 Concepts of Preventive Maintenance

The preventive maintenance programs can reduce the effect of aging or wear-out resulting in the extending of lifetime of HV circuit-breakers. It is assumed that after preventive maintenance, the reliability of HV circuit-breakers is restored to the original condition. The reliability of HV circuit-breakers with preventive maintenance is represented as

$$R_m(t) = R(t) \qquad \text{for } 0 \le t < T \tag{7.7}$$

$$R_m(t) = R(T) \cdot R(t - T) \qquad \text{for } T \le t < 2T \tag{7.8}$$

$R_m(t)$ in Eq. (7.7) is the reliability without maintenance and T is the interval to perform preventive maintenance. It is seen in Eq. (7.8) that the preventive maintenance is performed at time T, where R(T) is the survivor function until the first preventive maintenance and R(t - T) is the survivor function at additional time (t - T). HV circuit-breakers are restored to their original state at time T. The Eq. (7.8) can be generally expressed as:

$$R_m(t) = R(T)^n \cdot R(t - nT) \tag{7.9}$$

where $nT \le t < (n+1)T$, $n = 1, 2, 3, \ldots$

$R(T)^n$ is the survivor function of surviving n maintenance intervals and R(t - nT) is the survivor function of additional time (t - nT) after the last preventive maintenance. It is noted that the preventive maintenance cannot be applied during the useful life having exponential distribution. In other words, the preventive maintenance is not applicable under constant failure rate condition as represented below.

$$R(t) = e^{-\lambda t}$$

$$R_m(t) = R(T)^n \cdot R(t - nT)$$

$$R_m(t) = (e^{-\lambda T})^n \cdot (e^{-\lambda(t - nT)})$$

$$R_m(t) = e^{-\lambda nT} \cdot e^{-\lambda t} \cdot e^{\lambda nT} = e^{-\lambda t}$$

It can be seen that the preventive maintenance cannot increase the reliability under constant failure rate condition.

7.3.2 Application of Preventive Maintenance to HV Circuit-Breakers

It must be noted that the preventive maintenance is effective in the wear-out period in order to increase their reliabilities. After preventive maintenance is performed, the reliability of HV circuit-breakers is restored to the original condition. The equation of reliability of HV circuit-breakers with preventive maintenance is represented as followed:

$$R_m(t) = \exp\left[-n\left(\frac{T}{\alpha}\right)^{\beta}\right] \cdot \exp\left[-\left(\frac{t - nT}{\alpha}\right)^{\beta}\right] \qquad nT \leq t < (n+1)T \qquad (7.10)$$

where n: the number of preventive maintenance before the considered period of time

T: interval of time between preventive maintenance

The case of all types of HV circuit-breakers had been used to show the application of preventive maintenance. The failure rate distribution extracted from the failure database of all types of HV circuit-breakers is depicted in Fig. 7.8. The failure distribution represents the relative failure rate of the first failures of circuit-breakers. As a result, the trend of failure development during the lifetime can be investigated.

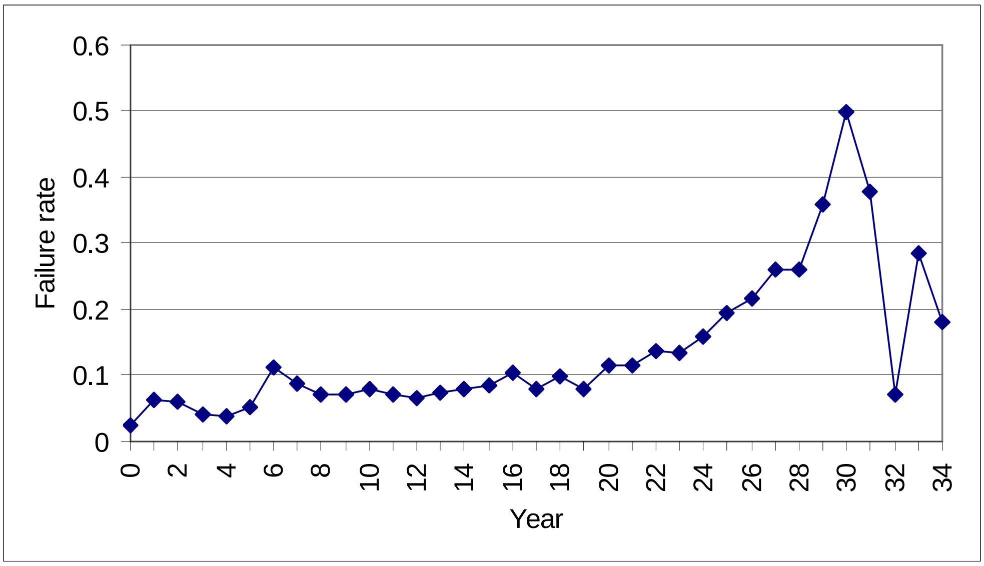


Figure 7.8: The relative failure rate distribution of all types of circuit-breakers

It can be seen from Fig. 7.8 that the failure rate is relatively constant until the 20^{th} year. From the 20^{th} year, the failure rate is increased and it is assumed that this is the Weibull distribution. From the 30^{th} year, the distribution is fluctuated and not precise because of small numbers of samples. Therefore, the parameters of Weibull distribution are determined by using the failure distribution during the 20^{th} - 30^{th} year.

From the failure database, it is found that the maintenance and overhaul are carried out every 7 and 12 years respectively. As discussed earlier, the preventive maintenance cannot increase the reliability when the failure rate is constant (the first 20 years). The investigation then starts at the 20^{th} year and it is assumed that the reliability of circuit-breakers starts at unity in this year in order to simplify the explanation of reliability under preventive maintenance. By using the MATLAB curve-fitting program, it is possible to find the Weibull parameters α and β which are equal to 10 and 4 respectively. The reliability with the preventive maintenance can be represented as:

$$R_m(t) = \exp\left[-n\left(\frac{T}{10}\right)^4\right] \cdot \exp\left[-\left(\frac{t - nT}{10}\right)^4\right] \qquad (7.11)$$

With the Eq. (7.11), the maintenance interval T is varied in order to study the effects of preventive maintenance to the reliability of HV circuit-breakers. The example of maintenance interval of 7 years is illustrated in Fig. 7.9. The effects of different preventive maintenance in terms of the maintenance frequency to the reliability are represented in Fig. 7.10.

It is obvious from Fig. 7.9 that the preventive maintenance has the same distribution as the original reliability distribution but it will be restored to the original condition at the specified maintenance period. When the preventive maintenance is implemented into the original reliability distribution, the decreasing reliability over time can be slowed down. As a result, the lifetime of the HV circuit-breaker can be extended.

The more frequent preventive maintenance results in the more effective extension of the lifetime. However, the cost of frequent maintenance during the wear-out period might be more expensive than the cost of replacing with the new circuit-breakers. Therefore, the optimal maintenance during wear-out period must be calculated.

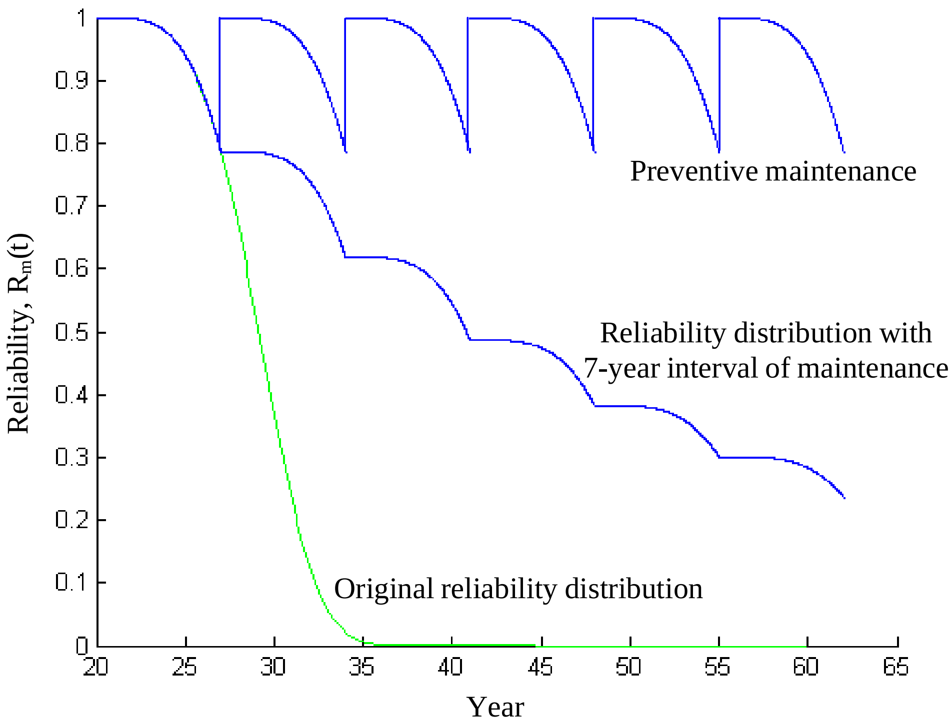


Figure 7.9: The reliability distribution with 7-year interval of maintenance

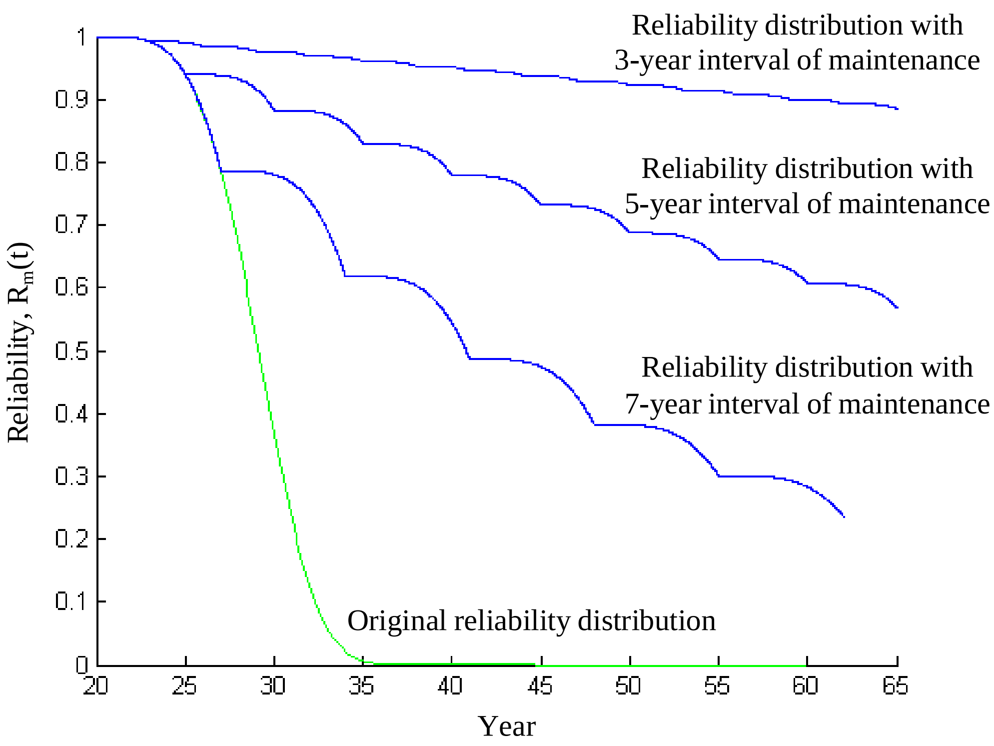


Figure 7.10: The comparison of preventive maintenance at different intervals

7.3.3 Preventive Maintenance during Wear-out Period

The optimal preventive maintenance during wear-out period is carried out after section 7.3.2. The maintenance costs of different maintenance programs are calculated. Afterwards, the maintenance costs are compared with the costs of new circuit-breakers. The results of the calculation represent when the circuit-breakers should be maintained and when those should be replaces by the new ones. Nevertheless, the results of optimal maintenance are different depending on the required reliability of circuit-breakers. The steps of optimal preventive maintenance can be listed as follows:

- The maximum lifetimes of circuit-breakers are set to around 40-50 years
- The different preventive maintenance programs from the 20th year (during wear-out period) are calculated. In this study, the maintenance interval of 3, 5 and 7 years are taken into account.
- The required reliabilities are determined. Therefore, the year in which the circuit-breakers having reliability below specified levels can be investigated. This year is referred to as the year-to-replace the circuit-breakers with the new ones. In addition, the year-to-replace is dependent on the maintenance programs. The more frequent maintenance programs are able to extend the year to replace. However, the addition maintenance costs are increased along with the more frequent maintenance programs.
- The preventive maintenance programs can be changed from one to another program in order to fulfill the reliability requirement.

The examples of different reliabilities can be explained from Fig. 7.11. The requirements of reliabilities of circuit-breakers after 20 years in service are set to 0.9, 0.7 and 0.5.

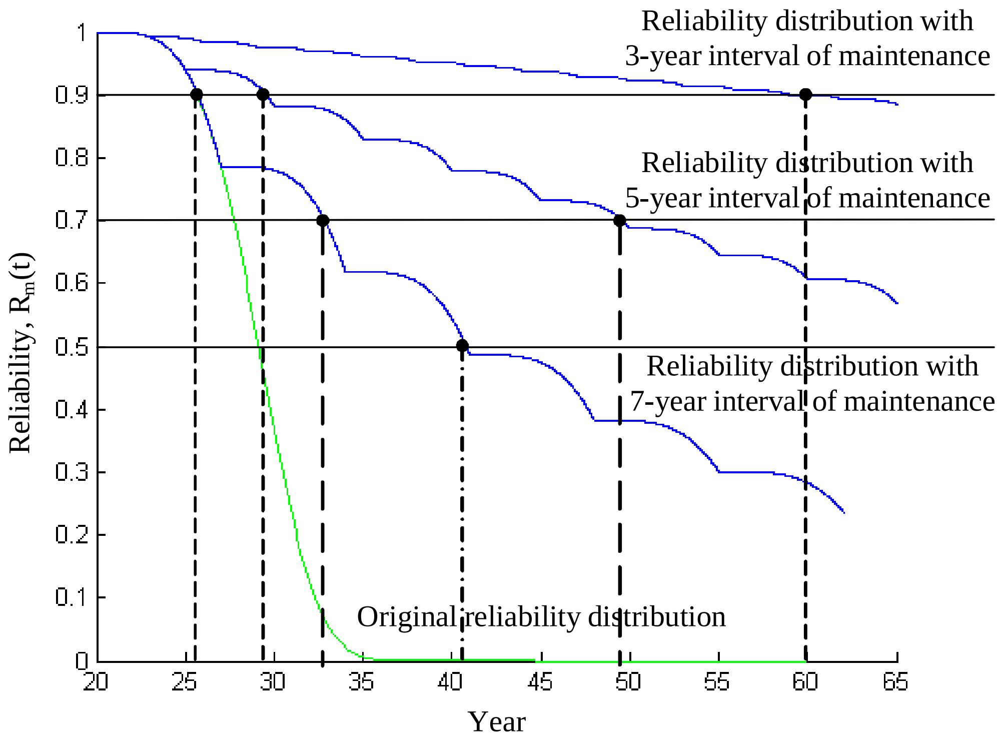


Figure 7.11: The requirements of reliabilities and the different maintenance programs

It can be concluded from the Fig. 7.11:

- When the reliability of circuit-breakers of 0.9 is desired, the 7-year interval maintenance cannot prolong the time to replace, since the time to replace (at the 26th year) takes place before the implementation of preventive maintenance. The time to replace can be prolonged to 29 years when the 5-year interval maintenance is applied. The time to replace can be even extended to 60 years, when the 3-year interval maintenance is implemented. However, the maximum lifetime is limited to 50 years and the 3-year maintenance might not be cost-effective.
- When the reliability of circuit-breakers of 0.7 is required, the original distribution shows the time to replace of 28 years. With the 7-year interval maintenance, the time to replace can be extended to 33 years. The time to replace can be prolonged to 49 years with the 5-year interval maintenance. The 3-year maintenance program is not considered, since the lifetimes of circuit-breakers are however limited to 50 years.
- When the reliability of 0.5 is acceptable, the original distribution represents the time to replace of 29 years. With the 7-year interval maintenance, the time to replace can be extended to 41 years. The 3 and 5-year interval maintenance programs are not taken into account, since the time to replace is beyond the maximum lifetime.

The time to replace due to the different maintenance programs and required reliabilities can be concluded in Table 7.10.

Reliability	Replacing time due to maintenance programs			
	Original maintenance	3-year maintenance	5-year maintenance	7-year maintenance
0.9	26	> 50	29	26
0.7	28	> 50	49	33
0.5	29	> 50	> 50	41

Table 7.10: The time to replace due to the different maintenance programs and required reliabilities

7.3.4 Consideration of Optimal Preventive Maintenance during Wear-out Period

The optimal preventive maintenance during wear-out period can be carried out by consideration of repair costs, maintenance costs and investment costs. The assumptions can be made as follows:

- The original reliability distribution in Fig. 7.8-7.10 is investigated from the first failures of circuit-breakers. Therefore, this reliability curve is a relative reliability distribution considering only the circuit-breakers subject to their first failures.
- The original reliability distribution represents the curve of circuit-breakers of which normal overhaul programs are included. From the database, the overhaul of circuit-breakers had been carried out every 12 years.
- The different additional preventive maintenance programs are introduced into the original reliability distribution. The costs of maintenance per year are calculated
- The cost of investment of a new circuit-breaker is calculated based of the economic lifetime of 30 years with the interest rate of 6.5%. The interest rate of 6.5% is also applied for the maintenance costs.
- The inflation rate is not taken into account.
- The outage costs for non-delivered energy are taken into account by using the outage costs of 5 € / kWh.

- The repair costs of old circuit-breakers are 25 % of the costs of new circuit-breakers, whereas the repair costs of new circuit-breakers are only 12.5 % of the costs of new circuit-breakers.

The failure rate to replace the old circuit-breakers with the new ones can be calculated from Eq. 7.12. This equation represents the costs of old and new circuit-breakers per year. The optimal reliability to replace circuit-breakers can be found when the costs of old circuit-breakers are equal to the costs of new ones. The example of 123 kV of circuit-breakers with the optimal reliabilities corresponding to the different maintenance programs are depicted in Fig. 7.12

$$\lambda_1(C_{R1} + C_O) + C_{M1} = \lambda_2(C_{R2} + C_O) + C_{M2} + C_i \qquad (7.12)$$

where: λ_1: failure rate of old circuit-breakers

λ_2: failure rate of new circuit-breakers

C_{R1}: Costs of repair of old circuit-breakers

C_{R2}: Costs of repair of new circuit-breakers

C_O: Outage costs (5 € / kWh)

C_{M1}: Maintenance costs per year of 3, 4, 5 and 7-year maintenance interval period

C_{M2}: Overhaul costs per year of 12-year interval period

C_i: Investment costs per year

From Eq. 7.12, the failure rate of old circuit-breakers, λ_1, is an unknown value and must be calculated. After that, the failure rate λ_1 is converted to investigate the time and reliability of the original distribution. The optimal reliabilities to replace circuit-breakers are then calculated from the λ_1 by using Eq. 7.12, 5.26 and 5.27. The additional details of the calculation of parameters can be explained:

- λ_2 is represented by the failure rates of SF_6 circuit-breakers (Table 7.5), since it is assumed that all the old circuit-breakers will be replaced with SF_6 circuit-breakers.
- The calculation with and without the influence of outage costs (C_O) is considered.
- The average outage time per year of Germany is 20 minutes.
- It is assumed that a circuit-breaker carries a load current of 500 A.

- In the case with the outage costs, it is assumed that the outage powers per circuit-breaker for 123, 245 and 420 kV are 106, 212 and 364 MW respectively.
- The maintenance and overhaul cost (C_{M1} and C_{M2}) per year are calculated by present value calculation and annuity method. The period of calculation is 30 years.
- Investment cost is calculated from the annuity method with the period of 30 years.

The mentioned parameters of HV circuit-breakers in different voltage levels can be concluded in Table 7.11

Parameter	123 kV	245 kV	420 kV
Interest rate	6.5%	6.5%	6.5%
Cost of new CB	25000 €	75000 €	220000 €
C_{R1}	6250 €	18750 €	55000 €
C_{R2}	3125 €	9375 €	27500 €
C_{M1}: 3-year program 4-year program 5-year program 7-year program	 1563 € 1107 € 878 € 573 €	 3126 € 2215 € 1756 € 1145 €	 6252 € 4430 € 3512 € 2291 €
C_{M2}: 12-year program	264 €	528 €	1057 €
C_O	176666€	353333€	606666€
C_i	1914 €	5743 €	16874 €
λ_2	0.002	0.0144	0.026

Table 7.11: The values of parameters represented in Eq. 7.12

Without the influence of outage costs (C_O = 0), the different maintenance programs result in the significantly different failure rates of old circuit-breakers. The optimal reliabilities from different maintenance programs are marked on the reliability axis in Fig. 7.12. The horizontal lines are drawn parallel to X axis and then cross the different reliability curves. The vertical lines are then drawn from the intersection points to the X axis. The optimal time to replace the old circuit-breakers with the new ones can be read from Fig. 7.12 and can be concluded in Table 7.12

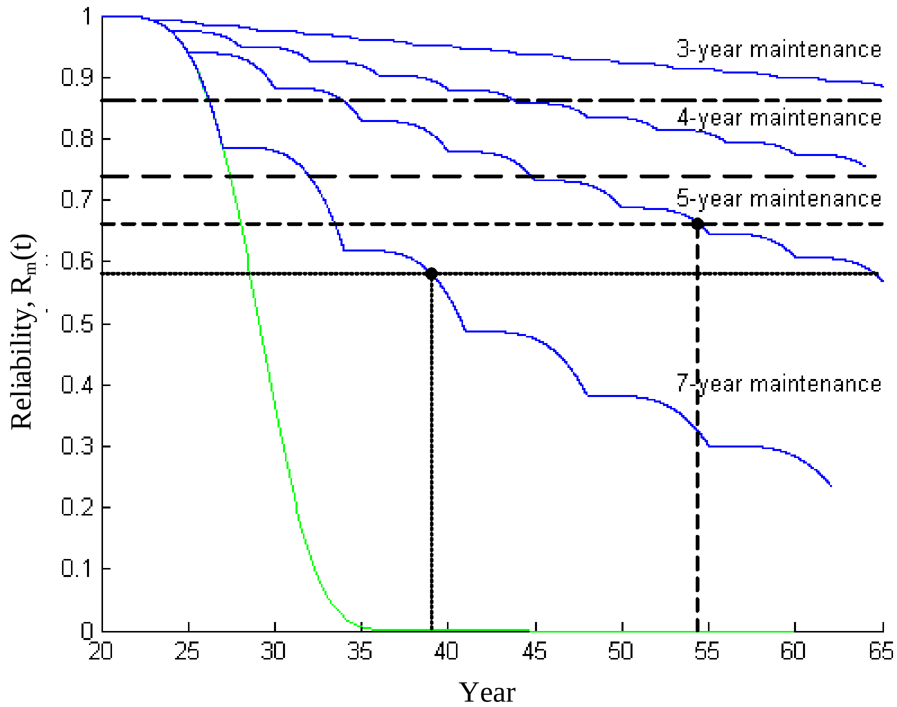


Figure 7.12: The optimal reliabilities and years to replace the old 123 kV circuit-breakers

The results from Table 7.12 must be carefully interpreted. It is obvious from the Fig. 7.12 and Table 7.12 that the 5-year and 7-year maintenance are the optimal maintenance programs which can prolong the time to replace up to 54 and 39 years while keeping the reliability of 0.66 and 0.58 respectively. Although the 3-year and 4-year maintenance can prolong the times to replace up to more than 65 years, they cannot be considered as the optimal maintenance, since the optimal years to replace are beyond the expected lifetime of circuit-breakers.

123 kV	Optimal reliability	Optimal time to replace (years)
3-year maintenance	0.86	> 65
4-year maintenance	0.73	> 65
5-year maintenance	0.66	54
7-year maintenance	0.58	39

Table 7.12: The optimal years to replace of 123 kV circuit-breakers regarding the different maintenance programs

The optimal years to replace of 245 kV and 420 kV circuit-breakers can be carried out in the same way by changing the costs of maintenance, repair costs and investment costs. The optimal times to replace and reliabilities of 245 kV and 420 kV circuit-breakers can be represented in Table 7.13.

	245 kV		420 kV	
	Optimal reliability	Optimal time to replace (years)	Optimal reliability	Optimal time to replace (years)
3-year maintenance	0.74	> 65	0.67	> 65
4-year maintenance	0.66	> 65	0.62	> 65
5-year maintenance	0.61	59	0.59	64
7-year maintenance	0.56	39	0.55	40

Table 7.13: The optimal years to replace of 245 and 420 kV circuit-breakers regarding the different maintenance programs

In case of 245 kV circuit-breakers, it is recommended to introduce the 7-year maintenance program in order to prolong the time to replace to 39 years while keeping the reliability of 0.56. The 7-year maintenance program can also be implemented for 420 kV circuit-breakers to prolong the time to replace up to 40 years at the reliability of 0.55.

When the outage costs (C_O) are taken into account, all the values in Table 7.11 are substituted into Eq. 7.12. Therefore, the failures rates of old circuit-breakers (λ_1) from different maintenance programs are determined. It is found that the failure rates of old circuit-breakers from different maintenance programs are not significantly different due to the high influence of outage costs. The small difference between the old failure rates and the new failure rates implies that the circuit-breakers must be replaced at the early ages (20-25 years), as only a small change of failure rate occurs. This circumstance leads to the fact that the different maintenance programs cannot prolong the time to replace, since the time to replace occurs before the first maintenance is carried out. The optimal reliabilities and the optimal times to place in the case of considering the outage costs are summarized in Table 7.13.

	123 kV		245 kV		420 kV	
	Optimal reliability	Optimal time to replace (years)	Optimal reliability	Optimal time to replace (years)	Optimal reliability	Optimal time to replace (years)
3-year maintenance	0.99	22	0.99	23	0.99	23
4-year maintenance	0.99	22	0.99	23	0.98	24
5-year maintenance	0.99	23	0.99	23	0.98	24
7-year maintenance	0.99	23	0.99	23	0.98	24

Table 7.13: The optimal reliabilities and years to place in the case of taking the outage costs into consideration

It can be seen from Table 7.13 that the optimal times to replace occur before the first maintenance programs are performed. In this case, the different preventive maintenance programs play no important role in order to prolong the times to replace.

Without consideration of outage costs, it is concluded from the optimal maintenance that different preventive maintenance programs can prolong the lifetimes of circuit-breakers. However, the life-cycle cost must be taken into consideration in order to find the optimal times to replace of circuit-breakers. This optimal calculation depends mainly on many parameters as shown in Eq. 7.12. Consequently, the results of the calculation could be varied when the parameters are changed.

It is obvious from the life-cycle cost calculation (Eq. 7.12) that the outage costs have the highest influence. When the high outage costs are taken into account, the difference between the old failure rates and the new failure rates is significantly small. Consequently, the old circuit-breakers should be replaced at the early ages (20-25 years). In this situation, the different maintenance programs have no influence on the time to replace.

8 Conclusions

The main objectives of this thesis were to analyze the risks of HV circuit-breakers, develop the probabilistic models, breakdown the cost structure and establish the improved maintenance strategies. Owing to deregulation of electricity markets, the competitiveness of markets is significantly concerned. This issue is related with the reliability, availability of systems and costs of maintenance. HV circuit-breakers which are one of the most important equipment in power systems have been served as interrupting equipment for operating and short-circuit currents for more than a century. Many technologies in terms of interrupting medium had been developed from oil, air-blast, vacuum to SF_6. At present, a number of HV circuit-breakers are reaching the aging period and they are required to be effectively handled. Some can be prolonged by using the effective maintenance, whereas some must be replaced before the major failures occur.

Normally, HV circuit-breakers have been maintained by using manufacturers' guidelines and experiences of operators. It is not well proved that such maintenance programs are effective regarding costs and performance. Although there are many literatures introducing the optimal maintenance for HV circuit-breakers, most of them propose only the ideas and mathematical models without the reference from the failure database. In this context it was challenging to design and investigate reliability and maintenance strategies in connection with the failure database.

This thesis was constructed of three main parts to handle such problems. In the first part, the failure modes and effects analysis method was applied to determine the risks of components of HV circuit-breakers. The second part was to develop the probabilistic models to investigate the reliability of HV circuit-breakers and failure development. In the last part the cost structure of HV circuit-breakers was determined. In addition, the optimal maintenance strategies during useful and wear-out period were established. The failure database of HV circuit-breakers collected by the Institute of Power Systems, Darmstadt University of Technology had been implemented in all parts.

In order to conduct the failure modes and effects analysis method, the functions of HV circuit-breakers and their functional failure modes were first defined. Next, the causes of failure related to the function and components were investigated and the numbers of failures were taken from the database. The consequences of each failure including personnel safety, environmental impact, operation availability and costs of repair were evaluated by using a score system. The criteria of failure detection must be considered to evaluate the severity of failures. Consequently, the risks of HV circuit-breaker components composed of the consequence of failure, the failure detection and the probability of failure could be calculated and the ranking of risk is then represented. The weighing factors for such three parameters were determined by using the decision matrix approach. It was discovered from the risk diagram that the components of HV circuit-breakers are in the low and medium risk region. The improved maintenance strategies should be applied to the components which are in the medium risk region to assure that those components will not reach the high risk region. The disadvantage of the risk diagram is that it is a time-independent diagram. Consequently, the diagram cannot predict which component should be replaced at which year.

The probabilistic models were developed to investigate the reliability of HV circuit-breakers and how the failures develop from year to year. The first model, treeing diagram, is the model representing the probability of failures occurring in any subsequent years. The development of failures from the failure-free state to the first and second failures was investigated by using the conditional probability method and represented as a treeing diagram. The critical pathways of failure development could be investigated with this model. The second model, the cascading reliability model, was the extension of the treeing diagram. The development of failures from failure-free state to the first, second and third failures was represented in terms of mean time to failure, transition and state probabilities. With this model, it is possible to discover when the failures could occur and at which probability. It is beneficial for the asset managers and maintenance personnel to be aware of the following failures. The last probabilistic model is the reliability model obtained by using the application of Markov process. In this model, HV circuit-breakers are composed of five main components. The reliability parameters such as mean time to failure and mean time to repair of each component were examined from the database. By using the Markov process method, the failure-free durations and availability of different types of HV circuit-breakers can be investigated. It was concluded from this Markov model that the availability of HV circuit-breakers is over 99%. The influence of repetitive failures resulting from human error or incomplete repair was taken into consideration.

In the first part of the last section, the cost structure of HV circuit-breakers related to specifications was broken down by using the decision matrix approach. This decision matrix was also applied to each main component resulting in the detailed cost structure. It was found from the cost breakdown that “rated voltage” has the highest influence on the total costs followed by “rated short circuit breaking current” and “rated lighting and switching impulse withstand voltage”. The cost structure provides the valuable information for the designers to design the cost-effective HV circuit-breakers for different applications.

Maintenance optimization was the last issue in this thesis. It can be divided into two periods: useful life and wear-out period. These periods were handled with the different maintenance models. The optimal maintenance frequency during useful life period was established from the principle that more frequent maintenance could result in more system downtime; on the other hand, less maintenance could result in downtime due to failures. The mathematical model and the failure rates of HV circuit-breakers were applied. The different types of HV circuit-breakers at different voltage levels were taken into consideration. It was found that the minor and major maintenance for 123 kV HV circuit-breakers should be performed every 8-10 and 24-33 years respectively. For 245 kV, the 4-year interval minor and 14-year interval major maintenance are suggested to be implemented. For the voltage level of 420 kV, it is suggested to introduce the minor and major maintenance every 3-4 and 8-10 years respectively.

During the wear-out period, the failure rate of HV circuit-breakers represents the Weibull distribution. With the preventive maintenance, it is possible to increase the reliability during this period. Nevertheless, the more frequent maintenance results in the more costs of maintenance. Therefore, the optimal maintenance was considered by taking the costs of repair, costs of undelivered energy, costs of maintenance and costs of investment into account. The different preventive maintenance programs show the different results regarding the reliability of HV circuit-breakers and optimal time to replace the old circuit-breakers with the new ones. It must be noted that this optimal maintenance model considerably relates to mentioned costs. The results could be changed when one or more costs are changed.

The optimal maintenance programs during useful life and wear-out period are very useful for asset managers to make a decision when and what kind of maintenance should be performed.

It is recommended that this optimal maintenance could be investigated in more detail in terms of the sensitivity of the different cost parameters.

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List of Symbols and Abbreviations

Symbols

Al_2O_3	Aluminium oxide
CaO	Calcium oxide
f(t)	Probability density function
I_{k1TF}	Single-phase short circuit-current at terminal
I_{k3TF}	Three-phase short circuit-current at terminal
I_{load}	Load current
I_r	Rated normal current
I_{rb}	Rated short-circuit breaking current
I_{sc}	Short-circuit current
MTTF	Mean time to failure
MTTR	Mean time to repair
NaOH	Sodium hydroxide
N_2	Nitrogen
$N_f(t)$	Number of component failed at time t
$N_s(t)$	Number of components surviving at time t
Q(t)	Cumulative distribution function
R(t)	Survivor function
SF_6	Sulphur hexafluoride
Z_w	Characteristic impedance
$\lambda(t)$	Failure rate
δ^2	Variance
β	Shape parameter of Weibull distribution
α	Scale parameter of Weibull distribution
ω	Operating frequency

Abbreviations

EPRI	Electric Power Research Institute
FMEA	Failure Modes and Effects Analysis
HV	High Voltage
IEEE	Institute of Electrical and Electronics Engineers
RCM	Reliability-Centred Maintenance
RRRV	Rate of Rise of Recovery Voltage
TRV	Transient Recovery Voltage
XLPE	Cross-linked polyethylene

Appendix A The Transformation Method Used for Decision Matrix Approach

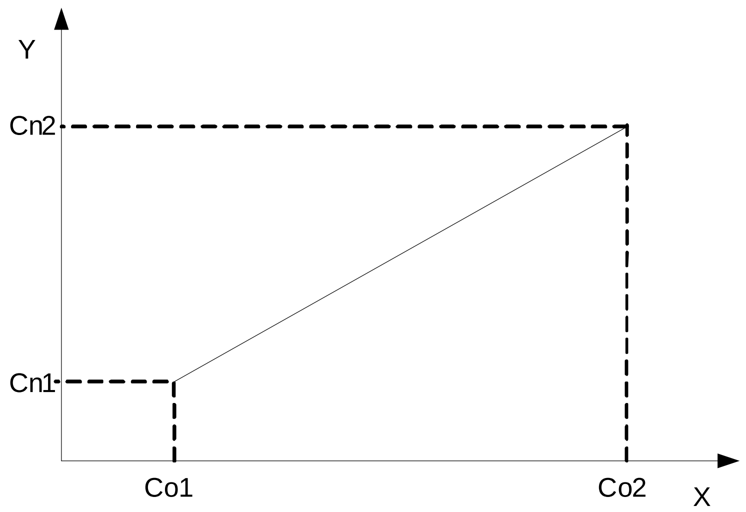

Figure A1: The transformation method

The transformation of the actual values from section 4.3 into the values with embedded weighting factors as described in section 4.4 can be explained by using Fig. A1. This method is suitable for the data that is linearly distributed. The variables on Fig. A1 are composed of:

Co1:	the real minimum value	Co2:	the real maximum value
Cn1:	the new minimum value	Cn2:	the new maximum value

The related equations are expressed as follows:

$$\begin{aligned} y &= a + b \cdot x \\ a &= Cn1 - \frac{Cn2 - Cn1}{Co2 - Co1} \cdot Co1 \\ b &= \frac{Cn2 - Cn1}{Co2 - Co1} \end{aligned} \qquad (A.1)$$

The real minimum values of the parameters can be obtained after FMEA Table (Appendix B) is formed and completed. For example, the Table A1 resulting in Table 4.5 and 4.6 shows the real values from FMEA table and the values after performing the decision matrix approach as explained in section 4.4. The priority scores of Table 4.5 can be calculated by the product of transformation of parameters 1,2 and 3, while the scores of Table 4.6 are calculated from parameter 1,2 and 4.

Parameter	Real values		Transformed values	
	minimum	maximum	minimum	maximum
1.Consequence of failure	1	28	1	17
2.Failure detection	1	3	1	50
3.Probability of failure by functional failure	7.7e-05	0.055	1	33
4.Probability of failure by component	7.0e-04	0.073	1	33

Table A1: The real values and transformed values.

By using the equation A.1, the transformed equation can be obtained as stated:

1. Consequence of failure: $y = 0.4074 + 0.5926x$ (A.2)
2. Failure detection $y = -23.5 + 24.5x$ (A.3)
3. Probability of failure by functional failure $y = 0.996 + 0.1363x$ (A.4)
4. Probability of failure by component $y = 0.69 + 0.103x$ (A.5)

The parameters for calculating the total consequences of section 4.6, risk diagram, are composed of only the consequence of failure and the failure detection. The decision matrix between these 2 parameters had been applied. It is found that the weighting ration between the failure detection and the consequence of failure is 75:25. By using the equation A.1, the transformed equations can be obtained.

1. Consequence of failure $y = 0.111 + 0.888x$ (A.6)
2. Failure detection $y = -36 + 37x$ (A.7)

Appendix B The FMEA Evaluation of SF_6 Circuit-Breakers

B1: The FMEA evaluation based on the functional failures: SF_6 circuit-breakers

Information Reference				Consequence evaluation										Score	Failure dectection			No. of failure	Rank ing
Failure mode	Failure cause			P	E+	E	E-	O+	O	O-	C+	C	C-		Impos-sible	Easy	Diffi-cult		
1. Does not close on command	1.Operating mechanism fails	1.1 Mechanical drive fails	1. Motor fails							X			X	5		X		4.49	47
			2. Spring fails						X				X	6		X		2.17	48
			3. inadequate lubrication							X			X				X		
			4. Energy transfer fails																
			4.1 Damping fails							X			X	5			X	0.72	19
			4.2 Hydraulic pump fails							X			X	5		X		0.72	52
			5. Others																
		1.2 Hydraulic drive fails	1. Motor fails							X			X	5		X		20.19	42
			2. N2 Storage fails						X				X	6		X		160.76	20
			3. inadequate lubrication							X			X				X		
			4. Energy transfer fails																
			4.1 Damping fails							X			X	5			X	8.22	14
			4.2 Linkage fails				X		X			X		14	X			51.39	2
			4.3 Hydraulic pump fails							X			X	5		X		71.78	30
			4.4 Hydraulic cylinder fails							X		X		6		X		77.02	27
			4.5 Conduit/Connection fails							X			X	5		X		229.55	18
			4.6 Collective tank fails		X					X		X		15		X		33.65	26
			4.7 Valves fail						X			X		7		X		119.40	24
			4.8 Others																
			5. Others																
	2. Control and auxiliary system fails		1. No supply voltage							X			X			X			
			2. Sensor fails							X			X	5		X		234.78	17
			3. Relay fails							X			X	5		X		184.20	22
			4. Connection cable fails							X			X	5		X		50.10	37
			5. Heater fails							X		X		6			X	75.52	7

Information Reference				Consequence evaluation										Score	Failure dectection			No. of failure	Rank ing
Failure mode	Failure cause			P	E+	E	E-	O+	O	O-	C+	C	C-		Impos-sible	Easy	Diffi-cult		
			6. Others																
	3. Current carrying parts fail	3.1 Arcing chamber fails	1. Low SF6 density				X			X		X		13		X		161.92	13
			2. Low temperature																
2. Does not open on command	1.Operating mechanism fails	1.1 Mechanical drive fails	1. Motor fails							X			X	5		X		1.51	50
			2. Spring fails						X				X	6		X		0.76	49
			3. inadequate lubrication							X			X				X		
			4. Energy transfer fails																
			4.1 Damping fails							X			X	5			X	0.24	21
			4.2 Hydraulic pump fails							X			X	5		X		0.24	54
			5. Others																
		1.2 Hydraulic drive fails	1. Motor fails							X			X	5		X		6.81	46
			2. N2 Storage fails						X				X	6		X		54.24	32
			3. inadequate lubrication							X			X				X		
			4. Energy transfer fails																
			4.1 Damping fails							X			X	5			X	2.78	16
			4.2 Linkage fails				X		X			X		14	X			18.50	3
			4.3 Hydraulic pump fails							X			X	5		X		24.22	41
			4.4 Hydraulic cylinder fails							X		X		6		X		25.98	40
			4.5 Conduit/Connection fail							X			X	5		X		77.45	29
			4.6 Collective tank fails		X					X		X		15		X		11.35	39
			4.7 Valves fail						X			X		7		X		40.29	35
			4.8 Others																
			5. Others																
	2. Control and auxiliary system fails		1. No supply voltage							X			X			X			
			2. Sensor fails							X			X	5		X		79.22	28
			3. Relay fails							X			X	5		X		62.15	33
			4. Connection cable fails							X			X	5		X		16.90	43
			5. Heater fails							X		X		6			X	25.48	12
			6. Others																
	3. Current carrying parts fail	3.1 Arcing chamber fails	1. Low SF6 density				X			X		X		13		X		54.63	25
			2. Low temperature																
3. Closes without command	1.Operating mechanism fails	1.1 Mechanical drive fails	1. Energy transfer fails																
			1.1 Damping fails							X			X	5			X	0.03	23

Information Reference				Consequence evaluation										Score	Failure dectection			No. of failure	Rank ing
Failure mode	Failure cause			P	E+	E	E-	O+	O	O-	C+	C	C-		Impos-sible	Easy	Diffi-cult		
			1.2 Spring fails						X				X	6		X		0.10	51
			1.3 Linkage fails							X			X	5		X		0.27	53
			1.4 Hydraulic pump fails							X			X	5		X		0.03	55
		1.2 Hydraulic drive fails	1. Valves fail						X			X		7		X		5.34	44
	2. Control and auxiliary system fails		1. Current flows in the close coil																
			2.Relay fails							X			X	5		X		8.24	45
	3. Other reasons		1. Vibration of circuit-breaker																
4. Opens without command	1.Operating mechanism fails	1.1 Mechanical drive fails	1. Trip latch not secure							X		X		6			X	4.00	15
		1.2 Hydraulic drive fails	1. Valves fail						X			X		7		X		33.98	38
	2. Control and auxiliary system fails		1. EMC fails						X				X						
			2.Relay fails							X			X	5		X		52.41	36
	3. Other reasons		1. Vibration of circuit-breaker																
5. Does not make the current	1. Current carrying parts fail	1.1 Arcing chamber fails	1. Contact fails	X	X			X			X			28			X	13.28	5
	2. Other reasons		1. Human failure																
6. Does not break the current	1.Operating mechanism fails	1.1 Mechanical drive fails	1. Mechanism does not travel complete distance		X				X		X				X				
			2. low velocity																
		1.2 Hydraulic drive fails	1. Mechanism does not travel complete distance		X				X		X								
			2. low velocity																
			3. Linkage breakdowns				X		X			X		14	X			6.69	10
	2.Current carrying parts fail	2.1 Arcing chamber fails	1. Insufficient contact opening	X	X			X			X						X		
			2. Low SF6 density				X			X		X		13		X		19.75	34
			3.Overvoltage stress from switching exceeds CB capability	X	X			X			X				X				
			4. Lightning		X				X			X			X				
		2.2 Controlled capacitor fails				X			X			X		15	X			56.00	1
7. Fails to carry the current	1. Current carrying parts fail	1.1 Arcing chamber fails	1. Contact fails	X	X			X			X			28			X	11.72	8
8. Breakdown to earth	1. Insulation fails	1.1 Insulating material fails	1. Damaged interrupter from external impacts	X	X					X		X				X			

Information Reference				Consequence evaluation										Score	Failure dectection			No. of failure	Rank ing
Failure mode	Failure cause			P	E+	E	E-	O+	O	O-	C+	C	C-		Impos-sible	Easy	Diffi-cult		
			2. Contact from animals																
			3. Lightning		X				X			X			X				
			4. insulation aging		X				X			X			X				
			5. Water infiltration		X				X			X			X				
			6.Flashover by transient effect							X	X				X				
			7. Porcelain fails			X				X	X			15	X			15.66	4
			8. Arcing Chamber Housing			X				X	X			15	X			11.57	6
			9.Pollution			X			X		X						X		
9. Breakdown between poles	1. Insulation fails	1.1 Insulating material fails	1. Contact from animals																
			2.Flashover by transient effect							X	X				X				
			3.Pollution			X			X		X						X		
10. Breakdown across open pole (internal)	1. Current carrying parts fail	1.1 Arcing chamber fails	1. Leak of SF6				X			X		X		13		X		23.70	31
			2. Low temperature																
			3.Flashover by transient effect							X	X				X				
11. Breakdown across open pole (external)	1. Insulation fails	1.1 Insulating material fails	1. Damaged interrupter from external impacts	X	X					X		X				X			
			2. Contact from animals																
			3. Lightning		X				X			X			X				
			4. insulation aging		X				X			X			X				
			5. Water infiltration		X				X			X			X				
			6.Flashover by transient effect							X	X				X				
			7. Porcelain fails			X				X	X			15	X			7.34	9
			8. Arcing Chamber Housing			X				X	X			15	X			5.43	11
			9.Pollution			X			X		X						X		
12. Others																			

Remark: There is no information from the database for some causes of failures. However, the consequence evaluation had been carried out for all possibilities of failures.

B2: The FMEA evaluation based on component failures: SF_6 circuit-breakers

failure cause		failure characteristic	Consequence evaluation										Failure detection			No. of failure	Conse-quence	Fault detec-tion	Ranking
			P	E+	E	E-	O+	O	O-	C+	C	C-	Impos-sible	Easy	Difficult				
1.Operating mechanism fails	1.1 Mechanical drive fails	1. Motor fails							X			X		X		6	5	1	20
		2. Spring fails						X				X		X		3	6	1	21
		3. inadequate lubrication							X			X			X				
		4. Energy transfer fails																	
		4.3 Trip latch not secure (closing latch)							X		X				X	6	6	2	9
		5. Mechanism does not travel complete distance		X				X		X			X						
	1.2 Hydraulic drive fails	1. Motor fails							X			X		X		27	5	1	19
		2. N2 Storage fails						X				X		X		215	6	1	14
		3. inadequate lubrication							X			X			X				
		4. Energy transfer fails																	
		4.1 Damping fails							X			X			X	12	5	2	8
		4.2 Linkage fails				X		X			X		X			75	14	3	1
		4.3 Hydraulic pump fails							X			X		X		96	5	1	17
		4.4 Hydraulic cylinder fails							X		X			X		103	6	1	16
		4.5 Conduit/Connection fails							X			X		X		307	5	1	11
		4.6 Collective tank fails		X					X		X			X		45	15	1	15
		4.7 Valves fail						X			X			X		199	7	1	13
		5. Mechanism does not travel complete distance		X				X		X			X						
2. Control and au1iliary system fails		1. No supply voltage							X			X		X					
		2. Sensor fails							X			X		X		314	5	1	10
		3. Relay fails							X			X		X		307	5	1	11
		4. Connection cable fails							X			X		X		67	5	1	18
		5. Heater fails							X		X				X	101	6	2	6
		6. EMC fails						X				X	X				6	3	
3. Current carrying parts fail	3.1 Arcing chamber fails	1. Low SF6 density				X			X		X			X		260	13	1	7
		2. Contact fails	X	X			X			X					X	25	28	2	4
		3. Insufficient contact opening	X	X			X			X					X				
		4.Overvoltage stress from switching exceeds CB capability	X	X			X			X			X						

failure cause		failure characteristic	Consequence evaluation										Failure detection			No. of failure	Conse-quence	Fault detec-tion	Ranking
			P	E+	E	E-	O+	O	O-	C+	C	C-	Impos-sible	Easy	Diffi cult				
	3.2 Controlled capacitor fails				X			X			X		X			56	15	3	2
4. Insulation fails	4.1 Insulating material fails	1. Damaged interrupter from external impacts	X	X					X		X			X					
		2. Lightning		X				X			X		X						
		3. insulation aging		X				X			X		X						
		4. Water infiltration		X				X			X		X						
		5.Flashover by transient effect							X	X			X						
		6. Porcelain fails			X				X	X			X			23	15	3	3
		7. Arcing Chamber fails			X				X	X			X			17	15	3	5
		8. Pollution			X			X		X					X				

Appendix C Two-dimensional Diagrams of Treeing Model

C.1 SF_6 circuit-breakers with hydraulic drives

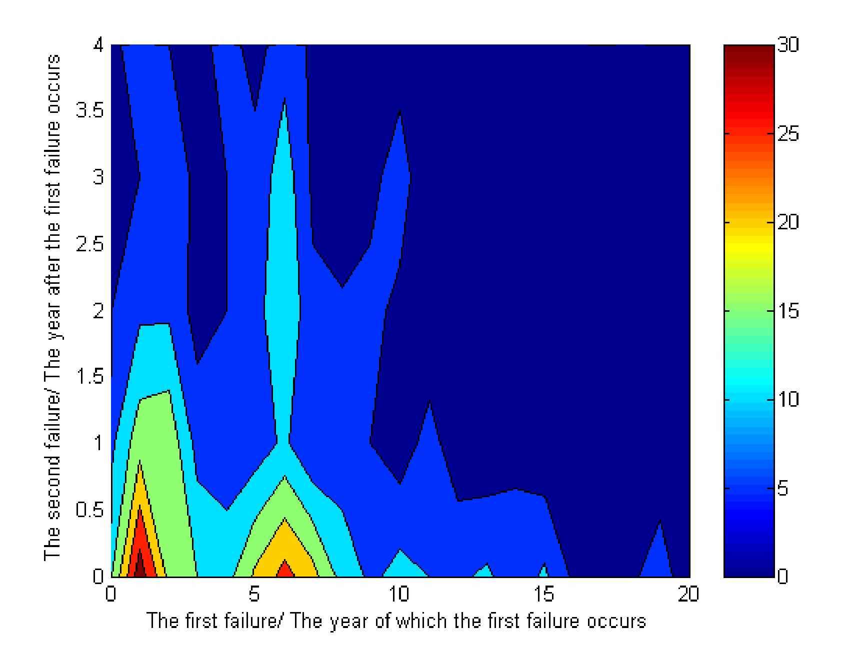

Figure C.1: Two-dimensional diagram representing the number of failures with respect to time (SF_6 circuit-breakers with hydraulic drives)

C.2 SF_6 circuit-breakers with mechanical drives

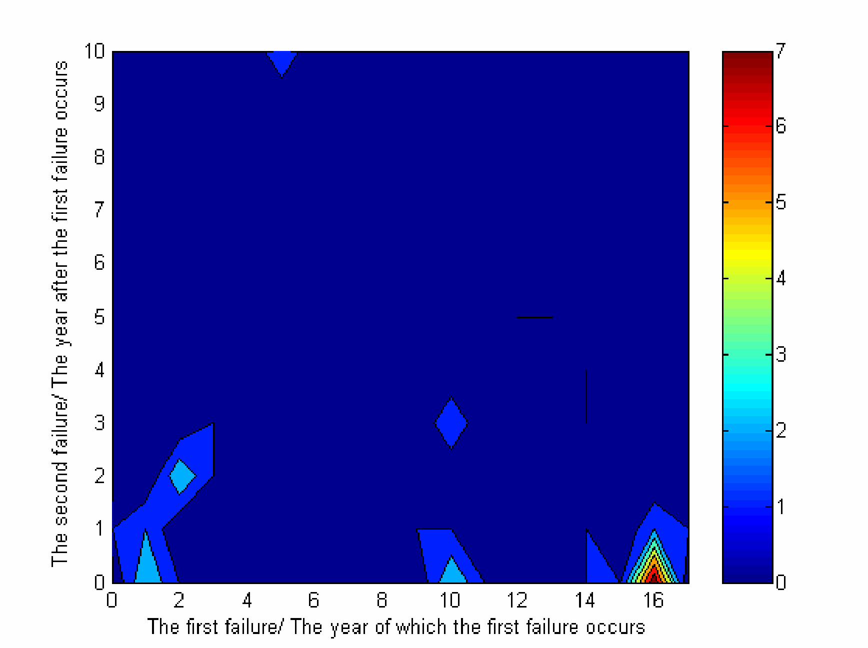

Figure C.2: Two-dimensional diagram representing the number of failures with respect to time (SF_6 circuit-breakers with mechanical drives)

C.3 Oil circuit-breakers with hydraulic drives

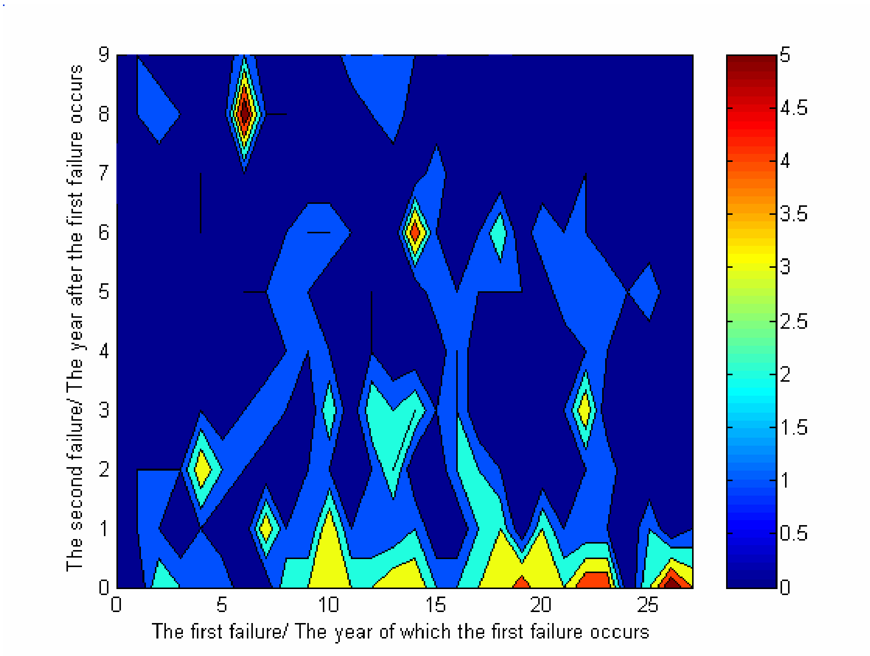

Figure C.3: Two-dimensional diagram representing the number of failures with respect to time (oil circuit-breakers with hydraulic drives)

C.4 Oil circuit-breakers with mechanical drives

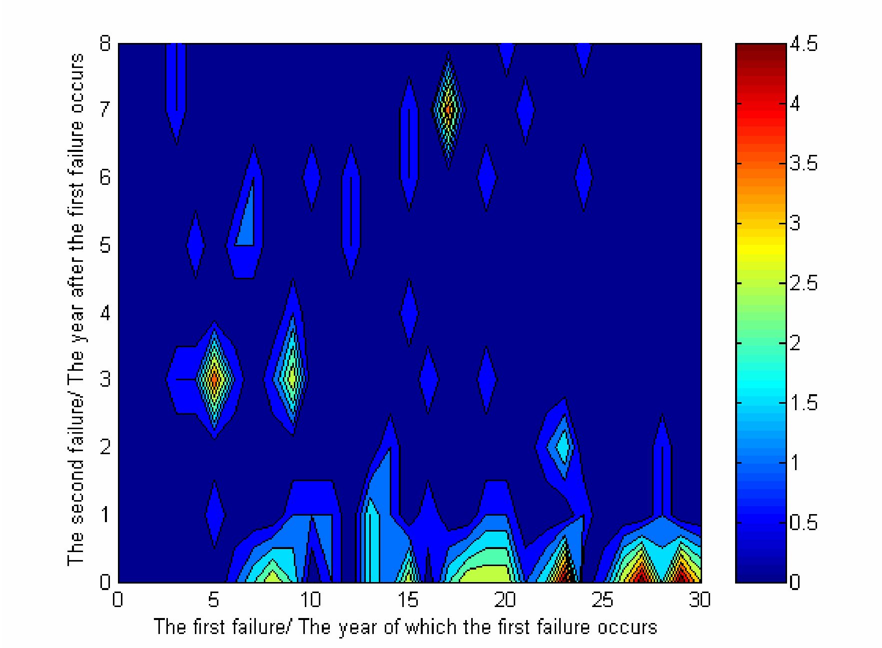

Figure C.4: Two-dimensional diagram representing the number of failures with respect to time (oil circuit-breakers with mechanical drives)

Appendix D The Decision Matrix of HV Circuit-Breaker's Main Components

Nr.	Kriterium	Rated voltage 1	Rated lightning impulse withstand voltage 2	Rated operating current 3	Rated duration of short circuit (1 s) 4	Rated short circuit breaking current 5	First pole-to-clear factor 6	Rated out-of-phase breaking current (optional) 7	Rated line-charging breaking current 8	Rated capacitor bank inrush making current 9	Rated operating sequence 10	Temperature class 11	Classification: number of operation 12	Rate of Rise of Recovery Voltage (RRRV) 13	Σ	WF/%
1	Rated voltage	0	4	3	5	2	4	5	5	3	4	3	4	4	46	9.829
2	Rated lightning impulse withstand voltage	2	0	2	4	1	3	3	5	4	4	2	3	3	36	7.692
3	Rated operating current	3	4	0	4	2	4	4	5	4	4	3	3	4	44	9.402
4	Rated duration of short circuit (1 s)	1	2	2	0	1	3	3	4	2	2	1	2	2	25	5.342
5	Rated short circuit breaking current	4	5	4	5	0	5	5	5	5	4	4	4	4	54	11.54
6	First pole-to-clear factor	2	3	2	3	1	0	4	4	3	2	3	3	3	33	7.051
7	Rated out-of-phase breaking current (optional)	1	3	2	3	1	2	0	4	3	2	2	2	3	28	5.983
8	Rated line-charging breaking current	1	1	1	2	1	2	2	0	1	1	1	1	1	15	3.205
9	Rated capacitor bank inrush making current	3	2	2	4	1	3	3	5	0	2	2	2	2	31	6.624
10	Rated operating sequence	2	2	2	4	2	4	4	5	4	0	3	4	3	39	8.333
11	Temperature class	3	4	3	5	2	3	4	5	4	3	0	4	4	44	9.402
12	Classification: number of operation	2	3	3	4	2	3	4	5	4	2	2	0	2	36	7.692
13	Rate of Rise of Recovery Voltage (RRRV)	2	3	2	4	2	3	3	5	4	3	2	4	0	37	7.906
															468	100

Table D.1: The decision matrix of quenching unit

Nr.	Kriterium	1 Rated voltage	2 Rated lightning impulse withstand voltage	3 Rated operating current	4 Rated short circuit breaking current	5 Earthquake level	6 Bending strength	7 Pollution level	Σ	WF/%
1	Rated voltage	0	1	5	4	4	3	3	20	15.87
2	Rated lightning impulse withstand voltage	5	0	5	4	4	4	4	26	20.63
3	Rated operating current	1	1	0	2	2	2	2	10	7.937
4	Rated short circuit breaking current	2	2	4	0	4	3	3	18	14.29
5	Earthquake level	2	2	4	2	0	3	3	16	12.7
6	Bending strength	3	2	4	3	3	0	3	18	14.29
7	Pollution level	3	2	4	3	3	3	0	18	14.29
									126	100

Table D.2: The decision matrix of HV Insulation

Nr.	Kriterium	1 Rated voltage	2 Rated lightning impulse withstand voltage	3 Rated operating current	4 Rated short circuit breaking current	5 Rated line-charging breaking current	6 Earthquake level	7 Bending strength	Σ	WF/%
1	Rated voltage	0	3	5	3	5	4	4	24	19.05
2	Rated lightning impulse withstand voltage	3	0	5	4	5	5	5	27	21.43
3	Rated operating current	1	1	0	1	3	1	1	8	6.349
4	Rated short circuit breaking current	3	2	5	0	5	4	4	23	18.25
5	Rated line-charging breaking current	1	1	3	1	0	1	1	8	6.349
6	Earthquake level	2	1	5	2	5	0	3	18	14.29
7	Bending strength	2	1	5	2	5	3	0	18	14.29
									126	100

Table D.3: The decision matrix of supporting structure

Nr.	Kriterium	1 Rated voltage	2 Rated operating current	3 Rated short circuit breaking current	4 First pole-to-clear factor	5 Rated line-charging breaking current	6 Rated operating sequence	7 Temperature class	8 Classification: number of operation	9 Earthquake level	10 Rate of Rise of Recovery Voltage (RRRV)	Σ	WF/%
1	Rated voltage	0	5	4	4	5	4	3	5	5	5	40	14.81
2	Rated operating current	1	0	1	2	3	1	1	1	3	2	15	5.556
3	Rated short circuit breaking current	2	5	0	5	5	4	3	4	5	5	38	14.07
4	First pole-to-clear factor	2	4	1	0	4	1	1	2	3	3	21	7.778
5	Rated line-charging breaking current	1	3	1	2	0	1	1	1	1	1	12	4.444
6	Rated operating sequence	2	5	2	5	5	0	3	4	5	5	36	13.33
7	Temperature class	3	5	3	5	5	3	0	4	5	5	38	14.07
8	Classification: number of operation	1	5	2	4	5	2	2	0	4	4	29	10.74
9	Earthquake level	1	3	1	3	5	1	1	2	0	2	19	7.037
10	Rate of Rise of Recovery Voltage	1	4	1	3	5	1	1	2	4	0	22	8.148
												270	100

Table D.4: The decision matrix of drive

Appendix E Zusammenfassung in Deutsch

Die Hauptziele der Arbeit sind Risiko Analyse der Leistungsschalter, Entwicklung der Wahrscheinlichkeitsmodelle, Aufstellung der Kostenstruktur und Aufbau optimierter Instandhaltungsmaßnahmen. Normalerweise werden die Instandhaltungsmaßnahmen an Leistungsschalter nach Hersteller-Richtlinien und Erfahrungen des Betreibers durchgeführt. Dieses Verfahren ist noch nicht überprüft worden, ob es leistungsfähig und kosteneffizient ist. Obwohl es viel Literatur über optimierte Instandhaltungsmaßnahmen gibt, stellen die meisten Beiträge nur Ideen und mathematische Modelle ohne Zusammenhang mit einer Datenbank vor. Es ist daher eine Herausforderung, die Zuverlässigkeit und Instandhaltungs-Strategie im Zusammenhang mit einer Datenbank zu untersuchen.

Diese Dissertation ist aus drei Hauptteilen zusammengesetzt. Im ersten Teil wird „Failure Modes and Effects Analysis (FMEA)“ vorgestellt, damit das Risiko der Komponenten festgelegt werden können. Der zweite Teil behandelt die Wahrscheinlichkeitsmodelle, um die Zuverlässigkeit und Entwicklung der Fehler zu erforschen. Im letzten Teil wird die Kostenstruktur aufgestellt. Außerdem werden optimierte Instandhaltungsmaßnahmen während der Betriebszeit und Alterungszeit vorgestellt. Auf Grundlage der umfangreichen Betriebsmittel-Datenbank des Instituts für Elektrische Energieversorgung der TU Darmstadt ist es möglich, alle Teile durchzuführen.

Das Ergebnis der FMEA-Methode repräsentiert, dass alle Komponenten im niedrigen und mittleren Risiko-Bereich liegen. Um das Risiko der Komponenten im mittleren Bereich zu reduzieren, sollten verbesserte Instandhaltungsmaßnahmen zum Einsatz gebracht werden. Mit Hilfe des „Treeing-und-Cascading-Reliability-Model“-Diagramm ist es möglich herauszufinden, wann die folgenden Fehler auftreten und mit welcher Wahrscheinlichkeit. Das Markov-Modell ist ein Wahrscheinlichkeitsmodell, um die Zuverlässigkeit einzelner Komponenten zu finden. Die Kostenstruktur ist nützlich für Designer, um optimale Leistungsschalter für verschiedene Anwendungen zu planen. Die Instandhaltung während der Betriebzeit wird mit Hilfe der Fehlerrate und der optimalen Instandhaltungsfrequenz durchgeführt. Während der Alterungszeit wird die optimale Instandhaltung mit Hilfe der Weibull-Verteilung und eines zeitorientierten Instandhaltungsmodells vorgestellt. Schließlich kann die optimale Zeit zum Austausch eines Leistungsschalters berechnet werden.

Lebenslauf

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1988 – 1991	Gymnasium: Chulalongkorn University Demonstration Secondary, Bangkok
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	Hochschulstudium
1993 – 1997	Studium der Elektrotechnik am King Mongkut's Institute of Technology, Ladkrabang, Bangkok
Juni 1997	Abschluss: Bachelor of Engineering
1997 – 2001	Studium der Elektrotechnik an der Chulalongkorn University, Bangkok
1999 – 2000	Studium der Elektrotechnik an der University of New South Wales, Sydney, Australien
März 2000	Abschluss: Master of Engineering Science, University of New South Wales
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Berufserfahrung

2000 – 2002	Mitarbeiter von Office of Atomic Energy for Peace (OAEP), Bangkok
2003 – 2007	Wissenschaftlicher Mitarbeiter am Institut für Elektrische Energieversorgung, Technische Universität Darmstadt